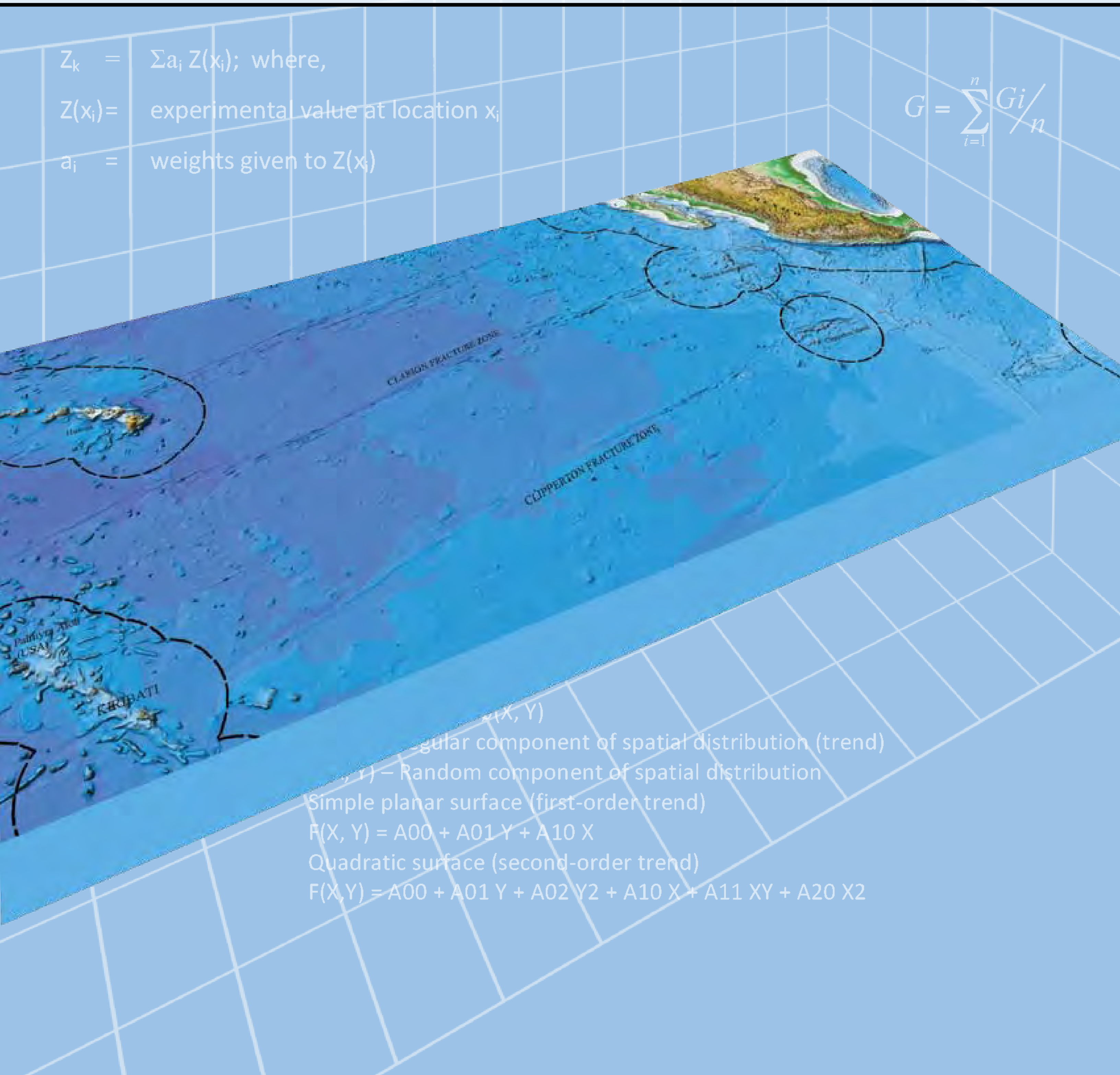
ESTABLISHMENT OF A GEOLOGICAL MODEL OF POLYMETALLIC NODULE DEPOSITS IN THE CLARION-CLIPPERTON FRACTURE ZONE OF THE EQUATORIAL NORTH PACIFIC OCEAN



ESTABLISHMENT OF A GEOLOGICAL MODEL OF POLYMETALLIC NODULE DEPOSITS IN THE CLARION-CLIPPERTON FRACTURE ZONE OF THE EQUATORIAL NORTH PACIFIC OCEAN

Proceedings of the International Seabed Authority's Workshop
held 13-20 May, 2003 in Nadi, Fiji

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FOREWORD

Welcoming remarks and address by the Honourable Jonetani Cokanasiga, Minister of Home Affairs and Acting Minister of Foreign Affairs of Fiji

Honourable Satya Nandan and all participants, welcome to Fiji. Your Excellency, Secretary-General of the International Seabed Authority, distinguished scientists and workshop participants, I would also like to say good morning and *bula* to my Fijian colleagues here: the Director of the South Pacific Applied Geoscience Commission (SOPAC), the Director of Mineral Resources and others from Fiji who are here this morning.

It is not often that we in Fiji have an opportunity to host such an important gathering of technical experts from the world at large who have been working in such a pioneering frontier such as deep-sea mineral exploration. This workshop on the establishment of a geological model of polymetallic nodule deposits in the Clarion-Clipperton Zone is one of several over the years hosted by the International Seabed Authority. I am given to understand that it is only the second time that such an important meeting of the International Seabed Authority is being held outside of Jamaica. We therefore feel very honoured to have been chosen to host this conference.

Fiji, ladies and gentlemen, has a long-standing interest in the oceans. We were one of the first coastal states to ratify the United Nations Law of the Sea Convention when it was opened for signature in 1982, and one of the four applicants to serve as host to the headquarters of the International Seabed Authority. Unfortunately, we lost out to Kingston, Jamaica. However, we remain committed to the Organization and its goals and we are indeed happy to note that one of our esteemed diplomats and a son of Fiji was the first (and continues to be) Secretary-General.

Fiji has a long history of mining and mineral exploration with continuous activity at our gold mine at Vatukoula for over 70 years. Fiji's location along the Pacific Rim of Fire means that there is good potential for the discovery of other significant deposits on land. We are therefore quite familiar with exploration for minerals being carried out in our land. It has therefore been of tremendous interest for us to see as well (for over three decades now) marine scientific research being carried out in and around our exclusive economic zone and we have actively encouraged and promoted these activities. Whilst some of this research has been for pure science, others have not. This has raised questions among some of us as to what such work entails, and raises hopes as to what economic benefits such research could bring, should some of these discoveries be exploited in the future. We have questions as to whether there will be mining in our offshore seas, and if so when? Fiji and other Pacific island States pin their future hopes on the development of their oceans, which exceed by inordinate orders of magnitude our land areas. We have often wondered, maybe even dreamed about, what vast unknown riches the ocean deeps hold. It is my understanding that the intention of a workshop such as this is to bring about a bit of realism to what we imagine exists. Hence our extreme interest in your forthcoming proceedings.

Ever since the discovery of mineral deposits on the seafloor well over a century ago, man has dreamed of potential benefits and untold riches. However, it is only in the past several decades that measured steps have been taken towards quantitatively assessing the deposits, and estimating resource and reserves, and of course, developing technologies to mine them. The difficulty has been one of access, to allow us to get an appreciation of the size, shape and structure of such deep ocean deposits. The Pacific Ocean is home to a wide variety and perhaps the whole spectrum of marine mineral deposits, from manganese nodules, cobalt-rich crusts to hydrothermal muds and polymetallic sulphides. While many of these deposits are to be found in international waters (such as the Clarion-Clipperton region), a significant number are to be found within the exclusive economic zones of the Pacific island States, including my own country, Fiji. As such, they represent a future economic, and possibly only mineral, resource for nations with limited resources on land.

The International Seabed Authority's mandate arises out of the United Nations Convention on the Law of the Sea, giving it a responsibility to oversee the exploration and development of resources in areas beyond national jurisdiction, in an area designated as the common heritage of all mankind. However, the technology to explore for, assess, quantify and perhaps one day, mine, does not differentiate ownership. This workshop is on the geological modelling one of the perhaps better known deposit types – manganese nodules. Would I then be incorrect in assuming that the techniques and methodologies you would apply in the Clarion–Clipperton Area might be equally applicable in our exclusive economic zones? If so, then modelling the resources in our exclusive economic zones might also enable us to determine the future viability of mining.

I would like to believe that one of the benefits resulting from this workshop is the transfer of some of the skills and expertise required to carry out deep-sea mineral resource modelling. This is not wishful thinking, for I am sure you will agree that, when the time comes for deep-sea mineral exploitation, it will be more than likely be here in our backyard, rather than somewhere else. Holding this workshop in the region is therefore appropriate and provides the region a golden opportunity to participate and learn. In between the hectic agenda of presentations and meetings - and I take note that it is a rather long workshop - I hope you find time to relax and enjoy yourselves a bit. Weather permitting; I also hope that you see a bit of the countryside. Of course, we do have a very eminent guide who will be able to show you around the countryside.

Your Excellency, the Secretary-General of the International Seabed Authority and distinguished participants, on behalf of the Fiji Government, it gives me great pleasure to now declare this workshop open and I wish you all much success in your deliberations. Thank you.

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Introductory remarks by His Excellency Mr. Satya N. Nandan, Secretary-General of the International Seabed Authority

On behalf of this gathering, I would like to thank the minister for opening the meeting. I particularly thank him for his very thoughtful and inspiring statement regarding our work and its implication for the international community and for the countries in this region. Indeed, this is a unique exercise and we hope it will benefit all. Mr. Minister, I would like, through you, to thank the Government of Fiji for receiving us here, for the warm welcome that it conveyed to us through you, as well as for the great willingness with which it welcomed our desire to hold the meeting here. I particularly wish to thank your cabinet colleagues for the decision to provide all that we need here. We are looking forward to the reception that is going to be provided tonight. I am sure it will meet its usual high standards. I am expressing our appreciation in advance because I know that shortly you will have to leave us.

May I take this opportunity to recognize the contribution of the South Pacific Applied Geoscience Commission (SOPAC) to this process, the entertainment that was provided this morning and for its cooperation in organizing this workshop. I also wish to personally recognize the Director of SOPAC, Mr. Alf Simpson who is a member of the International Seabed Authority's Legal and Technical Commission. His contribution to this Commission is very much appreciated by his colleagues and certainly by all of us at the Authority, and I hope that Fiji will continue to be represented by a geologist of his ilk. I wish to also personally thank the Director of Mines, Mr. Bhaskar Rao and his Ministry for their cooperation and the assistance that they have given us.

Finally, I wish to convey our thanks to the Acting Minister for Foreign Affairs who was quite supportive of hosting this meeting. The honourable Minister left Suva at 5:30 this morning and came all the way here to welcome us. Unfortunately, he has other commitments today and so must return to Suva.

I would like to inform you that this workshop has been convened in collaboration with the South Pacific Applied Geoscience Commission (SOPAC), which is based in Suva, the capital city of Fiji.

The purpose of this workshop is to determine a practical and positive approach to develop a geological model of the polymetallic nodule deposits that are found in the Clarion-Clipperton Zone. This is the area of the seabed where the Authority has issued most of the licenses for exploration for polymetallic nodules. Since the early 1970s, prospecting for polymetallic nodule deposits has been conducted by many States in this geographic area, resulting in the acquisition of a considerable amount of data and information about where various deposits containing high grades of the metals of commercial interest are to be found. While some of the consortia that were created to find and mine these deposits are no longer active, many more continue with the effort to develop the technology to mine and process nodules into the nickel, copper, cobalt and manganese that they contain. These efforts have resulted in considerable amounts of information on how nodules are formed; the factors that control their growth, the metals that they contain, and where nodules which are rich in the above metals and that occur in significant quantities might be found in this region.

The International Seabed Authority was established by the United Nations Convention on the Law of the Sea, and the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. In relation to nodule mining, the Authority has issued several exploration licenses since the adoption of the mining code for polymetallic nodules, and I think most of you know the entities to which those licenses were issued. Prior to this, during the period 1987-1990, these six private and public enterprises, along with a seventh, whose allocated area is in the Central Indian Ocean basin, were registered as pioneer investors by the Preparatory Commission for the International Seabed Authority and the International Seabed for the Law of the Sea, and given exclusive rights to carry out pioneer activities in their allocated areas.

One of the conditions for registration as a pioneer investor was for applicants to submit a total application area of sufficiently large estimated commercial value, to allow two mining operations. Along with the application, the applicant was required to submit all the data obtained with respect to both parts. If the applicant met all the requirements, one of the two areas was to be allocated to the applicant, with the exclusive right to carry out pioneer activities in this area, while the second was designated as a reserved area, which could be developed by the operating arm of the International Seabed Authority, called the Enterprise. A primary responsibility of the Authority is to assess the quantities of metals contained in polymetallic nodules of the area that might become available to the international community, should the economic viability of mining and processing be established. In this regard, the Authority undertook a resource assessment of the polymetallic nodule deposits in reserved areas in the Clarion-Clipperton Zone, using the data and information that were submitted by pioneer investors for registration. These data and information are contained in the Authority's POLYDAT database. It was discovered that the data and information submitted by the six applicants with respect to areas reserved through their applications, while allowing for a resource assessment, are not sufficient to allow for an estimate of the quantities of metals to be found in deposits in these areas with a reasonable amount of confidence. Mr. Kaiser de Souza, one of the members of the Secretariat, a marine geologist, and Dr. Robert de L'Etoile of Geostat, will later this morning, make presentations on the Authority's effort to assess resources in the reserved areas.

In January 2003, the Authority convened a meeting of expert scientists to make recommendations on how to overcome these problems and to recommend a programme of work to provide the Authority with the means of estimating the quantities of metals to be found in these areas, with a reasonable degree of confidence. The meeting, noting that the Authority is not financially equipped to assess these resources through exploring marine areas under its purview, recommended, inter alia, that the most cost-effective approach for the Authority would be the establishment of a geological model of the deposits in the Clarion Clipperton Fracture Zone.

The enormous size of the Clarion-Clipperton Zone, and varying quality of data and information on polymetallic nodule deposits to be found there, defines the challenge of the workshop. While sampling can be described as relatively sparse, many factors have been identified as being indicative of the occurrences of nodules. It would be useful if the model that the workshop defines incorporates these non-confidential data parameters and tests their relationship to good nodule grade and abundance. This would enable the international community to profit or benefit over time as these hypotheses are tested. At the same time, we must find a way of taking advantage of all the station data that are available on the Clarion-Clipperton Fracture Zone, for our model. As you are well aware, the Authority, for its part, has data and information on the reserved areas of the Clarion-Clipperton Zone. Other data are to be found with contractors and potential contractors, who undertook significant exploration work in the 1970s and 1980s. You must consider ways of creating the quantitative and qualitative model that both contractors and potential contractors feel confident with. Our intent, subsequent to your meeting here, is to convene a meeting of the contractors to discuss with them the possibility of cooperation by them, in obtaining the necessary data and information in a manner acceptable to them. These data and information, as well as data and information available in the public domain, will improve the quality of this model.

We will also try to gain access to the data and information acquired by the currently inactive consortia that undertook nodule resource development during the 1970s.

In any case, it is my hope that, during the coming days, the workshop will visit some of these issues and assist the Authority with a programme of work that makes it possible to acquire and utilize all relevant available data and information. I also hope that the agenda of the workshop and the pace of your work will give you an opportunity to see some of parts of my country.

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EXECUTIVE SUMMARY

A road map towards a clearer scientific assessment of polymetallic nodule deposits on the deep seabed of the Equatorial North Pacific Ocean was prepared by the Workshop of the International Seabed Authority (ISA), held at Nadi, Fiji, from 13 to 20 May 2003.

The project was designed to produce, over a four-year period, a geological model for nodule deposits in the Clarion-Clipperton Zone (CCZ), a 2,500-mile swath of the Pacific Ocean southeast of Hawaii that contains the richest supply of those materials anywhere in the world's oceans. The model is designed to identify the many factors – geological, chemical, physical and biological – that contribute to the creation and growth of nodules. It should assist scientists to understand the underlying processes and help prospectors to find the most valuable deposits.

The Workshop recommended a work programme leading to a reliable geological model within three or four years. It would be divided into three phases, starting with data acquisition and processing, moving on to analysis, and culminating in the production of a geological model with the stated aim of improving resource assessment. A "prospector's guide" is to accompany the model, giving descriptive explanations of nodule geology to complement the quantitative approach of the model. The guide will also provide information on all known polymetallic nodule deposits in the CCZ

The model is to cover the broad range of factors that affect the two measures of greatest interest to both prospectors and scientists: abundance of nodules and their metal content. The metals of commercial interest found in polymetallic nodules are cobalt, copper, manganese and nickel.

In addition to grade and abundance data that can be obtained from sampling nodule deposits, inputs to the model will consist primarily of non-confidential data that relate to the depositional environment of nodule deposits. These include seafloor topography and geology, as well as the structure and biology of the seawater overlying nodules. During the initial phase of model development, the relationship between these data types and high grade and high abundance nodules will be tested. If it is established that quantitative links between these data and nodule grade and abundance exist, such data will be used to predict nodule grade and abundance in the CCZ. The data are to come from two sources: entities that have contracted with the Authority to explore specified areas of the deep seabed for polymetallic nodules, and public and private research institutions. As work on the model progresses, the Authority would generate maps at various scales, from selected local areas to the entire CCZ.

The Workshop produced a number of specific recommendations on what the model should cover and how the work should proceed. Model components would include values of known variables such as seabed topography, sediment characteristics, tectonic and volcanic processes for the past 20 million years, water column processes and nodule types that are believed to be geologically related to the formation of nodule deposits. The model will be a geographic three-dimensional model. Intermediate products would include a sedimentological map and an evolutionary framework for the Pacific plate underlying the CCZ, in both instances, covering the past 20 million years – the life span of the oldest nodules. Evidence would also be examined on features such as hydrothermal activity (hot springs) on the ocean floor; the Workshop was informed of a recent discovery that signs of such activity had been found at the centre of the CCZ.

Material in the water column overlying the nodule fields would deal with its structure, with particular reference to two chemical layers that exist at varying depths throughout the ocean: the carbonate compensation depth (CCD), where dissolved calcium carbonate that has descended from biological activity near the ocean surface condenses on the seabed more than 4,000 metres down; and the oxygen minimum zone, also related to biological activity above. Nodules have been found to be most abundant in equatorial waters, where biological activity is highest; deposits are concentrated near the CCD. Ocean currents will also be brought into this picture as one of the factors.

The Workshop envisaged the prospective model as offering the best possible resource assessment of polymetallic nodule deposits in the CCZ, along with a summary of factors that would help in evaluating existing mining claims and in selecting areas for new claims. In general, it would provide an authoritative description of an important oceanic regime, integrating geological processes with those on the seabed and the waters above.

The model would not attempt to gauge what abundance and metal grades would be sufficient to support seabed mining, given the unpredictability of future mining costs and land-based mineral prices that has so far inhibited commercial activity.

1. Background for a Geological Model

Motivating the Authority's effort to generate a geological model for deep-sea polymetallic nodules has been the need to assess the resources in areas reserved for eventual exploitation by the Authority. While the Authority has a general mandate to administer and control deep-sea mineral resources in all ocean areas beyond national jurisdiction, it has a special role to play in certain parts of the seabed in the Central Pacific and the Central Indian Ocean.

Acting within rules established under the 1982 United Nations Convention on the Law of the Sea, the Authority, in 2001, signed contracts with seven nationally-sponsored enterprises, giving them exclusive rights to explore specified areas for polymetallic nodules. The contracts conform to regulations, which the Authority adopted in 2000, constituting an exploration code for these nodules, based on an elaboration of provisions in the Convention.

Between 1987 and 2001, these seven contractors had been designated as "pioneer investors". In that capacity, they had each registered claims for two seabed areas of equal estimated commercial value, one of which was later reserved for use by the Authority. The pioneers were initially accorded exploration areas of up to 150,000 square kilometres, on the understanding that, over the course of a decade, they would relinquish to the Authority enough of these areas to bring their claims down to 75,000 square kilometres. These relinquishments have now been accomplished.

As part of this process, these entities have turned over to the Authority data and information they had collected on the reserved areas, including the abundance and metal content of nodules in these areas. However, there was no requirement that they submit any information on the relinquished areas.

The model is to be used by the Authority to assess the metals of commercial interest in the reserved areas and to serve as a predictive model for poorly surveyed sectors of the CCZ. It is also expected to serve a broader audience, including contractors active in their assigned areas and independent scientific institutions working on nodule resource development issues. Moreover, Workshop participants have suggested that, while primarily applicable to the CCZ, the model could help clarify issues surrounding nodule formation elsewhere in the Pacific and in other oceans, in both international waters and those under the national jurisdiction of coastal States.

Land-based miners have long used models to identify the most favourable locales for prospecting. Such models attempt to predict where the richest ore deposits or petroleum fields occur on the basis of the surrounding topography and sub-surface formations. A model for nodules should prove even more challenging, as it must also take account of many biological determinants of nodule growth that do not figure in land-based assessments. Moreover, the CCZ model will cover a much larger area – about 4.5 million square kilometres – than the local models usually prepared for land-based mineral prospectors.

The model is to be developed in a step-by-step process that will allow scientists to suggest refinements as it proceeds. The work will be done by the same categories of experts who participated in the Workshop. They came from academic institutions, public and private enterprises, contractors, members of the Authority's Legal and Technical Commission, and ISA member States. The Workshop was attended by 35 participants.

The Workshop on the Establishment of a Geological Model of the Polymetallic Nodules in the Clarion-Clipperton Zone was organized by ISA with the collaboration of the South Pacific Applied Geoscience Commission (SOPAC), with headquarters in Suva, Fiji. It is the sixth in a series of technical workshops convened annually by the Authority. This was the second workshop held in the Asia/Pacific region, the first having been held at Sanya, China, in 1998; all other workshops have been held in Kingston, Jamaica, at ISA headquarters.

Co-Chairmen of the Workshop were Charles Morgan, Environmental Planner with the firm Planning Solutions Inc, Honolulu, Hawaii, and Alf Simpson, Director of the SOPAC Secretariat. Mr. Morgan, who drafted the Workshop's recommendations, remarked that the meeting had "cornered the vast majority of nodule fanatics in the world". Mr. Simpson spoke of the importance of human inputs in the process of moving from data to information to knowledge to wisdom; he thought the process might be aided by establishing a Website to which scientists could submit versions of a model and critique each other's work.

The output of the Workshop is based on a report and work plan drawn up by a meeting of scientists convened by ISA in January 2003. In its report, the meeting pointed out that modelling would not be easy, given the variability of nodule occurrences in the CCZ. It envisaged that future collaboration would involve a cross-pollination of ideas between scientists and seabed contractors.

2. Highlights of Presentations

In addition to their work on plans for a geological model, Workshop participants exchanged information on recent research into polymetallic nodule-bearing areas, both within the CCZ and elsewhere, including the Central Indian Ocean basin. Scientists associated with seabed contractors and universities described the findings of research cruises into promising areas. Other speakers offered analyses of the raw data, with special emphasis on the relationship between nodule formation and characteristics of the surrounding ocean environment.

Eighteen participants made oral presentations, supplementing their comments with computer-based images and transparencies of deep-sea photographs, maps and tables. Most of the presenters also submitted papers that will be published in the proceedings of the Workshop, along with a summary of the oral presentations and related discussions.

The Workshop addressed two questions in particular: (1) How features of the geology around and beneath nodule fields, and biological elements in the waters above, might be used to help in locating nodules, particularly those of high metallic grade and abundance; and (2) how a study of such features could help in understanding the process of nodule formation and growth, especially the ways in which economically valuable metals are accumulated.

Studies from several ocean areas have pointed to a number of indicators for the presence of enriched nodules. They are often found in areas of past volcanic activity, productive of mineral-bearing rocks that supply nodules with some of their metals. They occur where sediments have lain undisturbed for the millions of years that nodules require to grow. They are often found atop sediment called a "transparent layer" because it is a poor reflector of the sonic signals echo-sounders use to map the earth's strata beneath the seabed.

At the Workshop, Russian oceanographers announced a recent discovery of evidence that hydrothermal vent activity had occurred in the centre of the CCZ. They suggested the existence of a third, unnamed fracture zone between the Clarion and Clipperton fractures that defined the north and south limits, respectively, of the CCZ.

Nodules are most abundant where the seabed lies below a level known as the carbonate compensation depth (CCD), where dissolved calcium carbonate from dead organisms, sinking slowly through the water column, precipitates along with dissolved metals onto the surrounding surfaces. They occur beneath zones near the ocean surface that team with organisms, generating a high level of biological productivity.

Given those indicators for the presence of nodules, scientists and prospectors want to know exactly how they contribute to the development of nodule fields. Workshop participants made it clear that those processes were not well understood. For example, it was known that surface productivity contributed to nodule growth by supplying a steady flow of nutrients, including metals, to the deep ocean floor. In fact, nodule-bearing areas were closely correlated with highly productive surface zones. Yet, the most abundant nodule fields lay beneath the margins of the highest productivity areas, not at their centre. The overriding question was why nodule distribution followed current productivity patterns rather than the presumably different ones that were in place millions of years ago when the nodules began to form.

Oxygen-rich water has been known to enhance the chemical environment for the deposition of metals. A couple of researchers theorized that, in both the CCZ and the southwest Pacific, the flow of the Antarctic Bottom Current through undersea channels created a turbulence that dropped metals and supplied oxygen associated with richer nodule grades.

One researcher presented evidence that nodule growth in the CCZ had halted during glacial periods, when continental runoff into the ocean had greatly diminished. Many nodules had then broken into pieces, which had become the nuclei of new nodules once the sediment flow had resumed.

Speakers emphasized that several factors operating together were required to produce high grade and abundance of nodules.

Participants generally agreed that the geological model would have to depend mainly on data already collected, since would-be investors were not currently active in exploration and the Authority did not have funds for its own investigations. At the same time, it was pointed out that the model could benefit from more modern interpretations of existing data, using new equipment and techniques. One speaker suggested that contractors pull their collected nodules out of storage and have them reassessed, in order to ensure a correct reading of their chemical composition.

A consultant for the Authority presented an initial assessment of the nodule resources in areas relinquished to it by contractors. He calculated that those areas held an estimated 5,400 million tonnes of metal, including five times the amount of manganese as had been mined on land since 1940. However, before the Authority could put its wealth in the bank, market conditions and mining technology would have to be ripe.

One problem cited was the fact that the data which contractors had given the Authority on its reserved areas had been collected and processed using different and sometimes incompatible methods. For example, data from areas where sampling stations were close together yielded better results than when the stations were more widely placed; the discrepancy made it harder for the Authority to assess the abundance and quality of nodules in different areas. Suggestions were made that, alongside its work on a model, the Authority should try to develop data-collection standards. It was pointed out, however, that those would affect only future activity and not the value of data that was currently available for the model.

The Workshop was informed that the first of three research cruises under the Kaplan Project on biodiversity research in the CCZ, had taken place in February and March 2003. ISA participation in that five-year, privately funded cooperative venture by research institutions in several nations had been recommended by the Authority's Workshop of July/August 2002 on marine scientific research. That study of animals in the zone, and their geographical distribution, was expected to produce recommendations on the measures needed to protect deep-sea fauna from the effects of nodule mining.

3. Opening Remarks

The opening meeting of the Workshop was addressed by Jonetani Cokanasiga, Minister for Home Affairs and Acting Minister for Foreign Affairs of Fiji, who recalled that Fiji had been among the first countries to ratify the Law of the Sea Convention, as well as one of four nations to offer a site for the Authority's headquarters.

Minister Cokanasiga observed that Fiji had had a long history with land-based mining, going back to a 70-year old gold mine at Vatukoula, and said that he hoped the development of ocean resources within Fiji's 200-mile exclusive economic zone (EEZ) would one day exceed the output of its mineral resources on land. He noted that the Pacific Ocean was home to a broad spectrum of resources, in international waters as well as within national jurisdiction and, for that reason, Fiji was greatly interested in whatever the Workshop might do to throw light on the possibilities. He hoped the modelling techniques developed by the meeting for the CCZ might also help Fiji establish future benefits from its own EEZ, since ocean mineral development was "more than likely to be here in our backyard than someplace else".

ISA Secretary-General Satya N. Nandan, in his introductory remarks, said that the problem of assessing deep-ocean mineral resources could be simply stated: "The water is very transparent but the ocean is very opaque." He said that a geological model of the ocean floor would provide a better understanding of the geological and geophysical conditions of the seabed. He also said that the task of the Workshop was to provide a practical and cost-effective approach to developing such a model and suggested that the model could be built up from the wealth of data gathered since exploration for polymetallic nodule deposits that had begun in the 1970s. He noted that the data that had been gathered encompassed information on the growth and formation of nodules, their metal contents and where nodule deposits are located.

Mr. Nandan informed participants that a primary responsibility of the Authority was to assess the resources in the areas of the seabed reserved for it to undertake future mining. He said that that assessment had to be based on data submitted by the entities that had prospected significant areas of the seabed for polymetallic nodule deposits before applying to the Authority for contracts to explore smaller areas. He noted that this was the most cost-effective manner to acquire the data, since the Authority did not have funds to conduct its own prospecting campaigns. He further noted that the enormous size of the CCZ and the varying quality of the nodules within it defined the scope of the problem. He emphasized that to develop the best possible model, ways must be found to take advantage of all available data from contractors in their respective areas and from public sources of broader scope. He announced that ISA planned to convene a meeting with contractors to discuss ways of obtaining additional data.

4. The Authority's efforts in resource assessment of reserved areas

In outlining the Authority's expectations of the workshop, Nii Allotey Odunton, Deputy to the Secretary-General, stated that the initial presentations at the Workshop would be on the Authority's efforts to undertake resource assessments. Those would be made by Kaiser de Souza, marine geologist of the Authority, Robert de L'Etoile of Geostat Systems International, and Baidy Diène of the Authority's Legal and Technical Commission. They would inform the workshop of the status of the information and data maintained by the Authority for resource assessment, steps that had been undertaken to validate those data, the results of resource assessment undertaken by the Secretariat, as well as by its consultant (Geostat Systems International), and the framework contained in the Exploration Code for polymetallic nodules in the Area for the submission of data and information on deposits in reserved areas that are required of prospectors and exploration contractors, respectively.

Mr. Odunton said that the Authority hoped that the outcome of the workshop would be a programme of work that led to the establishment, not only of a quantitative and predictive geological model of polymetallic nodule deposits in the CCZ, but also of the establishment of a prospector's guide containing information on all known nodule deposits in the CCZ, along with information on prospective areas for future exploration. In addition, he said that any recommendations on the use of standardized methods for collecting grade and abundance data would be appreciated, particularly if such standardization resulted in a diminution of the problems faced by the Secretariat in undertaking resource assessment work.

Many of the problems confronting the Authority in trying to assess the metal resources in its reserved areas were identified by its marine geologist, Kaiser de Souza. He described the work the International Seabed Authority had undertaken to put together a database, called POLYDAT, on the nodule deposits in areas reserved for exploration by the Authority. The database incorporated the data on the abundance of nodules in various blocks of the seabed and the content of the four metals of commercial interest (copper, nickel, cobalt and manganese) that the nodules contained. He described the work accomplished to validate those data which had been submitted by the six contract applicants in the Pacific and noted how the evolution of technology had complicated the process. For example, in identifying resources by location, earlier prospectors during the 1970s had used a transit satellite system that was accurate to within between half a kilometre and several kilometres, whereas later, prospectors in other areas had utilized the Geographical Positioning System with accuracy as high as 10 metres. Moreover, different techniques had been used in collecting samples and photographing the sea bottom, with a view to determining nodule abundance. In some areas, samples had been taken 10 to 15 kilometres apart, whereas the sampling distance was up to 100 kilometres in other blocks. Depth-sounding techniques had produced bathymetric maps of greater or lesser reliability. Contractors also differed in their procedures for chemical analysis of samples.

Given these significant differences in the prospecting techniques/technologies used by different contractors, and their impact on the error in estimates of metals in nodule deposits, he suggested that efforts be made to make the necessary adjustments to some of the data. He noted that in one case, a contractor had recently submitted data that enabled the Authority to revise its original assessment based on the data initially provided.

Robert de L'Etoile, Vice President of Geostat Systems International, of Laval, Quebec (Canada), presented the results of a geostatistical analysis of the metal resources in polymetallic nodule deposits in the reserved areas. The Authority had commissioned this study from Geostat Systems International, an internationally recognized firm of mining consultants. Restricting their study to deposits in the areas reserved for the Authority, the study concluded that on the basis of data submitted by contract applicants between 1987 and 1994 some 5,400 million tonnes of metal lay on the seabed in the reserved areas. This included, for example, the amount of manganese metal which was estimated at five times the amount of all the manganese mined throughout the world since 1940. This resource he stated was so huge that it would make a good mining project even if only the cream of the resource were mined.

He cautioned, however, that the amount of economically recoverable metals was much less than their total weight. To present a more realistic picture, he offered a rough map of the area showing blocks of greater or lesser potential, based on three factors: metal content, nodule abundance and accessibility – the latter factor dependent largely on depth and topography. He also noted that the area surveyed covered 930,000 square kilometres, twice the size of France, with depths ranging from 4,300 to 5,300 metres. To avoid miscalculations based on faulty chemical analysis, he suggested that the nodule samples recovered by the earlier prospectors be re-assayed in modern laboratories.

Baidy Diène, Special Adviser to the Minister of Mining and Energy of Senegal, outlined the legal background underpinning the Authority's role in collecting resource assessment data from contractors, as spelled out in the Law of the Sea Convention and the regulations on exploration. Data were required from prospectors conducting unregulated research, but mainly from applicants for exploration contracts and the contractors themselves, annually and in still greater detail at the end of contracts. These submissions were to cover many types of physical, environmental and even financial data, and had to be reliable, representative and comparable. The Authority's task was not only to collect this information but also to organize it and make it publicly accessible.

Mr. Diène, who is also a member of the Authority's Legal and Technical Commission, suggested that the Authority try to develop standard procedures for data gathering and analysis by contractors. Such standards should be general; they should not extend to areas such as the equipment to be used. He suggested that the Legal and Technical Commission make recommendations on such standardization.

5. Data Issues

Dr. Charles Morgan of Planning Solutions Inc., Hawaii (United States), offered suggestions on the types of data that should enter into a geological model of the CCZ. The main aims of the model, in his view, were to clarify nodule formation processes, provide a guide for prospectors and assist in resource assessment. Data in each category should meet two criteria: ready availability without further significant effort or expense, and relevance to nodule abundance and metal content. The authors of the model should follow a process that would allow for continuing refinement. The outcome should include both statistical analysis, in the form of maps and tables, and qualitative descriptions.

He listed some key variables, starting with topography, which would be useful in understanding regional geology even if details were insufficient to select individual mine sites. Morphology – the shapes and sizes of nodules – should be brought into the picture, despite difficulties in quantifying this factor. Sedimentation was another element, since nodules did not grow in the absence of sediment and were likely to be buried where there was too much of sediment. Benthic (deep-water) currents were obviously important, but their use in a model would be limited by inadequate knowledge. Finally, primary productivity, a measure of biological activity in the ocean, was a major element. By measuring chlorophyll levels and extrapolating back 20 million years or so to the start of nodule formation, scientists could develop a more coherent picture of the occurrence and distribution patterns of nodule deposits.

Dr. Lindsay Parson, Project Leader in the Southampton National Oceanography Centre, in the United Kingdom, pointed out that a geological model would have to depend on existing data, since new information was not likely to arrive in the foreseeable future. At the same time, the model should take account of changes in scientific understanding of how nodules developed on the seabed. The model would have to serve both the public scientific community and the industrial community. Though it would be based on the CCZ, many of the factors it covered were generic, applicable throughout the oceans. It would have to synthesize data from many fields, from geology to biology to the environment.

As to the process of developing the model, he suggested that an initial version be prepared in three or four months and circulated to scientists, who would provide feedback on a continuing basis over the next three to four years, gradually refining the product. Once completed, the model should be accessible through the Authority's website.

6. Raw Material for the Model

Several marine scientists gave the workshop an account of studies into the geological and related features of the deep-sea environment that have resulted in discovering high grade and abundance nodule deposits in the CCZ, illustrating the sort of data and information that a geological model would require. Some of them discussed the kinds of nodule-formation processes that the model should attempt to elucidate.

Michel Hoffert, Professor at the Université Louis Pasteur, Institut de Géologie, Strasbourg, France, used undersea photographs to illustrate the complexity of geological features in a typical nodule field on the deep seabed. A short trek along the ocean floor by the French undersea submersible *Nautile* had revealed nodules of varying shapes and densities, including a flat plain with densely scattered nodules lying where they had been formed, and the base of a steep slope onto which they had fallen from higher areas. The trek had also crossed an erosion channel, formed by undersea currents, where there were almost no nodules. The occurrence of nodules was directly related to a “transparent layer” of sediment (one that poorly reflects echo-sounding pulses) atop the seabed in many areas.

Thus, the geological history of a small area, from which mineral explorers might have taken a single sample, was in fact a complicated matter. For this reason, he suggested that, rather than a single model, scientists should develop three to five models, each representing a different pattern of nodule evolution.

Mr. Hoffert described how dynamic processes on the seabed control the growth and location of nodules. Re-sedimentation, brought about by erosion, was more significant in this regard than the original formation of sediments. Animal activity also contributed to nodule relocation, exemplified by the fact that a nodule might be moved about by the food-seeking activity of holothurians (sea cucumbers) on the ocean floor. Nodule formation depended on a variety of raw materials, from the remains of dead organisms to continental runoff, and was governed by mineral processes at the ocean bottom. The quantity of sediment descending from near-surface waters helped to determine whether the seabed was composed of sediment, soil, nodules or crusts. “The nodule is a black box in which you have the story of the history of the sea”, he concluded.

Dr. Yuri Kazmin, a consultant with the Russian Ministry of Natural Resources and the Interoceanmetal Joint Organization (IOM), presented the results of a comparison between nodule data reported separately by Russian and United States groups. The Russian data had come came from Yuhzmorgeologiya, a state scientific centre and ISA contractor, while the earlier United States information had derived originally from a consortium of mining interests (Ocean Mining Company [OMCO]), as synthesized and published by Charles Morgan, Co-Chairman of the Workshop. Mr. Kazmin had found a “striking resemblance” between the two sets of results in respect of nodule abundance and metal content in the CCZ, although some differences had been due to different statistical approaches to handling sampling data. The Russian data had derived from some 10,000 sampling stations across the zone, compared to about 8,000 stations from the United States and about 2,800 stations included in POLYDAT, the database on areas reserved for the Authority.

The data showed that nodules occurred in three different geological structures – the abyssal plain in the centre of the Zone and flanking areas on the east and west sides. There was no correlation between nodule abundance and topography. On the other hand, abundance varied according to the type of sediment, among other factors. In general, nodule deposits in the eastern sectors of the CCZ were more valuable than those in the west, which, while similarly abundant, had a lower metal content.

Dr. Kazmin spoke of the relationship between nodules and tectonic and volcanic activity in the CCZ. The abyssal plain between the Clarion and Clipperton fracture lines was transversed by faults, marked by undersea hills and valleys, running northwest to southeast. Running east-west, parallel to the main fractures delineating the zone, was an unnamed and topographically indistinct fracture along which nodules were especially abundant. His calculations showed that these various tectonic features were aligned with variations in metal concentration in the nodules. He theorized that this relationship might be due to the higher oxygen level in bottom water as it passed though these undersea fissures, creating improved conditions for nodule formation and metal concentration.

Professor David Cronan of the Department of Earth Science and Engineering at Imperial College, London, cited data from areas surrounding the CCZ showing how nodule formation occurred under similar conditions over broad areas of the Pacific. He concentrated on the biological and geochemical chain in which dissolved elements generated by biological activity near the surface settle onto the deep seabed and accumulate into nodules. He observed that, in most areas, nodules were most abundant at the north and south edges, rather than the centre, of the high-productivity areas stretching along the equator. They were also most abundant, and richest in metals, when the seabed occurred at the carbonate compensation depth. Thus, concentrations of organic carbon - which correlated with biological productivity -- were a key factor in understanding nodule distribution. In his view, a model for the CCZ could be useful in understanding data throughout the Central Pacific.

Contrary to the geographical trend, however, nodules in a zone southeast of the CCZ were inexplicably richer in nickel further south of the equator, where the opposite was expected. This was one example of the type of anomaly that made it impossible to create a geological model that was 100 per cent accurate. Paradoxically, nodule distribution seemed to follow current patterns of biological productivity, despite the fact that nodules had begun forming millions of years ago, when environmental conditions presumably differed. One explanation was that the movement of tectonic plates had carried the nodules far from their place of formation. It was more likely, however, that once they began forming, they continued to accumulate metals through their porous structure.

Jincai Jin, Deputy Permanent Representative of China to the ISA, said the indeterminate time for the start of commercial seabed mining made it difficult to predict what factors of technical efficiency, mineral quality and environmental limitations might apply at that time. He suggested a formula that might be used to determine the size and required output of an economically viable mine site, based on various physical, economic, commercial and environmental variables. He described some of the survey work done in the assigned exploration area of the CCZ by the China Ocean Mineral Resources Research and Development Association (COMRA), which had recently selected a 2,000-square-kilometre area for more detailed study. Chinese scientists had published in several volumes the results of their work over several years, but they were unlikely to spend much more money, given the unpredictability of commercial mining.

He suggested that the Authority, in addition to its work on developing a geological model, could look into ways of standardizing the data and information required for resource assessment to increase confidence in the model. It could also apply such standards to the assessment of other deep-seabed resources.

Helmut Beiersdorf, retired Director and Professor at the Federal Institute for Geosciences and Natural Resources, Bergdorf, Germany, discussed research conducted in the 1970s on nodule deposits in the CCZ. These early studies had established for the first time the age of nodules, which turned out to be millions of years older than had been supposed. Nodules were found to vary greatly in shape and size, and the differences had been linked to differences in their formation, constituents and locale.

Seven growth types had been defined, with several sometimes occurring in the same nodule. These had been correlated with growth rates ranging from 5 to 200 millimetres per million years. Stratigraphic studies of the sediment underlying the nodules had disclosed gaps in deposition during glacial periods when organic fallout had been minimal. Nodules had formed before such gaps, then disintegrated, often forming the nuclei of new nodules that had began to grow when sedimentation had resumed. Digging into the seabed to locate buried nodules associated with strata laid down during various geological periods, the researchers had found that the smaller nodules lay towards the bottom, with the bigger ones near the surface. Bottom-dwelling organisms had moved the nodules around but had tended to keep them at the surface of the seabed.

Presenting further details based on echo-sounding of the seabed subsurface, Mr. Beiersdorf described a nodule-bearing, acoustically transparent upper layer of mud, derived in part from the shells of microscopic organisms called radiolarians, beneath which lay strata of successively earlier sediments, alternating between soft and hard. This transparent layer (described earlier by Mr. Hoffert) was associated with biological activity at the ocean surface. Eroded areas were characterized by fewer nodules, often buried.

7. Nodules Elsewhere in the Pacific

Three speakers described research on polymetallic nodules in Pacific areas south of the equator on the eastern and western sides of the ocean.

Michael Wiedicke-Hombach, of the German Federal Institute for Geosciences and Natural Resources, compared the CCZ results with studies in the Peru Basin, a deep-sea area to the southeast. The area was one of high organic carbon input (food availability) and abundant nodules. Nodules formed on the many steep slopes on the seabed tended to move down and become buried. The rough topography made many sections un-mineable. The carbonate compensation depth varied by up to 150 metres over small lateral distances, and had also changed over geological time. The layer moved up or down in relation to productivity variations that altered the quantity of available carbonates.

Dr. Allen L. Clark, Senior Fellow at the East-West Centre, Honolulu, Hawaii, presented some results from a project to identify resources, including nodules, in the exclusive economic zone of the Cook Islands in the South Central Pacific. Nodules had been found at an abundance of up to 32 kilogrammes per square metre, though the deposits were small compared to those of the CCZ. Most of the value of these deposits was due to their cobalt content.

He outlined some conclusions drawn about the possible genesis of these nodules, which he felt could be relevant to the proposed CCZ model. Mr. Clark said that one conclusion was that the nodules in this geographic area seemed to be associated with the flow of the Antarctic Bottom current, a deep-sea current of cold water that created turbulence as it passed through a channel between the islands. He said that the turbulence dropped minerals onto the seafloor, allowing nodules to develop. He also said that, like land–based minerals, nodules tended to accumulate in basins of varying sizes; therefore, the CCZ might be regarded by the modellers as a vast basin between the Clarion and Clipperton fractures.

Dr. Philomene Verlaan, a researcher at the Imperial College, London, described results from a recent study of biological factors influencing the marked variability of nodule content in the southwest Pacific Ocean. The main factor was biological productivity, which diminished towards the south from a high point at the equator. It had been found that the carbonate compensation depth varied no more than 150-200 metres from east to west, much less than the previously known decline from north to south. Data from some 1,000 samples indicated an increase in manganese, nickel and copper towards the north, while iron and cobalt showed a reverse trend. Nickel and copper enrichment had been found at the CCD level, while cobalt was richest just above that level. Thus, the data suggested that anyone looking for nodules rich in cobalt should examine seabed lying at specific depths.

Oxygen concentration at various water depths, and specifically the oxygen minimum level, should also be taken into account in a geological model for nodules, according to her findings. She also cited an area of productivity enhancement around islands and seamounts. She cautioned, however, that her study concerned the metal content of nodules, not their abundance.

8. Surveys of Exploration Areas

Scientists associated with four entities that have been awarded exploration contracts for polymetallic nodules (three in the CCZ and one in the Indian Ocean) described some results of the contractors' surveys.

Dr. Vijay Kodagali, Director in the Department of Ocean Development, New Delhi, India described the methods employed in India's initial exploration of its contract area which is 2,700 kilometres south of Goa in the Indian Ocean. Using 8 ships and 60 cruises, researchers had taken samples at regular intervals throughout the original application area of 150,000 square kilometres, of which half had later been relinquished to the Authority. India had used the results of this survey to select blocks of least economic potential that were then relinquished to the Authority.

The survey had shown that nodules were most abundant in areas of the roughest topography. In addition, whereas abundance varied over short distances, metal content tended to remain steady over broad areas. Indian scientists had found that their abundance figures increased by an average of 132 per cent when they shifted from one grab sampler to another, demonstrating the importance of adjusting estimates according to the equipment used for sampling. The metal resource (cobalt, copper and nickel) in the 75,000-square-kilometre Indian area had been estimated at 9.4 million tonnes.

Dr. Ryszard Kotliński, Director-General of IOM, headquartered in Szczecin, Poland, presented results from a research cruise conducted in 2001 in the 75,000-square-kilometre exploration area allocated to his organization in the CCZ. The aim of the cruise had been to acquire data related to the identification of nodule resources, including a detailed analysis of location, shapes, sizes and composition, and their relation to the surrounding environment. Nodules were most abundant at the sediment-water interface, a gummy, fluid layer from 2 to 12 centimetres thick. Abundance was greatest at depths of 4,300-4,500 metres below the ocean surface. Nodules varied greatly in distribution, size and composition over the exploration area, with concentrations of nickel and cobalt highest in the north, copper in the centre and manganese in the south.

Dr. Valeri Yubko, Deputy Director of the Okeanglofizika Research Institute, Yuhzmorgeologiya, discussed nodule distribution over the CCZ as a whole, with reference to differences between northern, central and southern segments. He found metal concentration patterns throughout the zone to be generally similar to those described for the IOM area. The northern segment of the CCZ was characterized by fewer and smaller nodules, while abundance was greatest in the central segment. These differences corresponded to a north-south gradation in surface-sediment zones. Seabed topography was characterized by long hills, abyssal valleys and inter-valley plateaus running north-south. Slopes greater than 6 degrees were devoid of nodules.

He revealed recently discovered evidence of hydrothermal vent activity, including polymetallic sulphides, along the undefined fracture at the centre of the CCZ.

Dr. Wenzheng Lu, of the Second Institute of Oceanography, State Oceanic Administration, Hangzhou, China, told of results from eight cruises conducted by COMRA from 1991 to 1998 in the Chinese-allocated area at the western margin of the CCZ, an area divided into two non-contiguous sectors. Linear north-south furrows marked the seabed of the eastern sector, along with seamounts scattered like a string of beads. In the west, five seamount chains up to 1,000 metres high were separated by basins and furrow areas. The sectors also differed in tectonic activity, with volcanism prominent in the west and faulting in the east. The west had a higher abundance of nodules but the east had a higher grade of metals.

Factors controlling nodule development in the area included the Antarctic Bottom current, which delivered extra oxygen conducive to nodule formation; the availability of metallic minerals from undersea volcanoes, and the presence of the CCD at 4,900 metres, just above the most favourable depth of nodule generation.

9. Biological Inputs

The final presentation addressed the ways in which knowledge of ocean biology might contribute to a geological model. Dr. Craig R. Smith, professor in the Department of Oceanography of the University of Hawaii (United States), described some of the main features of the CCZ deep-sea environment. He noted that about 90 per cent of the seabed was covered by sediment. The habitat was vast and largely continuous, bathed by cold water, around 4 degrees above zero Celsius. In this physically stable environment, productivity rates, biomass and animal growth rates were all low, due mainly to the paucity of food reaching the bottom from the ocean surface zone. Most animals were tiny, only a few millimetres long. Dr. Smith noted that the animals, though few in number were highly diverse, so that a collection of 100 individuals might represent 50 species – a diversity rivalling that of coral reefs and rainforests. Animals living in the soft sediments were easily disturbed and slow to recover from disturbances of the kind caused by mining.

Because scarce biological sampling had been done in the zone, little was known about the size of areas occupied by individual species. The fauna were so poorly described that 90 per cent of individuals in a typical collection were likely to be unknown to science. Moreover, classical techniques of identifying them by appearance were inadequate, highlighting the need to apply newly developed means of genetic testing.

Dr. Smith described recent activities by the Kaplan Project, a five-year investigation which had commenced the previous year into biodiversity, species ranges and rates of gene flow (a measure of species mobility) in the nodule areas. Three sampling stations had been selected, 1,500 kilometres apart, one each in the eastern, central and western parts of the zone. The first samples were already being processed, and would be forwarded to cooperating institutions in the United Kingdom for more elaborate investigation, using genetic techniques. After specimens were classified and their ranges calculated, recommendations would be made to the Authority on how mining could be managed, if necessary, to minimize risks to biodiversity. An initial research cruise had taken place in February and March, with two further cruises planned for 2004. Results would be published on the World Wide Web.

Biologists could contribute to the geological model by their studies on productivity as it relates to nodule growth. Beyond measuring surface productivity, there was a need to study export flux (the flow of nutrients to the depths). In the other direction, the model could help biologists understand habitat variables through a better understanding of sediments, current flow and sediment transport, topography and other factors.

10. Working Group Reports

The Workshop's recommendations emerged largely from three working groups that considered what sort of data should be entered into the geological model of the CCZ and what further work would be needed to assemble existing data: Group A, on tectonics and volcanism; Group B, on bathymetry and stratigraphy, and Group C, on sediment and water column characteristics. In all cases, the focus was on how natural processes affected the abundance and metal grade of nodules, and how information on those relationships could be derived by analysing earlier research.

Group A: Tectonics and Volcanism

Group A, chaired by Dr.Yuri Kazmin, looked at the "basement" underlying nodule deposits – specifically, the shifting patterns of the earth's crust (tectonics) and the contribution of volcanoes and magma flows in realigning undersea topography. The CCZ may be divided into three physiographic zones in which the crust varied in age from 10 to 74 million years. Nodule formation was seen as related to the motion of the crustal plates defining those zones, notably the Pacific plate that abutted the western edge of the North American continent. The group was of the view that the relationship deserved further study.

The group saw tectonic activity, including faulting and fracturing of the crust, as a major component of the geological model. Fissures in the seafloor provide channels through which deep currents might supply extra oxygen conducive to nodule formation. An unnamed, east-west fracture through the centre of the CCZ deserved study, along with similar but smaller features traversing the zone from north to south, as locales for above-average accumulations of nodules. The group recommended the compilation of maps defining such features in greater details.

Volcanic activity had played a major role in reworking the seabed in the CCZ, creating mountains, ridges, plateaus and seamounts. While that fact was well recognized, a comparison of the age and nature of such activity in different parts of the zone was seen to be needed, beginning with studies of the age of different structures.

Finally, the group urged a closer look at information presented to the Workshop about traces of recent hydrothermal activity in the CCZ. Nodule composition and structure may have been affected by past stages of intense hydrothermal activity.

***Group B*: Bathymetry and Stratigraphy**

Group B chaired by Dr. Allen L. Clark, dealt with mapping of the seabed (bathymetry) and the sediment layers underlying it (stratigraphy). Noting that past analyses had dealt mainly with the CCZ as a whole, the group suggested that greater emphasis be placed on models specific to sites and areas of the zone. It also favoured the creation of two exploration models – one in narrative form and the other predictive, with a mathematical base.

With regard to the narrative version, the group observed that, as general factors affecting the origin, distribution and metal content of nodules were well understood, the emphasis should be on how those factors interacted in specific instances. Most of the group's recommendations concerned the predictive model – what chemical and physical characteristics in the nodule environment could be used as indicators of the likely presence of high-grade and high-abundance deposits.

The group viewed the carbonate compensation depth as a critical factor for the abundance and metal content of nodules. When the seabed lay too far above or below this depth – which varied in different parts of the ocean – nodule formation was inhibited.

The "grain" of the seafloor and its gross local and regional structure was identified as another factor in determining the abundance of nodules and, to a lesser degree, their metal content. Alongside this factor is topography, including slope and surface texture.

Present and past sedimentation was cited as critical to almost every aspect of nodule abundance and grade. The highest nodule concentrations lay in beds of siliceous ooze and zeolite clays. At the same time, none were found outside zones of high biological productivity near the equator. Sedimentation rates, erosion and currents must be in balance; too little or too much of any of these factors had a deleterious impact on nodule formation.

While the group found that much data on those factors already existed, a lot of it had not been given to the Authority. It therefore felt that the Authority should identify and access such data from seabed contractors and public sources.

The group offered seven recommendations for action by ISA. These included the development of databases on seafloor nodule photography, seafloor morphology and sedimentation; a definition of the geological evolution of the CCZ over the past 20 million years; the creation of sediment maps; the collection of information on heat flow; the development of exploration models for specific areas; and additional work to acquire and study data and to develop a system of open data access.

***Group C*: Sediments and Seawater**

Professor David Cronan, chaired Group C, which concentrated on the interface between sediments and the overlying water. As the main element in this regard, it cited biological productivity, and specifically export productivity – the part of the chemical soup that reached the bottom. This was regarded as a much more important source of metals than the surrounding seabed. As abundance and mineral grade were not generally related, the group felt that separate models were needed for those two factors.

The group observed that the relationship between productivity and nodule formation was not linear. While abundance rose with greater productivity up to a certain level, beyond that point it diminished, eventually dropping to zero. Thus, it was critical to determine the turnaround point. The depth of the oxygen minimum zone was another important element, but more work was needed to establish how that factor operated differently from productivity.

Like Group B, Group C saw a need for further studies of the CCD, including its variations from east to west. Copper, manganese and nickel concentrations increased near the CCD, while cobalt and iron grades decreased. Given that relationship, the task was to plot areas likely to be richest in particular metals. While no convincing relationship existed between nodule grade and the surrounding water, nodules were more likely to be found in particular types of organic sediments, with the richest and most abundant occurring in siliceous radiolarian ooze rather than diatomaceous ooze or red clay. Rate of sedimentation was probably more important than sediment type in predicting abundance.

Organic carbon in the sediment also increased towards the CCD but little data were available on this factor in the CCZ. Other factors included the calcium carbonate and silicate content of sediments, and the content and composition of pore water -- the seawater within nodules that bore additional metals. On topics requiring further work, the group cited productivity, calcium carbonate dissolution, biologically generated silicates and organic carbon. The group cited evidence that nodules were most abundant in areas of greatest bioturbation – burrowing and other animal activity that rearranged sediments.

Finally, the group suggested that any differences between the CCZ and the South Pacific be examined. If there were no substantial differences, a model for one could be applied to the other. Otherwise, the reasons for any difference should be investigated.

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CHAPTER 1 PURPOSES OF THE MODEL AND THE INTERNATIONAL SEABED AUTHORITY'S REQUIREMENTS IN RELATION TO MODEL DEVELOPMENT

Nii Allotey Odunton, Deputy to the Secretary-General, International Seabed Authority, Kingston, Jamaica

Distinguished workshop participants, before you is the schedule for the workshop, from which you can see that meetings will be from 10:00 a.m. until 5:00 p.m. every day. Presentations and subsequent discussions following each presentation have been scheduled for three quarters of an hour. We have also set aside time for a number of working group sessions to take place. As noted earlier by the Secretary-General, the agenda for this workshop was recommended by a meeting of a Group of Scientists that was convened by the International Seabed Authority (ISA) in January this year. It is recalled that one of the primary responsibilities of the Authority is to assess the quantities of metals of commercial interest to be found in nodules. In this regard, the Authority undertook such an assessment of the reserved areas within the Clarion-Clipperton Fracture Zone (CCZ) in the Pacific Ocean, using the data and information that were submitted to it by the registered pioneer investors and that are maintained in the Authority's POLYDAT database.[1] The resource assessment undertaken by the Authority revealed that the data and information submitted by the six Registered Pioneer Investors (RPIs) with allocated areas in the CCZ, while adequate for some resource assessment, are not sufficient to allow an estimate of the quantities of metals of commercial interest in the reserved areas with a reasonable degree of confidence.[2]

The work of the Authority in assessing the resources of the reserved areas will be addressed by Mr. Kaiser de Souza, the Authority's Marine Geologist, Dr. Robert de L'Etoile of Geostat Systems International (consultants to the Authority) and Mr. Baidy Diène, a member of the Authority's Legal and Technical Commission. Mr. de Souza will inform you of the Authority's database for the reserved areas and the structural analysis, validation and adjustment work that was undertaken on the data contained therein; Mr. de L'Etoile will inform you about the results of the geostatistical work on the resulting data and information; and Mr. Diène will inform you of the framework that has been developed by ISA for the submission of data and information by exploration contractors with the Authority.

Since the International Seabed Authority does not have the financial resources to assess these resources through exploration of the international areas under its purview, it was determined that geological modelling of the polymetallic nodule deposits in the CCZ is the most cost-effective approach to overcome this problem.[3]

Given the variability of polymetallic nodule occurrences in the CCZ, it was recognized that modelling would not be an easy task. Therefore, the Authority convened a meeting of expert scientists, in Kingston, Jamaica, in January 2003, which considered various aspects and factors to be considered for such modelling. During the meeting, various interrelated processes in oceans, the lithosphere, and its sediment cover, as well as in the atmosphere and the biosphere that are involved in the formation of polymetallic nodule deposits were discussed. Participants also discussed the results of scientific research correlating nodule grade and abundance with, inter alia, a transparent layer to be found at potential nodule mine sites, seismic/volcanic

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1 POLYDAT is the ISA database on polymetallic nodule deposits in seabed areas to found in the Area, which are reserved for the conduct of activities by the Authority through the Enterprise or in association with developing States. The data and information currently contained in POLYDAT were provided by the RPIs upon their registration by the United Nations Preparatory Commission for the International Seabed Authority and for the International Tribunal for the Law of the Sea.

2 The metals of commercial interest are assumed to be nickel, copper, cobalt and manganese.

3 At a meeting between the Authority and the registered pioneer investors (RPIs) in March 2001, some of the RPIs suggested that the future work of the Authority in resource assessment of the reserved areas in the CCZ would be enhanced through the development of a geological model for this part of the seabed.

activity in the CCZ, seabed topography and certain properties of the sediment layer at known deposits. These discussions were particularly useful given the paucity of grade and abundance data for the CCZ as a whole. Participants additionally discussed geostatistical methods and techniques that have the potential of being very effective in geological modelling.

Taking into account the fact that the quality of input data and information will determine the reliability of the model, the expert scientists recommended that the data and information used for the development of the model should be as broad as possible, and that for future work, the date and information should be based on standards to be developed by the Authority. The group also recommended that participants in the workshop include experts from academic institutions, public and private enterprises, contractors, members of the Legal and Technical Commission and representatives of member States.

The meeting proposed an agenda for the workshop, as well as a programme of work to establish a reliable model in the next four years, based on all available data. The proposed agenda recommended that the following matters be addressed during the workshop: a review of the theoretical aspects of nodule formation, the basic geology of the CCZ, identification of the components of the geological structure of the CCZ that will be required for resource assessments, identification of key nodule parameters for inclusion in the model, proposals for scientific research to assist in confirming apparent correlations between nodule deposit grade and abundance with various events or environmental characteristics of the CCZ, and the application of geostatistical methods to resource estimation.

In addition to the above recommendations, the agenda for the workshop takes into account the work that has been undertaken by the ISA in resource assessment of polymetallic nodule deposits in the CCZ and provides for the use of working groups from among participants for the purpose of examining the candidate proxy variables that are to be the subject of some of the presentations, with a view to establishing their relationship with the formation of nodule deposits, and in particular their relationship to high grade and high abundance nodule fields. It is anticipated that the working groups will comment on the availability of data for tests of the relationship between the concerned proxy variables and high grade and high abundance nodule fields. It is also anticipated that the bulk of the work required to outline subsequent steps in developing the model will take place within the context of these working groups.

On the part of the Authority, there is a clear need for both a quantitative and a qualitative model. At the present time, the Authority has grade and abundance data and some of the other applicable information relevant to polymetallic nodule deposits for areas submitted in the applications by contractors. Contractors and potential contractors not only have grade and abundance data for several other areas, including areas under exploration contracts, the reserved areas, other areas of the Clarion-Clipperton Zone, and relinquished areas, but possibly other data, such as the proxy data that have been identified. There are also data and information available in the public domain on the CCZ that are contained in the Authority's Central Data Repository. For the vast area that is the Clarion-Clipperton Zone, therefore, we have sample station data for a relatively small portion. We can try to acquire additional sampling data from private sources, and we can try to acquire and test the use of proxy variable data for the remaining significant chunk. We would like to hear from some of the scientists gathered here this week about the different approaches to finding out if relationships exist between these variables and high grade and high abundance polymetallic nodule deposits.

Using the two sides of a coin as an example of the Authority's objectives with regard to the model and based on the great amount of work that has gone into nodule prospecting and exploration since their discovery by the *Challenger* Expedition, in particular in the Clarion-Clipperton Zone, one of the sides of the coin could be estimates of the resources of the metals of commercial interest (nickel, copper, cobalt and manganese) to be found in deposits there, and the data and methods utilized to establish the estimates. The other could contain a cartographic rendition of the distribution of the known and suspected deposits of polymetallic nodule deposits in the zone, along with the structural and other features that would have to be addressed to mine these deposits. In each case, we would hope that the model's structure lends itself to further development. For example, as additional sampling station data become available on interesting areas within the zone, we would hope that the original platform can be modified to more accurately provide resource estimates, and also be modified with regard to the initial relationships determined for proxy data and grade and abundance, and to have them incorporated in the model appropriately.

We would also hope that this process leads to some form of standardization of the data that are collected and utilized in the model to ensure their compatibility and to improve the accuracy of the model.

We look forward to your recommendations for a road map that, over the next few years, will enable the Authority to establish a quantitative and qualitative model that takes advantage of information on all the known deposits and station data on polymetallic nodule occurrences in the Clarion-Clipperton Fracture Zone (including the reserved, contractors, relinquished and potential contractors areas), that allows for the identification, collection and testing of proxy variables for high nodule grade and abundance deposits, and that both contractors and potential contractors feel confident with.

We would like to suggest that the workshop be organized with Dr. Charles Morgan and Mr. Alf Simpson, as co-chairpersons, and with Dr. Lindsay Parson as the rapporteur. Hearing no objections, we will proceed in this fashion. We will have a coffee break during the morning and afternoon sessions. These are scheduled for half an hour each, and will enable you to use some of the facilities that have been provided by SOPAC, including access to the Internet. The Secretariat also has an office in a building adjoining the hotel entrance, called Senitoa. Should you need to discuss any matters or problems with the Secretariat staff outside of the scheduled meetings that is the place to locate them. In addition to the Secretary-General, the members of the Secretariat that are present for the workshop are: Kaiser de Souza, Anna Elaise, Margaret Holmes and I.

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CHAPTER 2 THE INTERNATIONAL SEABED AUTHORITY'S RESOURCE ASSESSMENT OF THE METALS OF COMMERCIAL INTEREST IN POLYMETALLIC NODULE DEPOSITS IN RESERVED AREAS

Kaiser de Souza, Scientific Affairs Officer (Marine Geologist,) International Seabed Authority, Kingston, Jamaica

Distinguished participants, I will present the efforts of the Authority to undertake resource assessments of the metals of commercial interest that are found in polymetallic nodule deposits in the reserved areas. This presentation will focus on POLYDAT, the Authority's database on polymetallic nodule deposits found in the reserved areas. The objectives of the resource assessment work that was carried out by the Authority were:

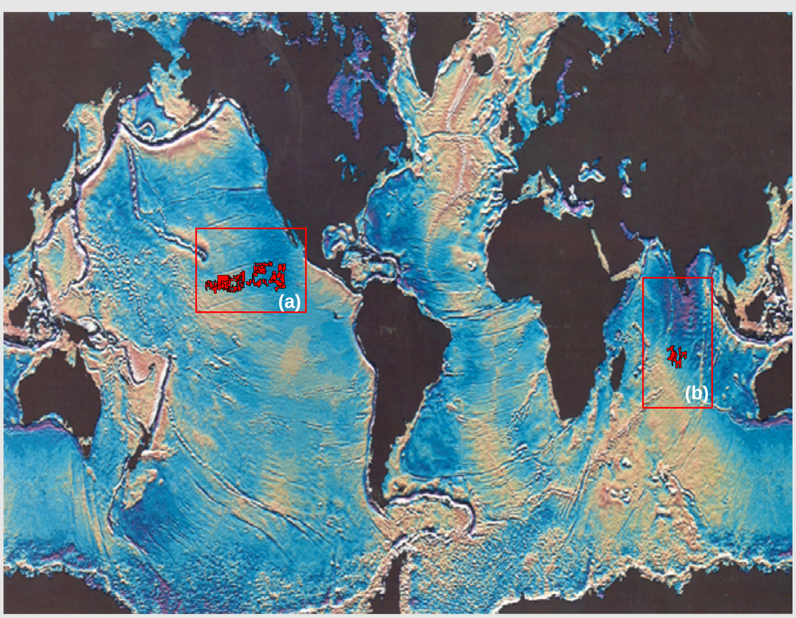
(a) To provide an inventory, homogenisation, critical analysis and validation of the available data and information in POLYDAT;

(b) To estimate the quantities of the metals of commercial interest in polymetallic nodule deposits in the reserved areas; and

(c) To propose modalities for the future development of POLYDAT, in a way that it can facilitate the fulfilment of the Authority's mandate to administer the mineral resources of the Area.

The actual resource assessment was carried out in three steps: the first was the structural analysis of the data and information in POLYDAT; the second was the validation and adjustment of the data and information that it contains, and the third was the geostatistical analysis and estimate of the metals contained in deposits in reserved areas, including the Clarion-Clipperton Zone (CCZ).

Figure 1 shows the location of application areas in the Pacific and Indian Oceans for registration as pioneer investors during the Preparatory Commission for the International Seabed Authority and for the International Tribunal for the Law of the Sea.



GLOBAL LOCATION OF APPLICATION AREAS FOR REGISTRATION OF PLAN OF WORK FOR EXPLORATION FOR POLYMETALLIC NODULES IN THE (a) PACIFIC OCEAN (b) INDIAN OCEAN.

Figure 1

Seven entities submitted applications for registration as pioneer investors during this period: six applications were for areas in the Pacific Ocean and one was for an application area in the Central Indian Ocean.

Figure 2 shows the location of application areas for pioneer investor status in the Pacific Ocean. The applications were received from COMRA (Peoples Republic of China, Yuhzmorgeologiya (Russian Federation), DORD (Japan), KORDI (Republic of Korea), IFREMER/AFERNOD (France) and Interoceanmetal Joint Organization (IOM), composed of Bulgaria, Cuba, the Czech

Republic, the Russian Federation, the Slovak Republic and the Republic of Poland. The Government of India's application area is in the Central Indian Ocean basin (Department of Ocean Development).

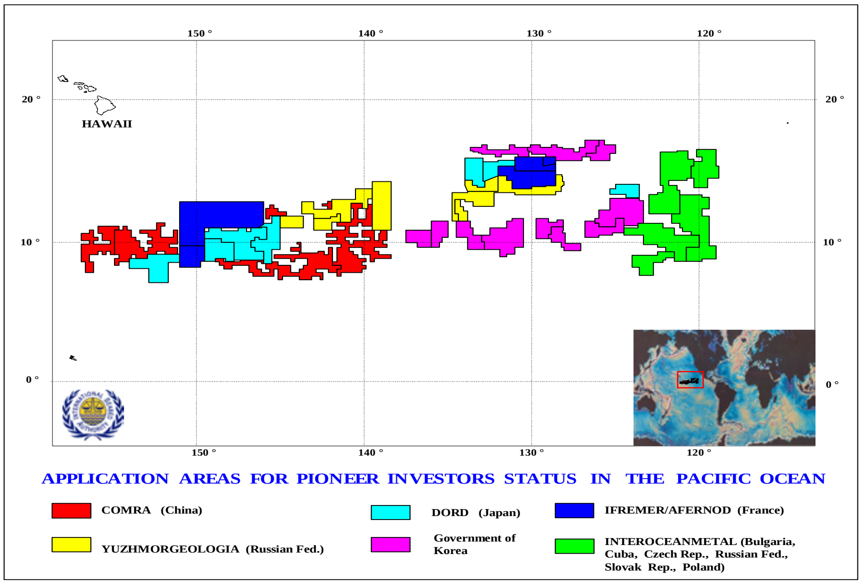


Figure 2

Figure 3 shows the areas reserved for the conduct of activities by the International Seabed Authority in the Pacific Ocean resulting from registration

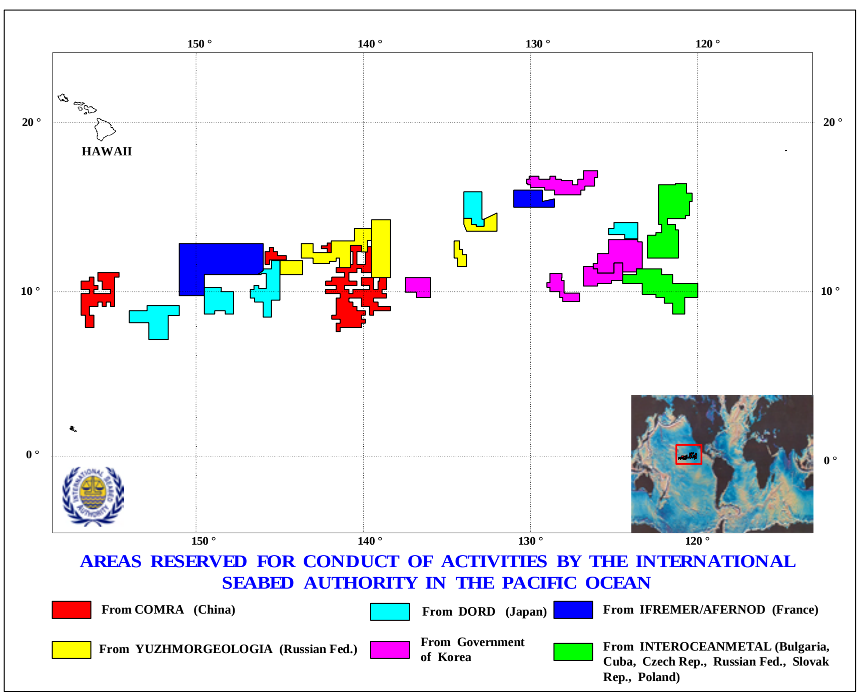


Figure 3

Each of the six pioneer investors in the Pacific Ocean provided the Authority with half of their application areas as reserved areas. It was in respect of these areas that the resource assessment was conducted. It is important to mention that the pioneer investors provided data and information for each reserved area and for their individual pioneer areas. In order to proceed with the resource assessment, the reserved areas were divided into twelve sectors, each one containing one to four blocks. *Figure 4* shows the blocks in the Clarion-Clipperton Zone; these were further divided into three different regions, Western, Central and Eastern.

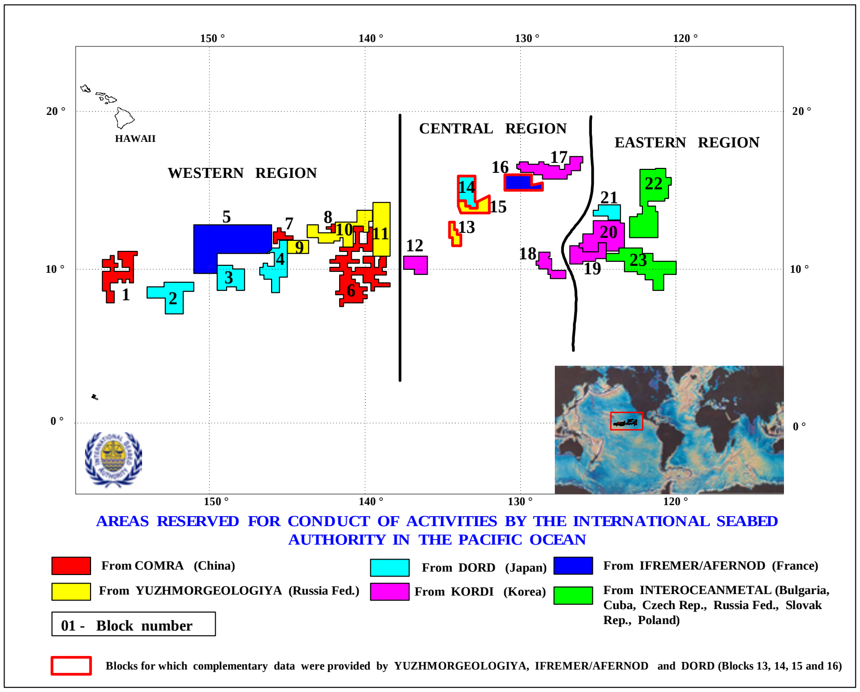


Figure 4

The first step in the resource assessment of the metals of commercial interest in polymetallic nodule deposits in the CCZ was to analyse the data and information that came from the pioneer investors. Data and information include the coordinates of areas, turning points and sampling positions, and sampling data, (which consists of nodule abundance and nodule composition), seabed topography, and methods and equipment used for data collection and analysis.

Coordinates and sampling data

Coordinates refer to turning points and sampling data. Turning points are locations described by latitude and longitude. By drawing a line from one turning point to another, the perimeter of each block is revealed. Sampling data include information on latitude and longitude to indicate where the sample(s) were collected, the depth, the abundance and the mineral composition of recovered nodules. The mineral composition provides information of the content of the following metals: manganese, nickel, copper, cobalt, and for some blocks, iron. *Figure 5* contains an example of turning points and sampling data.

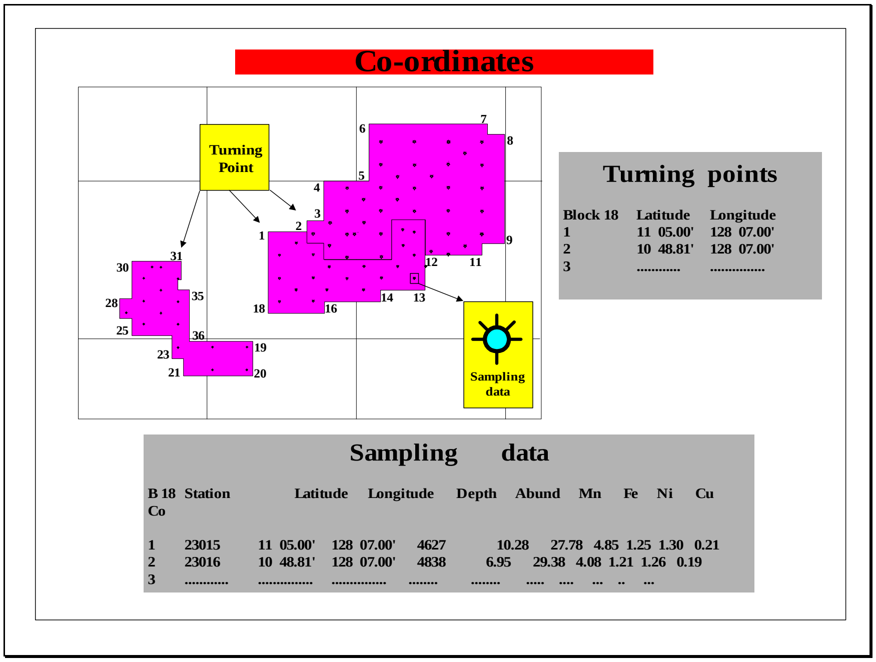


Figure 5

With regard to coordinates, it is important to bear in mind that the Authority was provided with different sets of data and information by each of the pioneer investors. The first group of applicants for areas in the Clarion-Clipperton Zone provided coordinates obtained with the transit satellite system, which was based on satellite fixes received every 2-6 hours. The precision of those coordinates is between a few hundred metres to several kilometres. After 1994, the other group of pioneer investors started to use the Global Positioning System with a fixed point every second, providing an accuracy of 100 metres. Since 2000, the accuracy of positioning systems has increased to 10 metres. As such, the accuracy of the data on coordinates in POLYDAT shows considerable variation *(Figure 6)*.

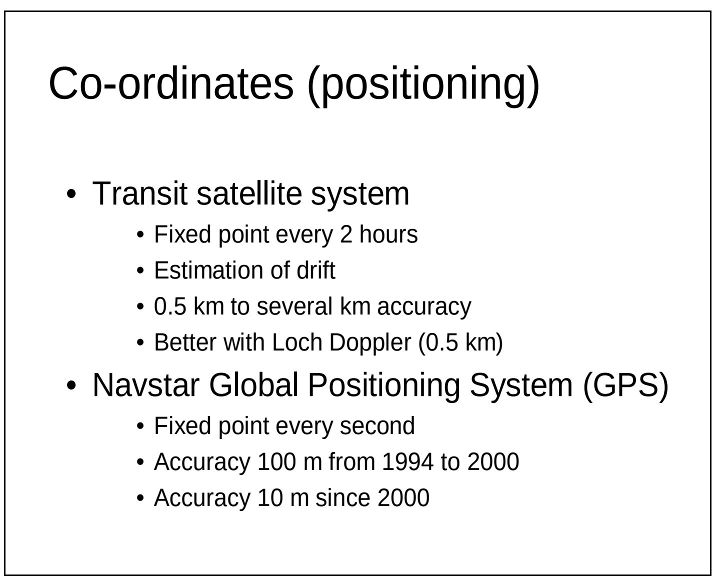


Figure 6

Sampling data include the latitude and longitude of each sample station, the abundance of nodules at the station in kilograms per square metres, the metal content of nodules (percentage) recovered from the station, that is, nickel, copper, cobalt and manganese, and in some cases, the iron content of the nodules *(Figure 5).*

It is important to understand what is referred to as sampling data and how they are acquired. Sampling data are the averages of several measurements that were taken in a nearby location. Some of the pioneer investors, for example, used seven sampling devices that could collect nodules and take pictures of the seafloor. Others used three devices, with two collecting nodules and the other taking pictures of the seafloor. Yet others used four sampling devices. One pioneer investor, however, used only one device at each sampling station, but that device could take pictures before the sampler touched the seafloor to collect nodules and re-photograph the area. Therefore, different methodologies were used to collect nodules and quantify them with regard to abundance and metal content. On one hand, samplers, such as free-fall grabs, which were used by most of the pioneers, could sample an area of approximately 20 per cent of a square metre, which is about 20 times the size of a nodule. Others used cable-operated grabs that could sample an area 20 times larger than a nodule. Still others, using box-corers, could sample one square metre, representing 100 times the size of a nodule. A photograph, on the other hand, normally shows about four square metres of the seabed, which is, 200 to 400 times the size of a nodule. It is important to point this out, because without photographs of the seafloor, abundance becomes difficult to determine.

Figure 7 shows one of the sampling devices used by the pioneer investors. It is a free-fall grab. It is launched from the surface ship and dives to the sea bottom, where it takes photographs and collects nodules. Upon releasing a dead weight, it starts its ascent to the surface. Free-fall grabs are generally equipped with a radio, a flashlight and a flag which allows them to be located and recovered by the surface ship.

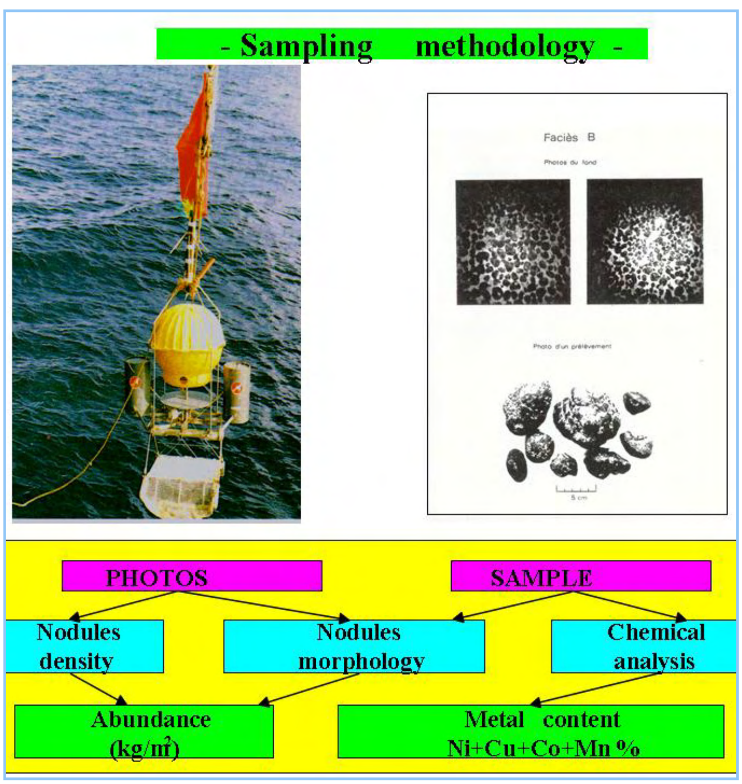


Figure 7

Figure 7 also shows an example of collected nodules along with photographs taken at the location. With the photographs, the pioneer investors could observe nodule density and nodule morphology and through them, determine the abundance of nodules in a given area.

The collected nodule samples are first described through the number of pieces, dimensions, colour, shape, texture, size, etc. Their internal structure is also described after cutting and polishing aand a representative part of the sample is extracted for chemical analysis. All of this information is essential for studying resource distribution on the seabed. However, POLYDAT does not contain any of the above information, in particular, in photographs. Therefore, no critical analysis of nodule abundance in the reserved areas is possible.

The collected samples also make it possible to proceed with chemical analysis, and to determine the percentage of the metals of economic interest and others in the nodules.

Figure 8 illustrates one of the problems encountered in collecting nodules. For example, the sampler showed in this figure, used by one of the pioneer investors, underestimated the density of nodules and thus, when its collector opened to collect nodules, it pulled them apart and failed to collect most of them. In addition, the photographs of the sampled area revealed that most of the nodules found there were covered by sediments.

As a result, when the determination of the distribution of nodules was made, it was underestimated.

In the determination of nodule composition, after collecting samples, the nodule samples were divided and then prepared for chemical analysis. Different methods were used by the different pioneer investors to analyse samples.

Another factor that was taken into consideration during the Authority's resource assessment was the sampling grid used by each pioneer investor. Each pioneer investor provided data and information based on different sampling grids.

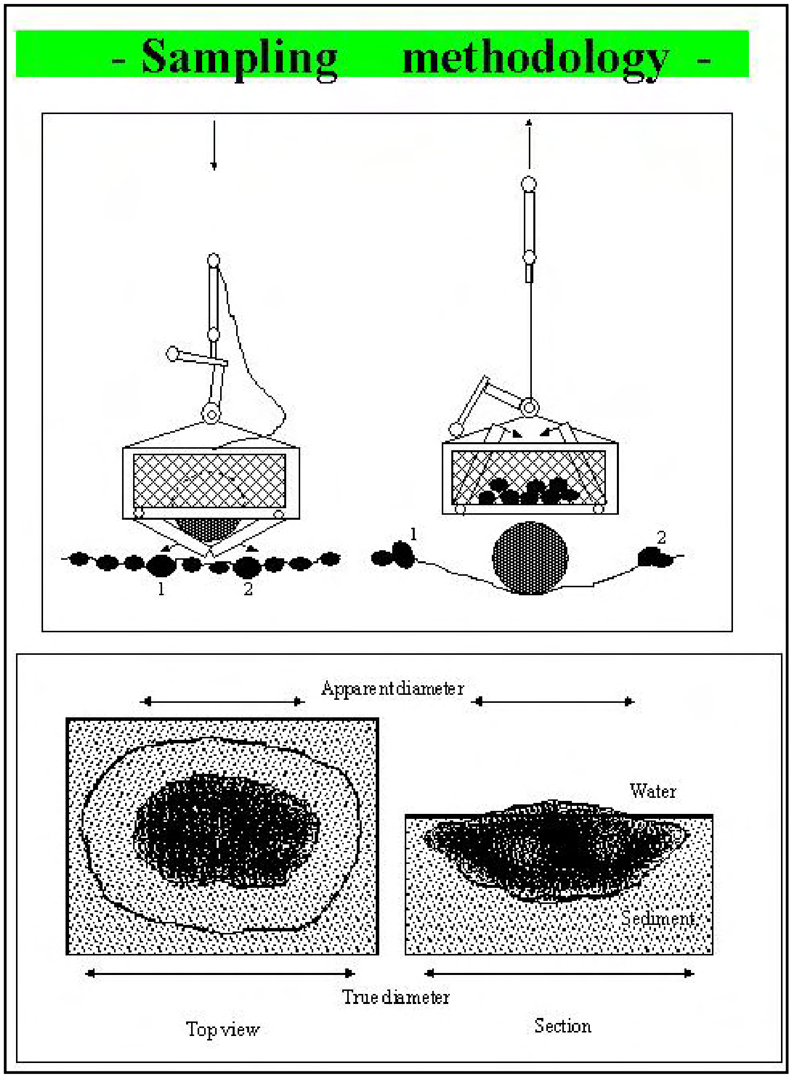


Figure 8

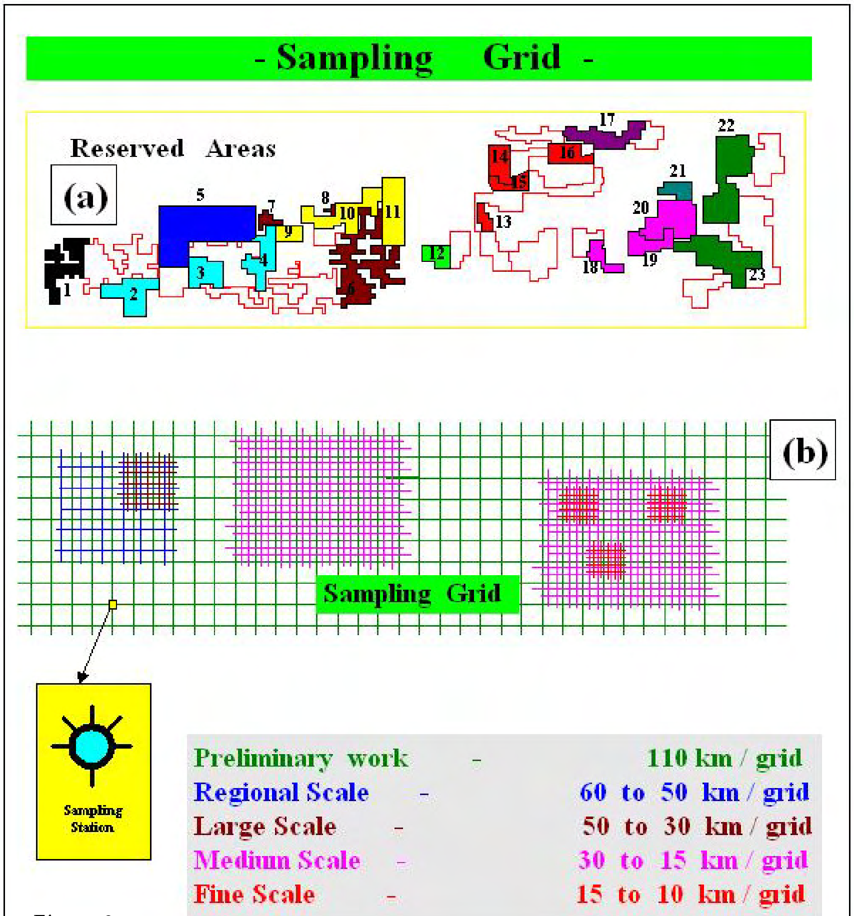


Figure 9

Figure 9 illustrates the different grid sizes that were used by the pioneer investors in the CCZ.

For example, the green-coloured grid has a 110-km size, meaning that each sample station on this grid is 110 kilometres apart. This was the sampling grid used in the preliminary work undertaken by three of the pioneer investors.[4] One of the pioneer investors provided sampling data on a 50 to 60 km grid. The best grid size in POLYDAT is for sampling stations that are between 10 and 15 km apart. Most of the data are from grids that are between 20 and 30 kms apart.

The sampling data in the reserved areas came from 2004 stations where the occurrence of nodules was investigated.

The nodules were systematically analysed for their manganese, nickel, copper and cobalt contents. Therefore, the density of available data in the reserved areas is irregular and sometimes not adequate to evaluate the nodule resources and compare the various sectors from which they were obtained. The spread of data that have been gathered actually reflects work at different stages; from marine scientific research/prospecting to the early stages of exploration.

Figure 10 is a map of sector 7 of the reserved areas, and illustrates the varying density of information available to the Authority from one block to another. Sector 7 contains blocks 13, 14, 15 and 16.

[4] IFREMER/AFERNOD, DORD and YUZHMORGEOLOGIYA

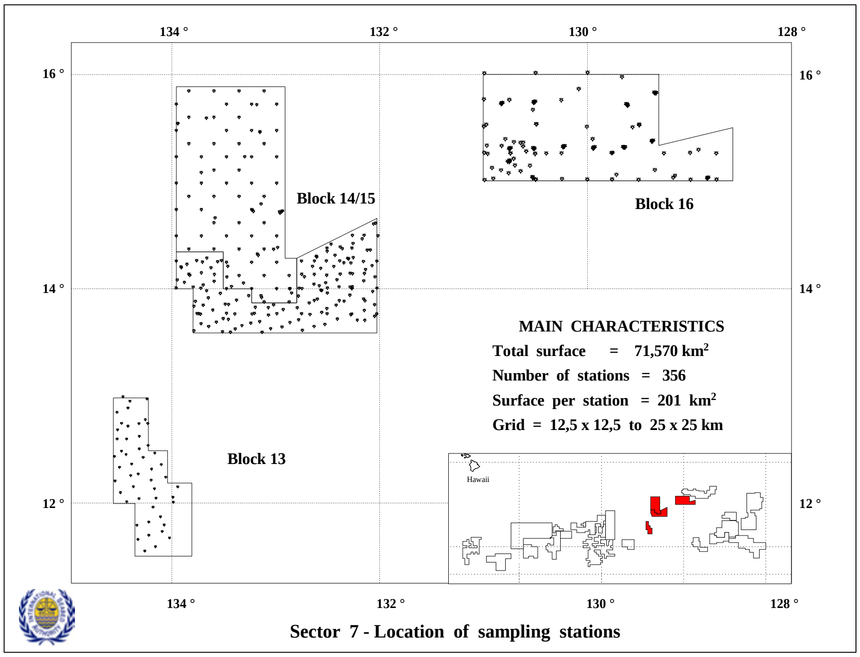


Figure 10

Figure 11 shows block 15 from sector 7 of the reserved areas. Block 15 is one of four blocks for which information has been provided to the Authority by more than one pioneer investor. These four blocks were initially prospected by DORD, Yuhzmorgeologiya and IFREMER/AFERNOD. Following negotiations with the General Committee of the Preparatory Commission, these blocks became part of the areas reserved for the Authority as a result of their registration.

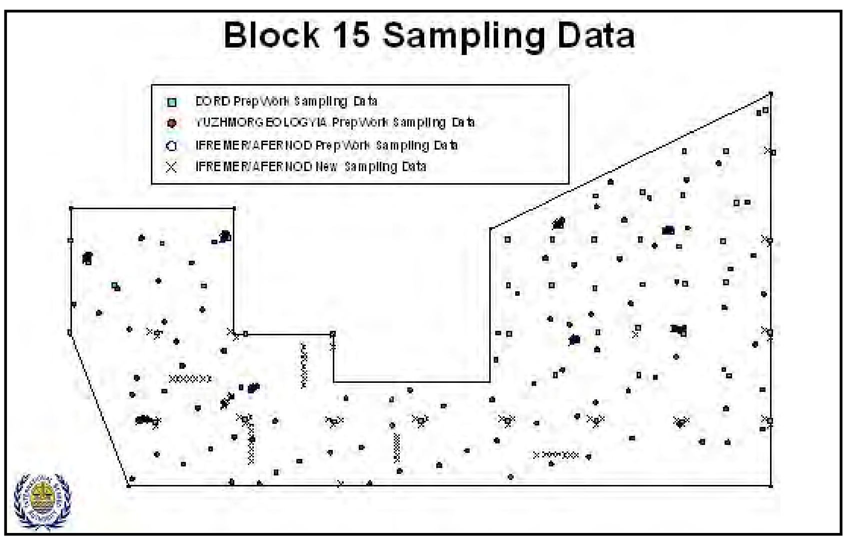


Figure 11

Pioneer investors also provided bathymetric maps of their application areas on the scale of 1 to 1 million metres to the Authority. These maps were created using different technologies. The bathymetry of the seabed was investigated by echo sounders, which transmit a sound signal from the ship and records the signal on its return from the sea bottom, thereby providing the depth.

Two types of echo sounders were used: conventional echo sounders, which provide only a single profile along the ship's course, and a multi-beam echo sounder, which provides maps of bottom topography over a strip centered along the ship's course. The multi-beam echo sounder has the advantage of covering large areas in a relatively short period of time. This system brought out morphological and structural features that would have gone unnoticed by conventional echo sounders. Thus, it helped to select regions for detailed work, such as exploration by towed and free photographic vehicles or side-scan sonar surveys.

Some of the pioneer investors used conventional echo sounders, while others used multi-beam echo sounders, resulting in significant differences in the maps. *Figure 12* illustrates the multi-beam system used to map large areas along the ship's route and the conventional echo sounder that was able to map just a small area.

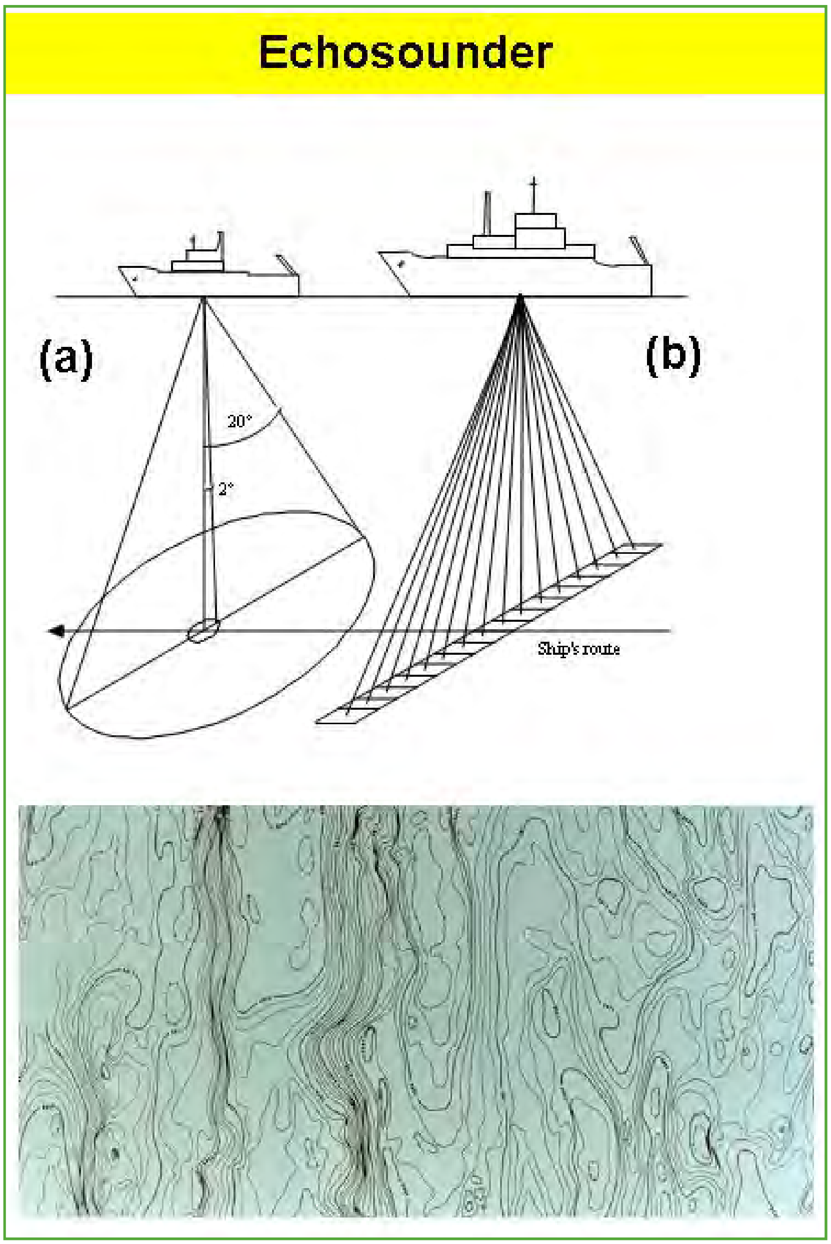


Figure 12

Figure 13 depicts different maps (A, B, C) provided by three different pioneer investors in exactly the same area. As can be seen, none of them look alike. These types of unexplained differences resulted in the Authority requesting clarification from the pioneer investors as to the source of the discrepancies. In the event that they were as a result of technological or analysis problems, ISA also requested information on the adjustments to be made.

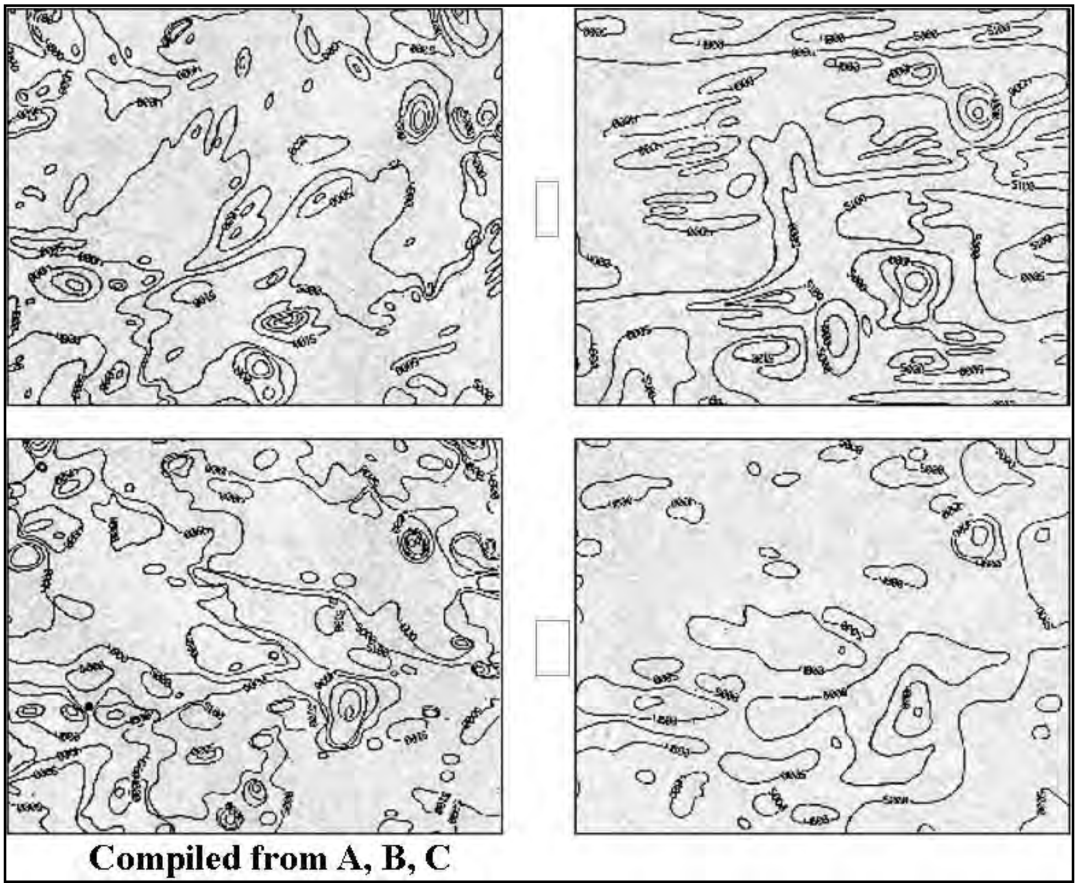


Figure 13

SUMMARY OF THE DISCUSSION

The discussions that followed Mr. de Souza's presentation focused on the scales of the maps that had been provided to the Authority, the sizes of the blocks that the reserved areas had been divided into, why they had been divided into these blocks and the discrepancies that he talked about in his presentation.

In response to a question about the scale of the bathymetric maps that he had spoken about, Mr. de Souza said that they had been produced at a scale of 1/1,000,000. In response to a question on the size of block 15, he said that the reserved areas in the CCZ had been divided into 23 blocks and pointed out that the individual blocks had certain characteristics. When these characteristics were viewed in the context of the six datasets that comprised POLYDAT, some of the results obtained caused concern to ISA. He then described the inventory, homogenization, critical analysis and validation of the available data and information in POLYDAT.

Mr. de Souza said that one of the steps taken by the Authority in analysing the data and information contained in POLYDAT was to ensure that there were no discrepancies in the six datasets. He said that, in order to identify possible discrepancies between datasets for different blocks of the reserved areas, the dataset for each block needed to be compared with those of neighboring blocks.

Mr. de Souza informed participants that the comparison carried out by the Secretariat took into consideration:

(a) Statistical parameters, such as the average value, the maximum and the minimum values, and the standard deviation of nodule abundance and similarly of the metals of economic interest in different regions of the CCZ;

(b) The distribution of nodule abundance and metal content in each block.

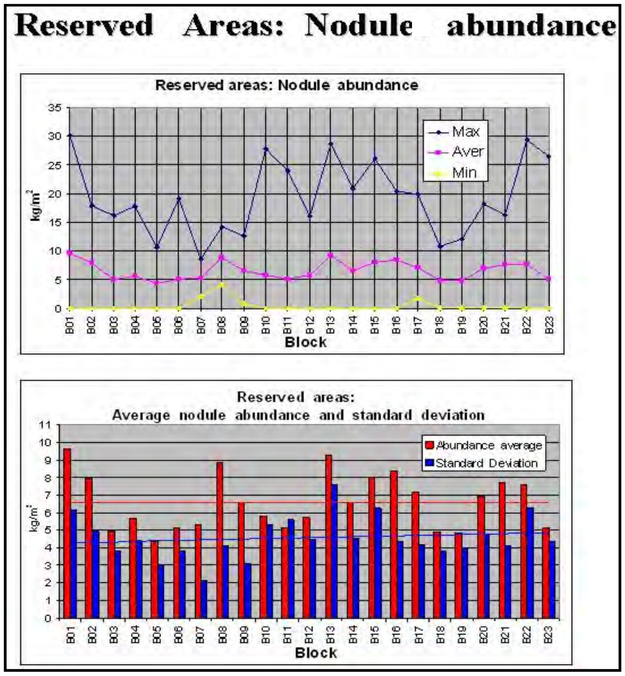
He said that these comparisons were made through the analyses of histograms and correlograms of those values.

He informed participants that, for each block of the reserved areas, the statistical analysis performed resulted in the tabulation contained in *Figure 14*. The tabulation indicated the area, number of stations, surface stations and the grid used by the pioneer investors. It also indicated nodule abundance, metal content and the combined grades of the metals of interest.

Statistical Parameters

STATISTICAL RECORD OF BLOCK 01							
Origin of data	COMRA						
Block surface (km^2) 44,170	Number of stations 56		Surface per stations (km^2) 789			Grid (km^2) 25 x 25	
	Water Depth	Abundance (kg/m2)	Mn_%	Ni_%	Cu_%	Co_%	Ni+Cu+Co
Average	5180	9.64	24.58	1.00	0.81	0.24	2.05
Maximum	5404	30.19	30.34	1.54	1.60	0.37	3.35
Minimum	4488	0.02	17.04	0.61	0.34	0.12	1.29
Standard deviation	183	6.17	2.49	0.23	0.32	0.05	0.50
Standard deviation/mean	4	64.01	10.12	22.63	39.56	22.60	24.49

Figure 14



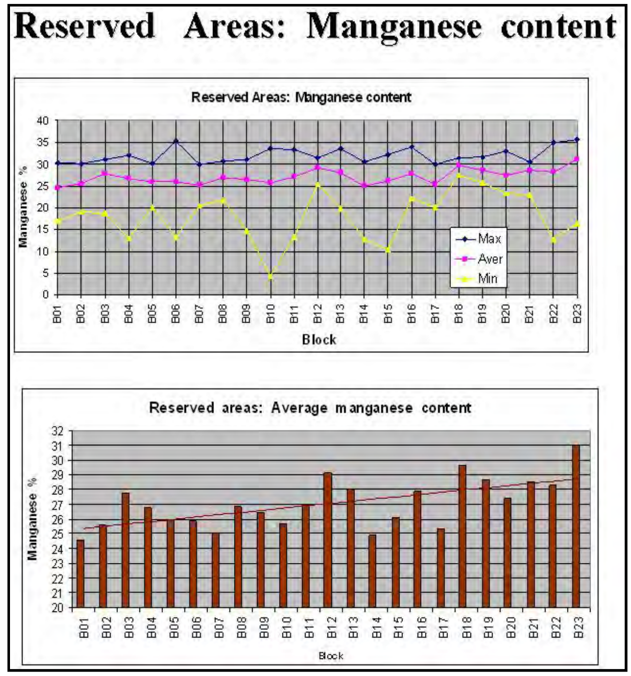
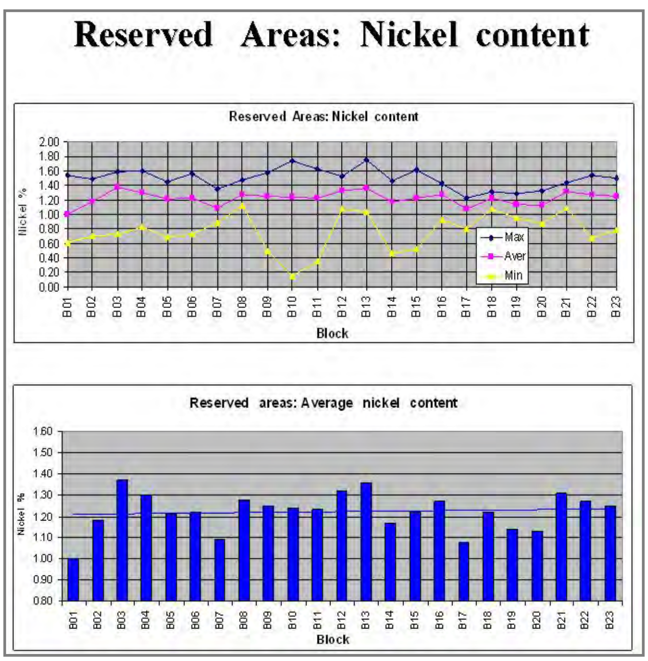


Figure 15

Figure 16

Utilizing *Figure 15*, Mr. de Souza said that the different blocks within the CCZ could be compared. He also provided participants with histograms and correlograms of the metal values from the 23 blocks of the CCZ *(Figures 16, 17, and 18).*



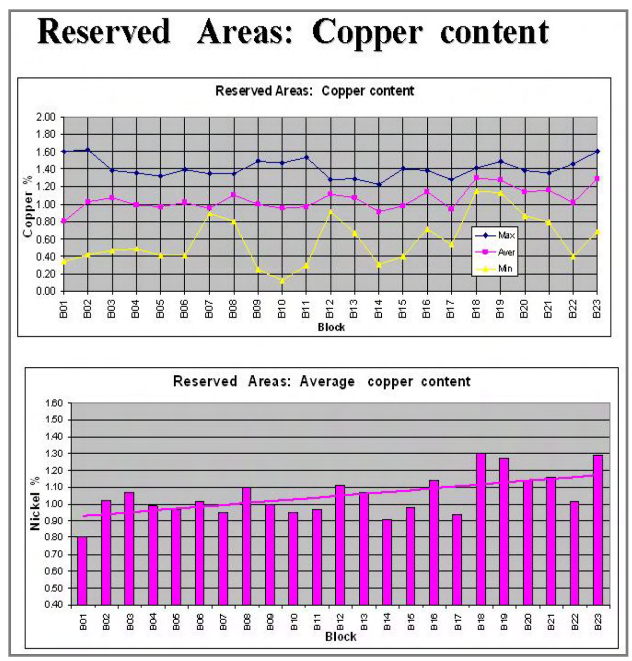


Figure 17

Figure 18

Utilizing these statistics, Mr. de Souza said that it had been observed that, in some cases, for neighbouring blocks, the values of abundance varied considerably from one block to the next. He said that the same analysis was performed for the different metals, noting that metal distribution generally exhibited changes after several hundred kilometres. He emphasized that, unless blocks had different geological characteristics, they were supposed to be more or less similar. He noted, however, that differences were found in the metal content in adjoining blocks, which suggested that the problem was not related to the geological characteristics of the blocks, but rather, appeared to be related to a problem in using different methods for analysing the metals in the nodules.

To illustrate the point, Mr. de Souza provided participants with an example, using the manganese content of blocks in the eastern region of the Clarion-Clipperton Zone. He defined the eastern region as composed of five blocks containing data from three pioneer investors *(Figure 19).*

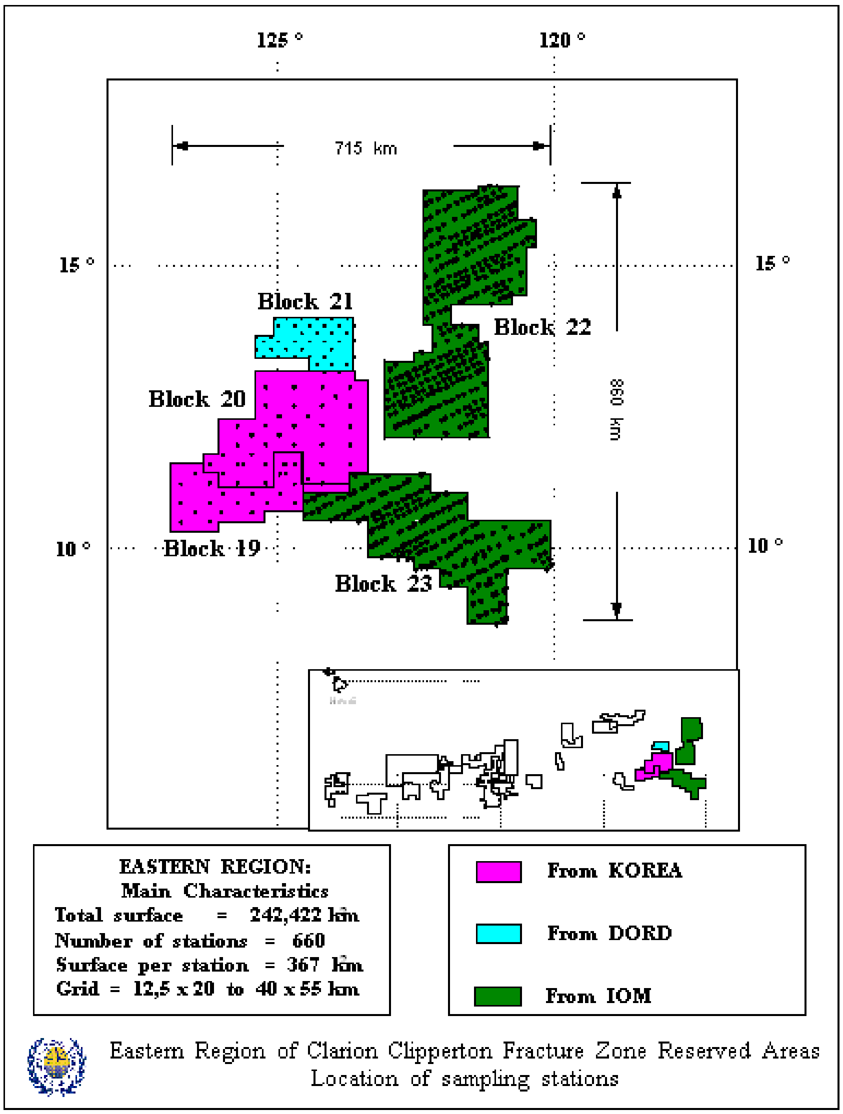


Figure 19: Eastern region of the Clarion-Clipperton Fracture Zone

Mr. de Souza pointed out that, through histograms of each block, the distribution of nodules and other parameters related to them varied from block to block. With nickel content data for the blocks, he pointed to two blocks for which data had been provided by the same contractor, noting that the nickel content of the two blocks was quite different from the other three blocks. He said that, as part of the Authority's resource assessment of the CCZ, an effort had been made to determine why the two blocks were significantly different from the others, and whether the significant difference was as a result of problems with data analysis, or whether the blocks were located in geological environments that differed from the other three blocks. Mr. de Souza indicated that similar problems could be found in the datasets for abundance throughout the 23 blocks. He suggested that additional data and information, such as seafloor photographs and more precise oceanic data, would enhance the results of resource assessment.

With regard to the Authority's resource assessment work, Mr. de Souza said that the discrepancies that had been found in the datasets for different blocks of the reserved areas suggested that parameters, such as abundance and metal content in different blocks of the reserved areas, might require adjustment. Before merging the data and information for the purposes of resource assessment, Mr. de Souza said the Authority convened a meeting with representatives of contractors. The purpose of the meeting was to inform them of these concerns, determine whether these differences were indeed discrepancies, and to agree on methodologies for making the necessary adjustments before merging the data. Proposals made by the Secretariat to the representatives of contractors included utilizing the method adopted by IFREMER/AFERNOD, Yuzhmorgeologiya and DORD in the preparatory work they provided on four blocks in the reserved areas, and for contractors to provide the Authority with additional data because most of them had prospected much larger areas than their application areas.

During the meeting, some of the representatives of the contractors suggested that the future work of the work of the Authority on resource assessments of the reserved areas would be enhanced through the development of a geological model of the CCZ.

As a result of the meeting, IFREMER/AFERNOD provided the Authority with a considerable amount of additional data and information from other sampling stations in the CCZ. The additional data and information were introduced into the 23 blocks of the reserved areas and consequently used to augment the confidence factor of the resource evaluation in this area. IFREMER/AFERNOD indicated that the abundance values contained in its original application had been adjusted. The datasets provided to the Authority by IFREMER/AFERNOD included the adjusted sampling data from block 5. COMRA also provided data and information in its possession from the part of its application designated as a reserved area that had not been submitted as part of its application.

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CHAPTER 3 A RESOURCE MODEL FOR DEEP SEABED POLYMETALLIC NODULES IN THE RESERVED AREAS

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FOREWORD

This document describes a resource model of the Clarion-Clipperton Zone. The model was elaborated in 2001 and was described in a technical report submitted to the Authority by the author. It should be viewed as a presentation document focused on the description of the resource model and its potential uses.

A. Introduction

The objective of this study is to model the resources of seabed polymetallic nodules confined in the reserved areas. The reserved areas are located in the Pacific Ocean between 150° and 158° longitude and between 8° and 17° latitude approximately, and in the Central Indian Ocean. The reserved areas are subdivided into 24 blocks (blocks 1 to 24). Blocks 1 to 23 are located in the Pacific Ocean and block 24 is located in the Indian Ocean. The description of the international status of these blocks is beyond the scope of this study. From a technical standpoint, they will be referenced only by their number. Reference to their country of origin, when mentioned, is used solely for clarity and historical references.

This technical study will help the Authority to establish the global seabed nodules resources under its jurisdiction.

A resource model characterizes and describes the quantity and grade of the chemical elements and the abundance of nodules in the areas. As such, it is a component of a broader model called the geologic model. The latter describes all aspects of the seabed nodules deposits; the genesis, the nodule formation mechanisms, the natural characteristics of the environment, etc.

The resource model is deterministic. It is constructed from data coming from the collected samples over the areas. The geologic model contains both deterministic data and characteristics that are assumed, hypothesized or derived from related science and knowledge.

This document describes the nature of the resource model that was derived by Geostat Systems International Inc. during an assignment carried out by the International Seabed Authority in May 2001. The first part of the document describes the characteristics, its construction methodology and parameters.

1. Geographical aspects of the reserved areas

The geographical aspect pertinent to the resource model is characterized by the locale of the reserved areas and by the bathymetry over the areas. Other characteristics such as the paleo-climate, water temperature, and currents, are not considered material to the resource model but are an integral part of the broader geologic model.

2. Location and size of the reserved areas

Figure 1 shows the location of reserved and pioneer areas in the Pacific Ocean.

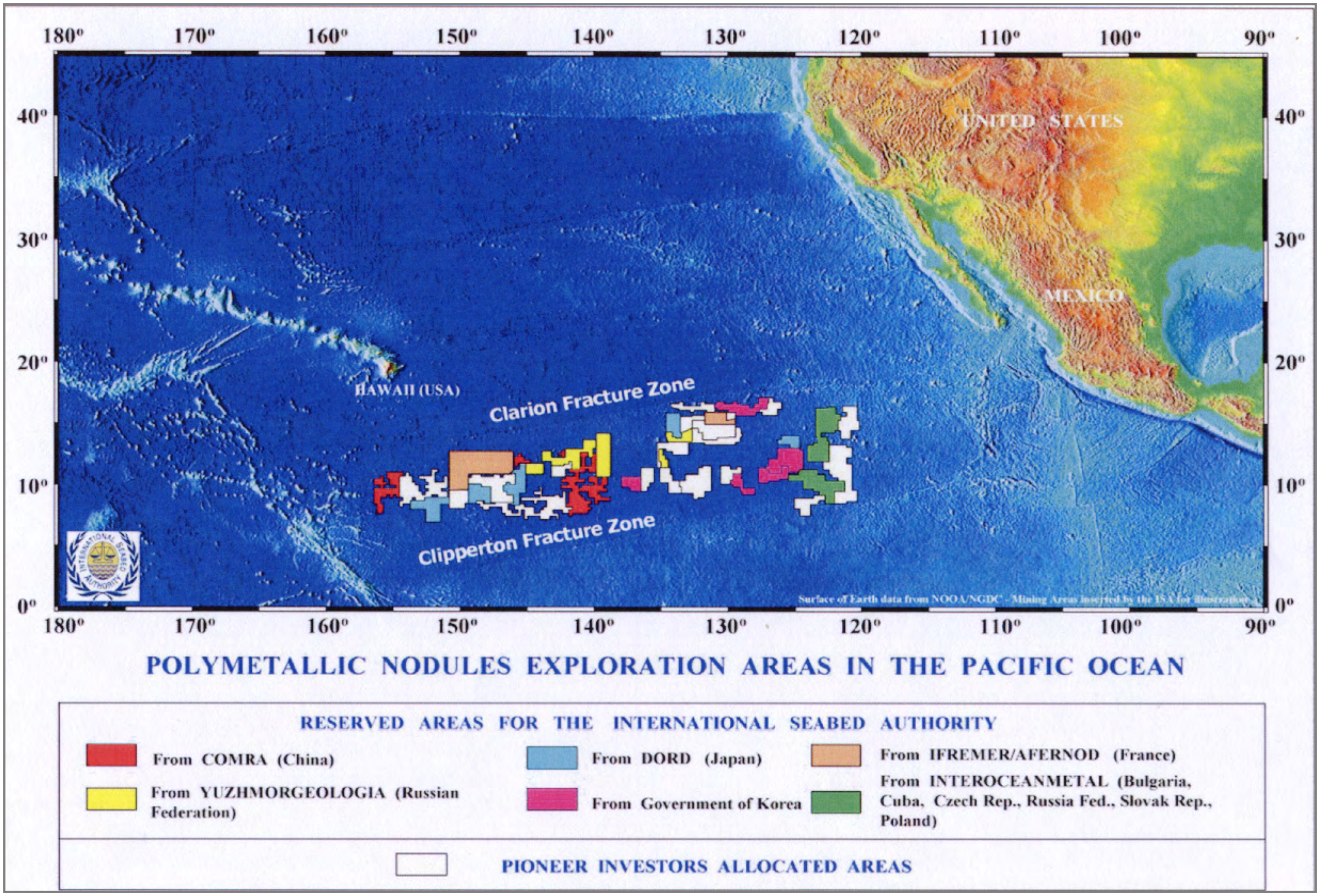


Figure 1: Geographical location of the Reserved Areas in the Pacific Ocean

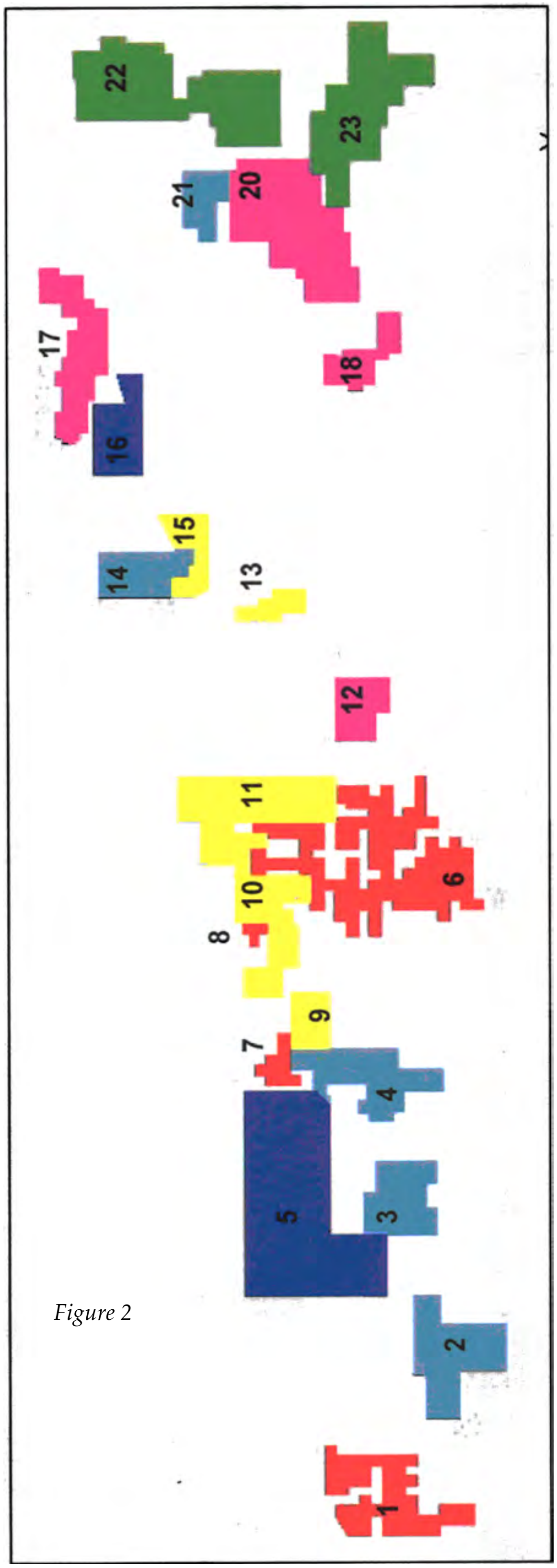


Figure 2

The reserved areas are delimited by boundaries in the form of polygons. Each of the 24 blocks of the reserved areas has such a boundary. In *Figure 2*, the boundaries of blocks 1 to 23 are presented.

For practical reasons, the geodetic coordinate system used to delimit the areas will be replaced by a Cartesian coordinate system, using the Mercator projection.

The size of the reserved areas in the Clarion-Clipperton Zone is rather large, amounting to 930,000 km^2. By comparison, it is the size of the United Republic of Tanzania or Nigeria, almost twice the size of France, and 2.5 times the size of Germany or Japan. We assume that not all of the areas are of economic interest, but they all participate in the resource model.

Linearly, the east-west extent of the reserved areas along the east-west direction is approximately 4,000 kilometres and the north-south extent is somewhat over 1,000 kilometres. By comparison, to fly over the entire area with an Airbus 340-300 airplane flying at its maximum speed of 900 km/h would take a little less than five hours. Travelling by sea on an oceanographic ship, such as the *Ronald H. Brown* of the National Oceanic and Atmospheric Administration (NOAA), cruising at a speed of 12 knots, it would take nine days to cross the reserved areas from west to east.

3. Bathymetry of the reserved areas

The ocean floor in the reserved areas lies at depths between 4,300 to 5,300 metres. By comparison, Mont Blanc in France peaks at 4,800 metres above sea level. *Figure 3* contains a schematic presentation of the bathymetry of the seafloor in the reserved areas in the Pacific Ocean.

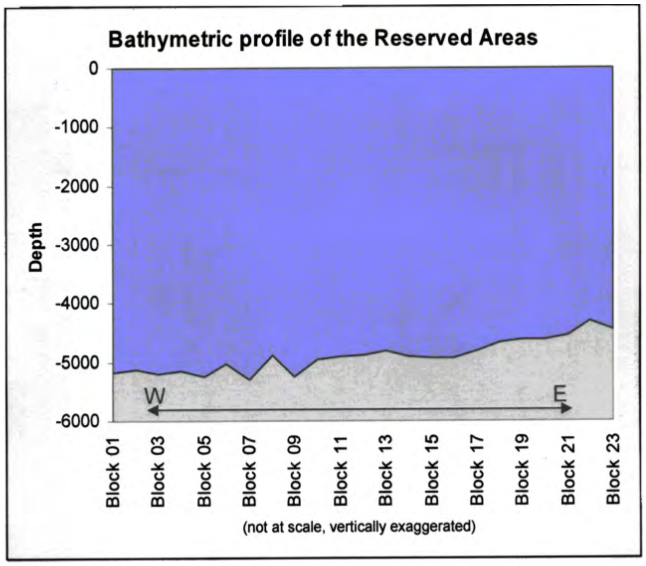


Figure 3: Schematic representation of the ocean floor from West to East

As can be seen, generally speaking, the eastern part of the reserved areas is shallower than its western counterpart.

Figure 4 presents the topography of the seafloor, derived from the predictive 2 minutes by 2 minutes bathymetry model from NOAA, in the area of block 22. The bathymetric values have been exaggerated 10 times to enhance the contrasts.

At the scale of the reserved areas, the topography is rather flat and smooth. However, it is expected that, at the scale of a potential mining operation, the ocean floor might be much more rugged, with ridges and valleys. Detailed topographic surveys will then be required.

Pioneer investors submitted bathymetric maps with their respective applications. All maps were provided in hard copy and were based on Mercator projection, at a 1:1,000,000 scale. Later, three pioneer investors from France, Japan and Russian Federation submitted maps at 1:500,000 scales. *Figure 5* presents an example of maps submitted by the pioneer investors at 1:500,000 scales. *Figure 6* presents the bathymetry of the seafloor as compiled by NOAA, while *Figure 6* presents the topographic contours for the reserved areas.

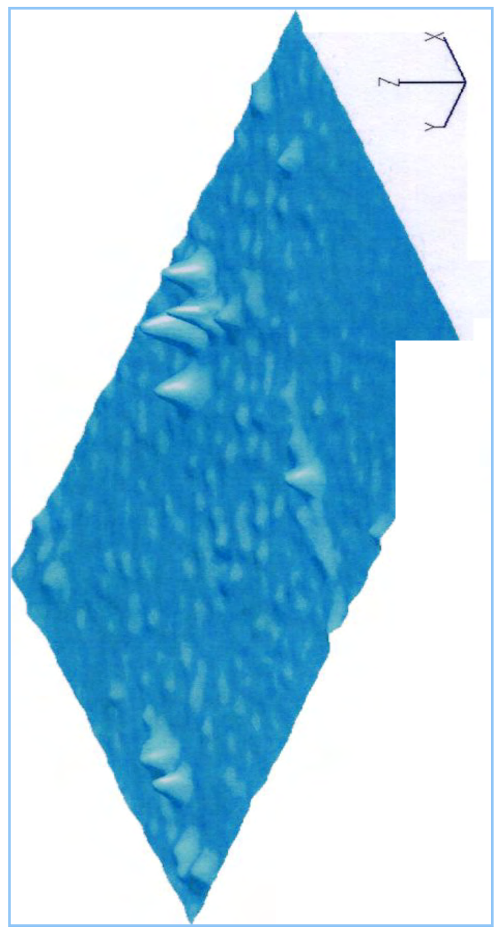


Figure 4: Bathymetry of the seafloor in Block 22 (Vertical exaggeration applied to the elevation) (NOAA)

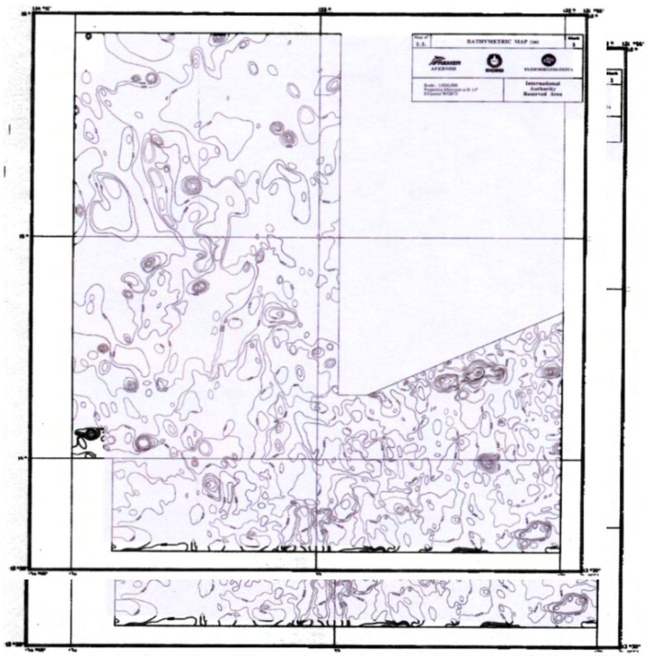


Figure 5: Bathymetric map of Blocks 14 and 15 submitted by pioneer investors

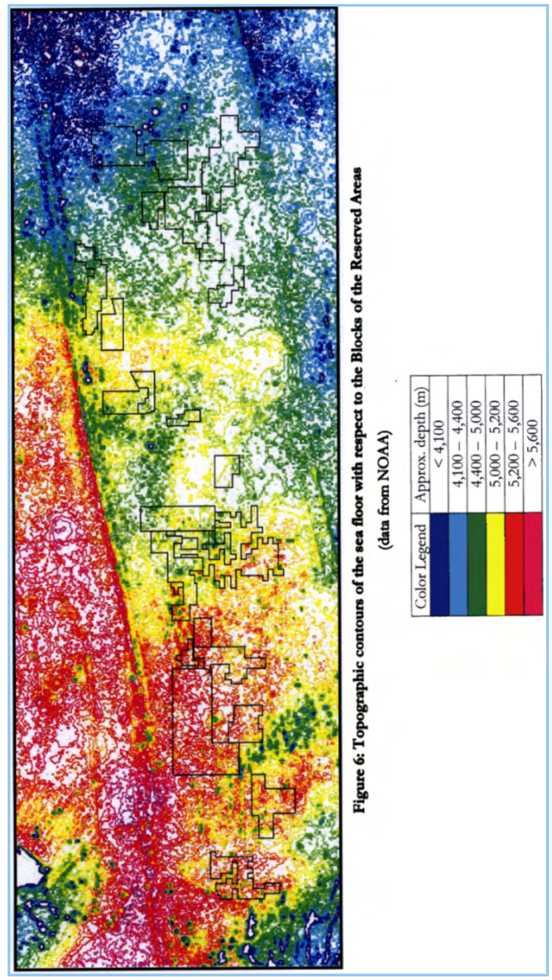


Figure 6: Topographic contours of the seafloor with respect to the Blocks of the Reserved Areas

B. Nature of the data used in building a resource model

1. Samples and stations

The stations are locations on the seafloor where one or more samples have been taken. Stations contain usually three or more samples depending on the block they are coming from. The samples were collected by each of the pioneer investors. Each pioneer investor had its own sampling protocol and procedures. The description of the procedures for each of the blocks is beyond the scope of this study. For the purpose of the resource model, the station data are considered as discrete points and are used for the interpolation of nodule grades. The original sample data are not directly used in the resource model.

Station data comprise coordinates (measured in longitude and latitude), an abundance measurement in Kg/m^2, and manganese, nickel, copper and cobalt grades in percent (%). The station data available for the resource model originates from 2,785 stations. Some blocks, such as block 8, contain very different sizes; it is appropriate to express the sampling density in stations per km^2 or in relative density.

Figure 7 illustrates sampling density by block and shows that block 15 has the highest density of stations.

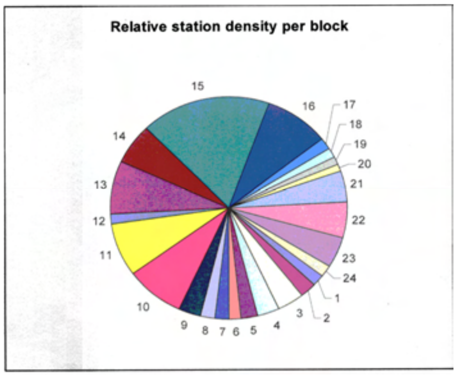


Figure 7: Graph of the relative section density per block

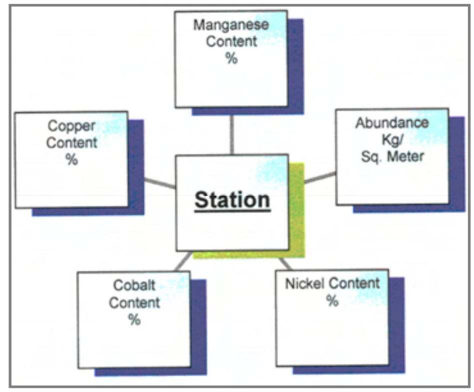


Figure 8: Schemativ view of a station's content

Figure 8 illustrates station component data. Each component expresses a characteristic of the nodule chemical content.

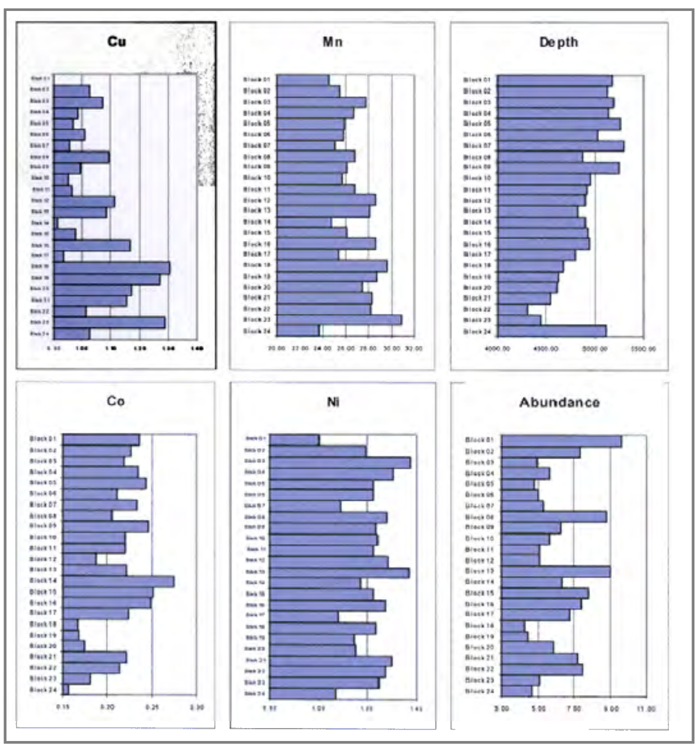


Figure 9 is a schematic representation of the variability of station data across the blocks. Note that block 24 is from the Indian Ocean.

Figure 9: Variability of station data across blocks

2. Compatibility of station datasets from the different pioneer investors

The Global data set that is currently available to the International Seabed Authority comes from a variety of sources. Indeed, the original blocks were explored and sampled by different groups or organizations representing the pioneer investors.

As can be seen in *Figure 9* above, there are differences between the average parameter values across the blocks. There have been several attempts made by the International Seabed Authority to characterize those differences and perhaps take action to identify possible sources of errors.

Errors were identified in some of the French blocks regarding measurements of nodule abundance. The French acknowledged that and made corrections to their datasets.

Other parameters show marked differences in particular blocks. For example, cobalt is particularly low in blocks 12, 18, 19 and 20. In addition, manganese in block 23 is significantly higher than in surrounding blocks.

Considering the available data sets, it is not possible to state whether the differences observed are due to errors or to natural differences related to geological or geographical characteristics of the blocks. More information is needed to fully characterize those differences. For example, suspect nodules should be reassessed by different independent laboratories under controlled conditions. Only then can one assess the presence of analytical or sampling errors. When this kind of error is excluded, one can assume that the differences are related to natural factors. If collected nodules are still available, a pilot study could be undertaken to evaluate the possibility of analytical errors in the sample datasets.

Nevertheless, the differences observed practically only affect the blocks they are coming from. There is virtually no cross-contamination of samples across block boundaries as far as resource estimation is concerned. For example, the low cobalt samples in blocks 12, 18, 19 and 20 basically only affect the resource in those blocks and do not affect the neighbouring blocks.

At this stage, we might assume that the data used are valid and can be used to derive resource estimates. Since nodule abundance is certainly the most important parameter to characterize because it varies a lot, anything that could improve the quality of the abundance measurements should be used. For example, photographs taken at the sampling sites could be studied. In addition, if detailed bathymetric data were available, one could analyse the relationship between small-scale bathymetry and nodule abundance. The concept of transparent layers described by scientists may well be related to nodule abundance and could be used to infer nodule abundance if a relationship exists between abundance and the transparent layer thickness.

A discussion of possible difference or discrepancies between station data in the different blocks is presented in a paper by Mr. Kaiser de Souza, Marine Geologist for the International Seabed Authority, entitled “Polymetallic nodules resource assessment of the reserved areas for the conduct of activities by the Authority”, (2002).

C. The Resource Model

The resource model is the component of the geological model that characterizes and qualifies the mineral content of the nodules and the abundance of nodules throughout the reserved areas. The abundance and mineral content of the nodules vary spatially. The resource model reflects that. It can be queried by zone or block or by grade range. From the model it is possible to estimate the tonnage and average grades of nodules. The model can also be used to characterize areas of best economic potential.

1. Components of the resource model

The resource model is an array of cells of size of 12.5km by 12.5km or 156.25 square kilometres. This array is superimposed on the outlines of the reserved areas. Each block is covered by a number of cells. Each cell contains estimated values of nodule abundance and metal grades. By summing the cells of a block, we derive the total tonnage of nodules and metal content for that block.

Figure 10 shows a schematic representation of a portion of the resource model.

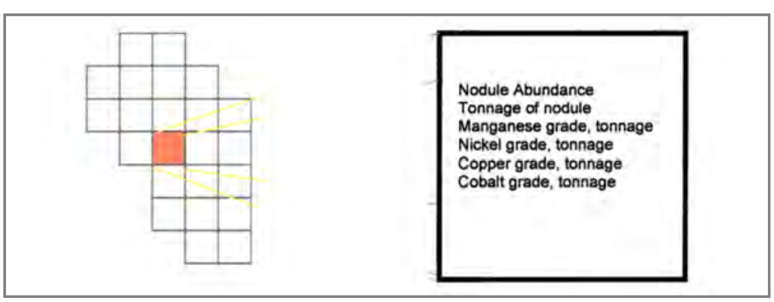


Figure 10: Schematic representation of the resource model cells

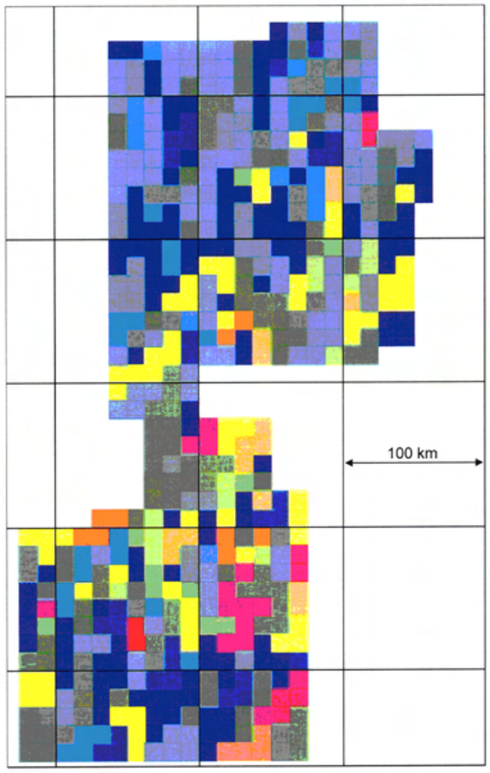


Figure 11: Block 22 resource model

Figure 11 below shows the actual resource model for block 22. The cells are colour-coded according to nodule abundance in Kg/m^2. Blue cells have lowest abundance, magenta cells have highest abundance.

2. Model construction method

The cells of the resource model obtain their values through a process called interpolation. Station data surrounding the cells are interpolated, giving the cells values representing the local average of the station data. Several interpolation techniques have been utilized. In this section, the geostatistical resource model will be described. Detailed explanations of the different interpolation methods are given in subsequent sections.

In short, geostatistics is an interpolation method, called Kriging, which takes into account the spatial continuity of the data. The spatial continuity is related to the relationship that exists between the grade of two stations and the distance that separates them. This is a statistical concept that is expressed by the so-called variogram.

Each of the five components (abundance, Mn, Ni, Cu, Co) of each cell of the resource model is interpolated independently. Prior to the actual interpolation, the variograms of the components are calculated. The variograms take the form of a mathematical equation that is used by the Kriging process.

3. Global resources

The global resources are the accumulation of cell data across all the blocks interpolated from the station data without taking the block boundaries into account. That is, each block interpolated from the surrounding stations *whether they belong to the block or not*. In fact, block boundaries are artificial attributes that have no relationship with nodule grade and abundance. However, since the blocks were sampled by different organizations, and their sampling and assaying methodologies were different, which has resulted in defects in the distribution of station grades that are not explained naturally, it is important to keep a reference to block boundaries in the model.

The current resource model suggests that the reserved areas contain the following:

5,400 million tonnes of nodules (average abundance of 5.98 kg/m^2);
1,490 million tonnes of manganese (average Mn grade of 25%);
66 million tonnes of nickel (average Ni grade of 1.23%)
54 million tonnes of copper (average Cu grade of 1.01%)
12 million tonnes of cobalt (average Co grade of 0.23%)

Of the above resources, it is unclear how much will be available as reserves. Previous studies have mentioned that an abundance of at least 6kg/m^2 would be required for a deposit to be considered as reserves. On that basis, the resources that meet this criterion are:

3,200 million tonnes of nodules (average abundance of 8.14 kg/m^2);
855 million tonnes of manganese (average Mn grade of 26.73%);
37 million tonnes of nickel (average Ni grade of 1.17%)
30 million tonnes of copper (average Cu grade of 0.95%)
7 million tonnes of cobalt (average Co grade of 0.23%)

Figures 12, 13, 14, 15, and *16* present components of the resource model.

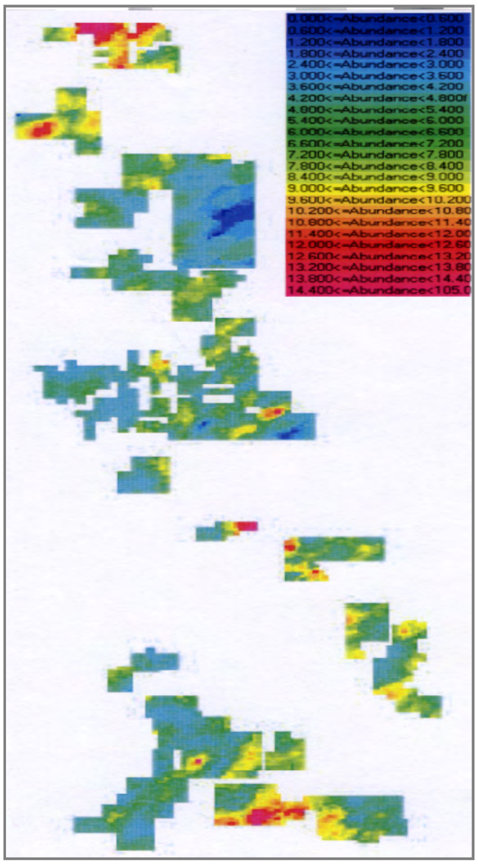


Figure 12: Global resources model showing abundance

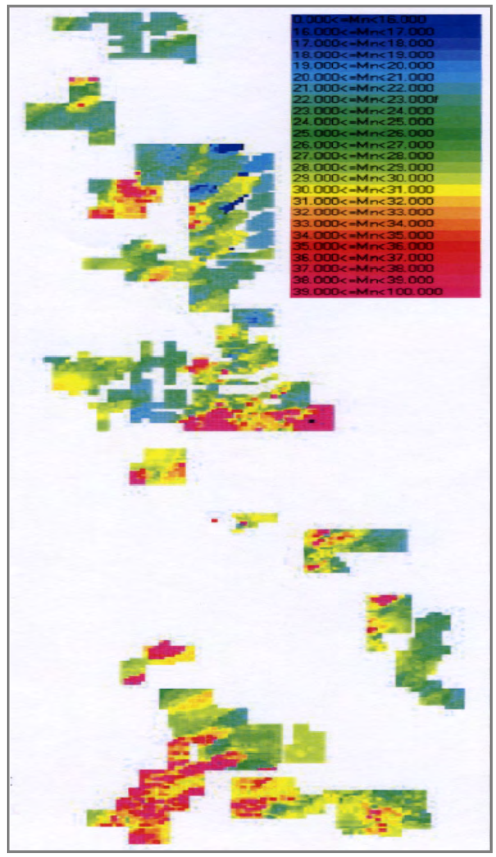


Figure 13: Global resource model showing manganese grade

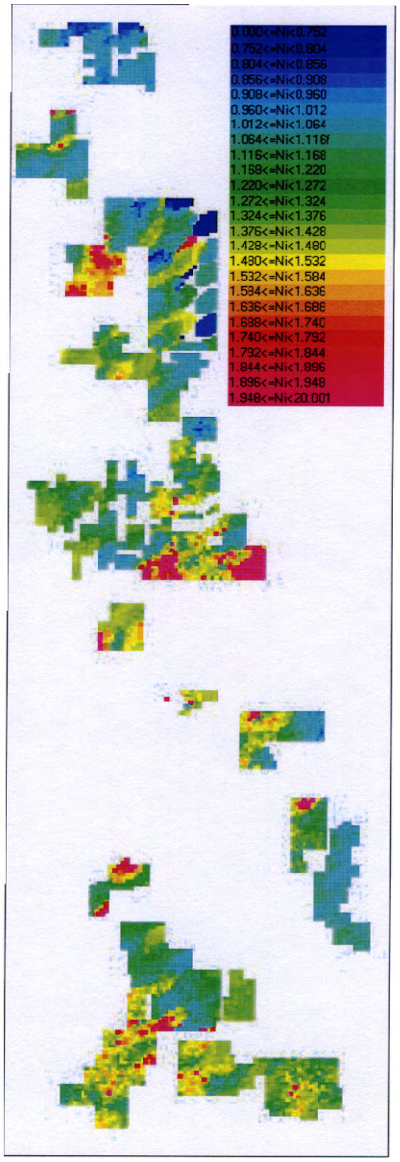


Figure 14: Global resource model showing nickel grade

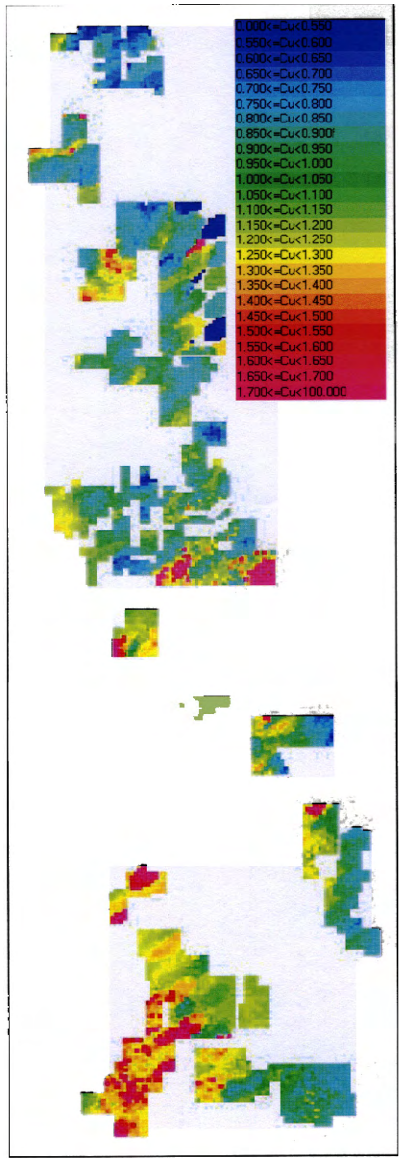


Figure 15: Global resource model showing copper grade

Figure 16: Global resource model showing cobalt grade

Table 1 presents the results of the global resource model on a block by block basis with no cut-off applied to abundance.

Table 1
Global resource model results at no cut-off

Block	Surface (km^2)	Tonnage (Mt)	AveAb (kg/m^2)	AveMn	AveNi	AveCu	AveCo
Block 01	46562.50	442.10	9.49	23.74	0.92	0.69	0.26
Block 02	42656.25	340.45	7.98	25.38	1.12	0.89	0.25
Block 03	30468.75	148.35	4.87	30.81	1.52	1.17	0.25
Block 04	39062.50	215.72	5.52	27.17	1.28	0.95	0.25
Block 05	123750.00	508.40	4.11	23.40	1.07	0.82	0.25
Block 06	95156.25	475.92	5.00	26.38	1.21	0.96	0.22
Block 07	7968.75	47.43	5.95	23.79	1.04	0.85	0.25
Block 08	2500.00	15.27	6.11	27.44	1.27	1.10	0.20
Block 09	15000.00	95.78	6.39	25.87	1.21	0.96	0.24
Block 10	44843.75	271.26	6.05	25.61	1.20	0.89	0.23
Block 11	48437.50	238.80	4.93	33.64	1.52	1.17	0.27
Block 12	21250.00	111.26	5.24	31.08	1.43	1.21	0.19
Block 13	5625.00	55.74	9.91	29.09	1.41	1.10	0.22
Block 14	23593.75	155.80	6.60	26.28	1.20	0.93	0.30
Block 15	15156.25	118.79	7.84	28.66	1.32	1.04	0.26
Block 16	24843.75	164.52	6.62	29.51	1.31	1.19	0.26
Block 17	42968.75	291.09	6.77	25.49	1.08	0.91	0.22
Block 18	18281.25	90.93	4.97	32.38	1.38	1.40	0.18
Block 19	26093.75	128.09	4.91	29.15	1.25	1.25	0.18
Block 20	55468.75	345.72	6.23	28.04	1.20	1.15	0.19
Block 21	14843.75	105.02	7.08	28.63	1.31	1.15	0.22
Block 22	90000.00	687.11	7.63	29.46	1.33	1.04	0.22
Block 23	67812.50	343.18	5.06	34.04	1.39	1.40	0.20
Total 1-23	**902343.75**	**5396.72**	**5.98**	**27.64**	**1.23**	**1.01**	**0.23**
Block 24	160000.00	803.37	5.02	22.50	0.96	0.83	0.18

4. Characteristics of the resource model

The resource model contains a total of 5,787 cells of size 12.5km by 12.5km each. The model is bi-dimensional. Its components only vary in the east-west and north-south directions. Because of the nature of the nodules, there is only one layer, so the grades do not vary in the third direction.

The metal available in each cell is determined by multiplying the cell area by the abundance and by the metal grade in %. As mentioned above, the resources above a minimum abundance of 6kg/m2 are:

3,200 million tonnes of nodules (average abundance of 8.14 kg/m^2);
855 million tonnes of manganese (average Mn grade of 26.73%);
37 million tonnes of nickel (average Ni grade of 1.17%)
30 million of tonnes of copper (average Cu grade of 0.95%)
7 million tonnes of cobalt (average Co grade of 0.23%)

According to the International Manganese Institute, land-based world resources of manganese, including low grade ore, amounts to several billion tonnes of manganese. Between 1981 and 2000, production fluctuated around a yearly average of about 7 million tonnes of manganese content. Between 1940 and 2000 approximately 400 million tonnes of manganese contained in ore were mined.

In 2002, world nickel production amounted to 1,174 million tonnes. In 1996, world copper production exceeded 10 million tonnes. The current world production of cobalt is estimated at 27,000 tonnes per year. At the scale of a mine, Mount Keith mine in Western Australia produces 47,500 tonnes of nickel per year for a total quantity of 950,000 tonnes of nickel over the entire mine life. The Escondido mine in Chile has reserves of over 23.5 million tonnes of copper.

D. Economic applications of the resource model

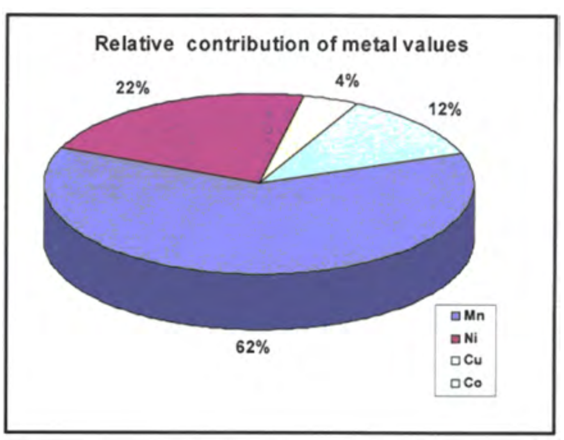
The resource model reveals huge amounts of metal in the reserved areas. Because of its size, the reserved areas cannot be considered as a single mineral deposit. They exceed by far human manageable dimensions. However, the resource model represents an inventory of seabed nodules that may become economically extractable in the future. This model can be used to delineate areas that offer greater potential. For that purpose, it is appropriate to evaluate the contribution of all the metals to the revenue stream from extraction. This contribution can be displayed in such a way that high potential areas will be identified in the global reserved areas.

1. Economic value of the resources

Polymetallic nodules contain four metals with economic potential; manganese, nickel, copper and cobalt. Hence each metal contributes to the value of the ore. The simplest way to characterize the economic value of the resources is to assign to each cell a dollar value derived from cell abundance, grades and the estimated metal prices. The absolute value of the metal prices is not really important but the relative value of each metal is. Thus, one can take the metal prices at a given time. In the end, the cells will be compared with one another and the highest cell values will highlight the areas of best potential.

The current resource model uses the following metal prices:

	Grade %	***US$/lb***
Mn	23.74	$0.35
Ni	0.92	$3.27
Cu	0.79	$0.70
Co	0.26	$6.30



Figures 17 and 18 show the relative contribution of metal values and the relative value of each block respectively.

Figure 17: Relative metal values of the nodules

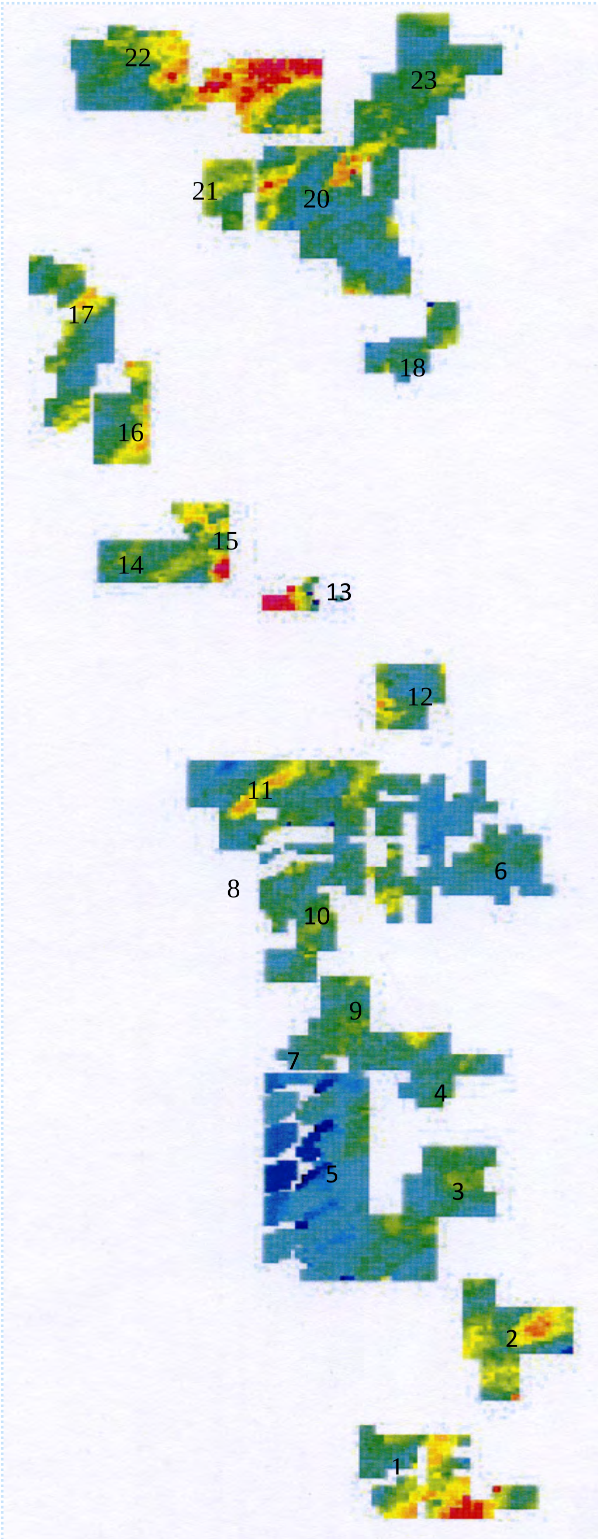


Figure 18: Resource model showing relative economic values in cells

2. Preferred areas

From *Figure 18*, it appears that the best areas are block 22, block 13 and block 1. Block 22 has one major advantage: it is the shallowest one of the three. The resource model, combined with economic parameters becomes an efficient tool for identifying potential exploration targets.

Sorting preferred areas by potential is difficult and should be only done qualitatively. Such a list derived from the resource model as shown above has many limitations and could be misleading. However, if used with caution, this list, combined with other factors, can be useful in identifying targets for further exploration and advanced work. *Figure 18* shows the resources coloured by metal value. It is natural to consider the highest value areas as most promising. However, we must also weigh this by the quality and abundance of data available in the blocks. Also, mineral extraction, at first glance, would most likely commence in the most accessible areas. At this stage, the resource model is not detailed enough to characterize the terrain at the scale of mining activity. The only relation to accessibility we can use is the actual depth of the sea floor. Hence, with great caution, we can propose a qualitative short list of blocks, sorted by their potential in terms of value, quality and accessibility. The potential illustrated below in Table 2 does not refer to entire blocks but rather to portions of them.

Table 2
Preferred areas sorted by potential

Block	*Value*	*Quality of data (sample density)*	*Accessibility (depth)*
22	**high**	**medium**	**high**
13	**high**	**high**	**medium**
15	**high**	**high**	**medium**
1	**high**	**low**	**low**
19	**medium**	**low**	**high**

Important note:

Table 2 is derived from the current resource model as estimated from the available data sets. It treats all blocks equally, regardless of differences highlighted above in specific blocks. If for any reason, cobalt was found to be higher in blocks 12, 18, 19 and 20, it could change the rankings.

3. Quality and classification of the resources

In mining terms, mineral resources are classified as Measured, Indicated or Inferred. The classification is used to give the public an appreciation of how well the resources are known. The Measured category is the highest and represents the resources that have sampling so closely spaced and the geologic character so well defined that size, shape, depth and mineral content are well established. The Indicated category is similar to the measured category but the samples are farther apart and less adequately spaced. Inferred resources are based on an assumed continuity beyond Measured and Indicated resources, for which there is geologic evidence and limited sampling.

In the case of polymetallic nodules, this classification scheme does not apply since sampling is so far apart that it is beyond reasonable mining scales. On earth, bauxite deposits that are exceptionally continuous have a sampling pattern of no more than 100 meters, and even coal deposits have a sampling pattern not exceeding 100 meters.

It is the opinion of Geostat Systems International that it is not realistic to classify the resources of the reserved areas. Rather, they constitute a mineral inventory. Only when areas of potential human-scale mining are delineated, will we be able to attempt to classify the resources.

When stating resources, it is often appropriate to evaluate how accurate those numbers are. Like polls, resources estimates are in fact estimates that are not equal to the real values. Obviously, we do not know the real values but we can assess the order of magnitude of the errors we could make. We call this precision. Such precision is always accompanied by the so-called confidence interval; most of the time expressed a percentage. For example, precision could be expressed as ±10%, 95% of the time. This means that we are 95% confident that the real value does not exceed the estimated value by more than 10%.

Due to the limited sampling, it is not possible to evaluate the precision accurately but we can derive a good approximation of the precision. However, we can only derive a precision at the block level. Hence, we can evaluate a precision for each of the 23 blocks of the reserved areas. The precision is related to two factors: 1- the variability of the data within the blocks and 2- the number of data available inside the blocks.

The use of precision is intimately related to risk management. One is interested in assessing the chance of making the wrong decision based on a resource model. In the case of polymetallic nodules, it is very unlikely that major decisions will be made on resource information at the scale of a block. Rather, when a human-scale area is delineated, precision will be useful in terms of risk management.

The precision of the tonnage estimates of nodules is equivalent to the precision on the abundance estimates in the blocks since there are no errors on the surface area of the blocks. In fact the block outlines are determined artificially and bear no uncertainties.

Table 3, below, presents the precision of nodule tonnage per block. It is expressed as a percentage of the estimated tonnage. The precision is given at a 95% confidence interval.

Table 3
Precision of block tonnage estimates

Block	Surface (km2)	Abundance (kg/m2)	Tonnage (Mt)	Precision on Tonnage (%) (95% conf. Int.)
Block 01	46562.50	9.49	442.10	8.65%
Block 02	42656.25	7.98	340.45	7.09%
Block 03	30468.75	4.87	148.35	8.91%
Block 04	39062.50	5.52	215.72	8.11%
Block 05	123750.00	4.11	508.40	6.56%
Block 06	95156.25	5.00	475.92	6.55%
Block 07	7968.75	5.95	47.43	11.76%
Block 08	2500.00	6.11	15.27	31.27%
Block 09	15000.00	6.39	95.78	9.07%
Block 10	44843.75	6.05	271.26	5.14%
Block 11	48437.50	4.93	238.80	6.73%
Block 12	21250.00	5.24	111.26	17.86%
Block 13	5625.00	9.91	55.74	13.40%
Block 14	23593.75	6.60	155.80	6.96%
Block 15	15156.25	7.84	118.79	5.45%
Block 16	24843.75	6.62	164.52	5.05%
Block 17	42968.75	6.77	291.09	8.96%
Block 18	18281.25	4.97	90.93	17.51%
Block 19	26093.75	4.91	128.09	16.80%
Block 20	55468.75	6.23	345.72	11.70%
Block 21	14843.75	7.08	105.02	8.60%
Block 22	90000.00	7.63	687.11	4.36%
Block 23	67812.50	5.06	343.18	5.72%
Total 1-23	**902343.75**	**5.98**	**5396.72**	**1.75%**

Errors are also involved in the estimation of block average grades. *Table 4* presents precision estimates of the average nodule grades per block at a 95% confidence interval.

Table 4:
Precision of average grades of nodules per block at 95% confidence interval

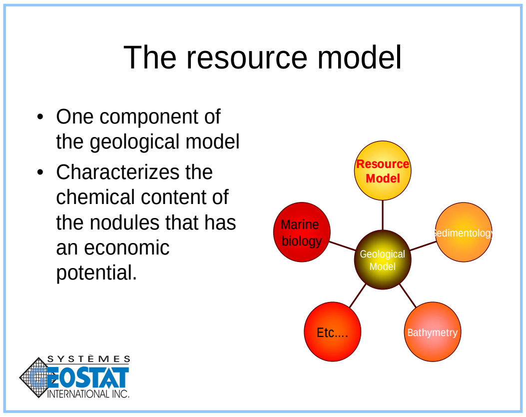
Block	Manganese		Nickel		Copper		Cobalt	
	Average (%)	Precision (%)	Average (%)	Precision (%)	Average (%)	Precision (%)	Average (%)	Precision (%)
Block 01	23.81	1.40%	0.92	3.26%	0.70	6.14%	0.25	2.80%
Block 02	24.60	1.25%	1.08	2.41 %	0.86	4.65%	0.24	2.08%
Block 03	27.37	0.93%	1.34	1.12%	1.03	1.75%	0.22	1.36%
Block 04	26.56	1.48%	1.26	1.75%	0.93	2.80%	0.24	2.08%
Block 05	24.60	0.93%	1.12	1.25%	0.85	1.88%	0.25	1.60%
Block 06	25.81	1.24%	1.19	1.09%	0.95	1.79%	0.22	1.82%
Block 07	24.03	4.22%	1.04	4.04%	0.86	5.00%	0.25	5.60%
Block 08	28.20	7.35%	1.31	6.34%	1.13	11.15%	0.21	4.29%
Block 09	26.81	2.91%	1.25	3.04%	0.99	4.14%	0.24	2.50%
Block 10	25.77	1.11%	1.22	1.23%	0.89	1.80%	0.22	1.36%
Block 11	27.20	1.02%	1.23	1.22%	0.95	1.68%	0.22	1.36%
Block 12	29.19	1.89%	1.35	2.44%	1.15	3.04%	0.19	5.79%
Block 13	28.51	1.32%	1.38	1.16%	1.07	1.68%	0.22	1.36%
Block 14	25.15	1.74%	1.15	2.00%	0.90	2.78%	0.28	1.79%
Block 15	27.04	1.04%	1.27	1.26%	1.00	1.70%	0.25	1.20%
Block 16	28.54	0.65%	1.27	0.55%	1.16	1.03%	0.25	0.80%
Block 17	25.57	1.49%	1.09	1.56%	0.92	3.15%	0.22	2.27%
Block 18	29.90	1.20%	1.23	1.14%	1.25	1.60%	0.17	2.94%
Block 19	27.95	1.09%	1.19	1.68%	1.21	1.49%	0.17	2.35%
Block 20	27.19	1.01%	1.16	1.55%	1.12	1.61%	0.18	2.78%
Block 21	28.67	0.97%	1.32	1.06%	1.15	1.39%	0.22	1.82%
Block 22	28.13	0.66%	1.27	0.63%	0.99	1.31%	0.21	0.95%
Block 23	30.64	0.56%	1.25	0.64	1.26	0.87%	0.18	1.67%
Block 1-23	**26.61**	**0.29%**	**1.18**	**0.34%**	**0.97**	**0.52%**	**0.22**	**0.45%**

SUMMARY OF THE PRESENTATION

Mr. de L'Etoile made a presentation on a resource model for polymetallic nodule deposits in reserved areas in the Pacific Ocean. He informed participants that his article dated January 2003, which had been prepared for the Meeting of Scientists in preparation for the workshop, was slightly modified to highlight the results obtained from the resource model that had been developed, rather than the method used to develop the model. He introduced himself as a land-based geological engineer and informed the workshop that Geostat Systems International Inc undertook consulting services for mining companies, such as INCO, Noranda and Falconbridge, and had spent the past 20 years creating resource models for mining companies.

Mr. de L'Etoile said that Geostat Systems had been contracted by the Authority to carry out resource estimation for the reserved areas, much in the same way that Geostat does for normal mines. Geostat had done that in 2001, and it had studied 23 blocks of seabed covering the reserved areas in the Pacific Ocean, and one block covering the reserved area in the Indian Ocean. He informed participants that his presentation would present the results of that resource model, highlighting its characteristics, and making proposals as to how information contained in the resource model could be used. He also said that the presentation reflected his view of where the resource model fit into the geological model. He illustrated what he believed the geological model *(Figure* 19) to be, and indicated that the resource model was only one component of the geological model.

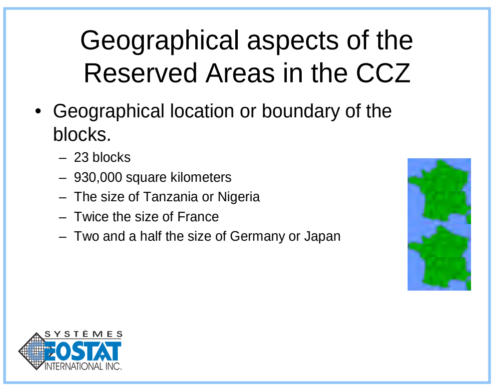
Figure 19



Mr. de L'Etoile pointed out that there would be many other aspects of, or inputs to, the geological model and that while he would concentrate on the resources, he would also point out how the other aspects could be taken into consideration to improve the quality of resource estimation during the presentation.

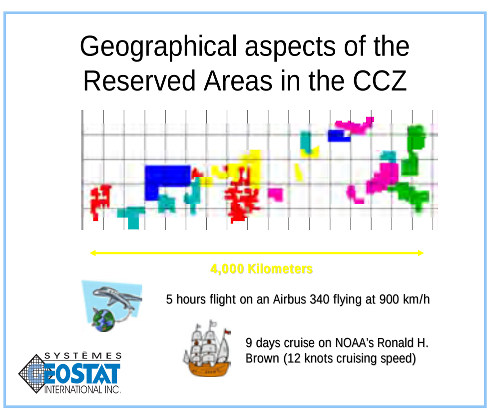
Using the figures below *(Figures 20 and 21)*, Mr. de L'Etoile showed participants the geographic area covered by the reserved areas in the Clarion-Clipperton Zone, drawing comparisons with the sizes of countries and travel times to traverse them. He said that Geostat Systems had divided the reserved areas into 23 blocks to facilitate resource assessment. With *Figures 20 and 21*, he summarized some of the geographical aspects of the reserved areas in the CCZ.

Figure 20



Mr. de L'Etoile said that the area covered by the reserved areas in the CCZ was almost a million square kms. He also said that, not having worked on a mine that size, he found the area to be very large. He noted that the area under discussion was the size of the United Republic of Tanzania, or twice the size of France, and he likened the work that was being undertaken to mining either of these two countries as a single deposit.

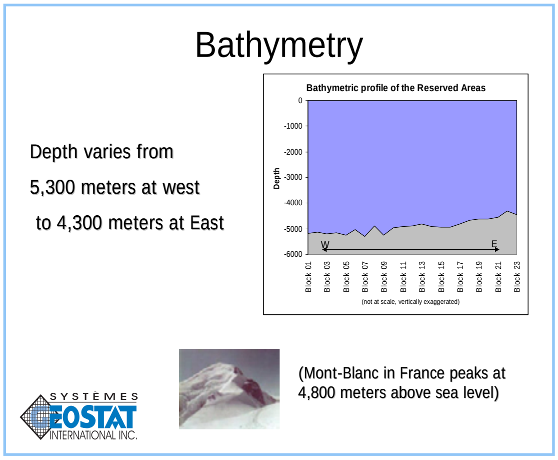
Figure 21



He further pointed out that the area in question stretched over 4,000 km, and said that it would take five hours to fly over it going from one end to the other, and nine days by ship just to traverse it without doing anything else. He concluded that the CCZ was a huge area that was beyond any land-based configurations.

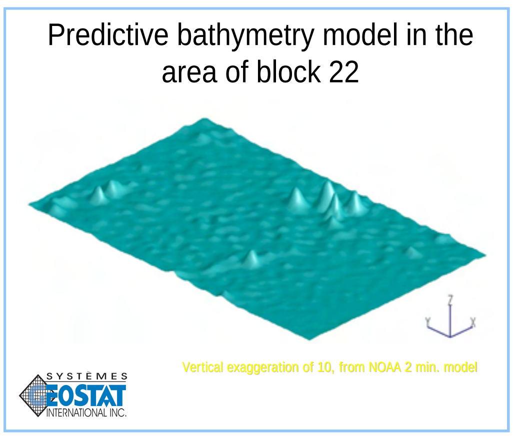
Using *Figure 21 above*, Mr. de L'Etoile showed participants the location of the reserved areas in the CCZ. He pointed out that the data from the pioneer investors' allocated areas were not used in the resource assessment and that the only data provided to Geostat Systems by the Secretariat were for the reserved areas. In relation to the work that had been carried out, Mr. de L'Etoile said that an important aspect was the bathymetry of the area. He provided participants with a figure containing the general bathymetry of the area *(Figure 22).*

Figure 22



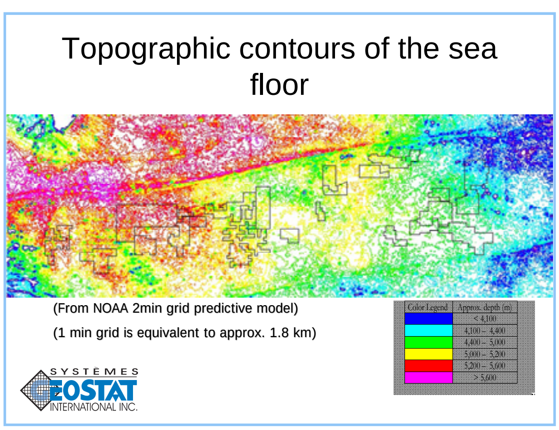
Mr. de L'Etoile said that the depth of the reserved areas in the CCZ varied from 4,300 metres in the east, to 5,300 metres in the west. He said that this could be placed in perspective by recalling that Mont Blanc in France peaked at 4,600 metres. The analogy he drew was that, from the surface of the ocean, looking down at nodules in the CCZ was perhaps like assessing the quality of the ice cap on top of Mont Blanc, from sea level. Physically, he said, one had to look down a great distance to the seafloor where it was very dark, and rather difficult to assess resources with a high level of confidence. However, he said, the Authority had some data on the bathymetry. It had depth data at station locations in its POLYDAT database that could be used to estimate the bathymetry. He noted that the Authority had been provided large-scale maps, at 1,500,000 or 500,000, depending on the blocks. He added that bathymetric information was also available from other sources, including the NOAA predictive bathymetry that was on a regular two-minute grid and that covered the entire globe or planet. With *Figure 23*, he provided an illustration of the predicted bathymetry for block 22 of the reserved areas.

Figure 23



With regard to *Figure 23*, Mr. de L'Etoile said that the predicted two-minute grid model of NOAA had been exaggerated by a factor of ten to enable participants to see bumps and valleys; otherwise, what would be seen would be just a square, with a very flat type of topography. With another diagram, *Figure 24*, he showed participants the topographic contours of the seafloor over the entire reserved area, where the areas in blue were the shallowest and those in magenta the deepest.

Figure 24



Mr. de L'Etoile pointed out that a two-minute grid represented 3.6 km on land. In that regard, he pointed out that with a two-minute grid, knowledge or information of the topography was only available every 3.6 km. Based on that model, knowledge of what was happening in between any two stations as far as the bathymetry was concerned had to be assumed. He further pointed out that, in land-based exploration and mining, 3.6 km was more than the size of a normal mine, so obviously, even though the Authority had a decent bathymetric coverage of the reserved areas, looking at *Figure 24*, the data was insufficient for a basic resource assessment.

Recalling Mr. de Souza’s presentation, Mr. de L’Etoile said that station data had been used for the resource model. He emphasized that the original samples had not been used. He said that stations were made up from the data for three or more samples, depending on the block in which they were found and that samples were collected by each pioneer investor, using their own sampling and grouping protocols. All in all, he concluded, that the data comprising 2,785 stations, with coordinates, abundance and metal grades comprised a fair amount of information. He noted that, while he would be very happy to assess a mine or an exploration project on land with 2,000 data samples, in this case, the data was spread over 4,000,000 sq. km.

Station density

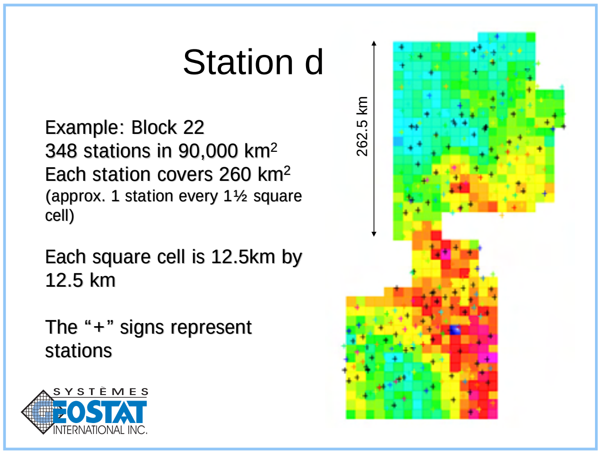


Figure 25

With regard to the sampling grids used by the different pioneer investors, Mr. de L’Etoile recalled that Mr. de Souza had said that the blocks contained different sampling grids. Using *Figure 25*, Mr. de L’Etoile provided an illustration of the relative density of samples in each block. He observed that, as was readily seen, the number of samples in each block showed considerable variation. For example, he noted that block 8 contained 4 stations and that block 22 contained 348 stations.

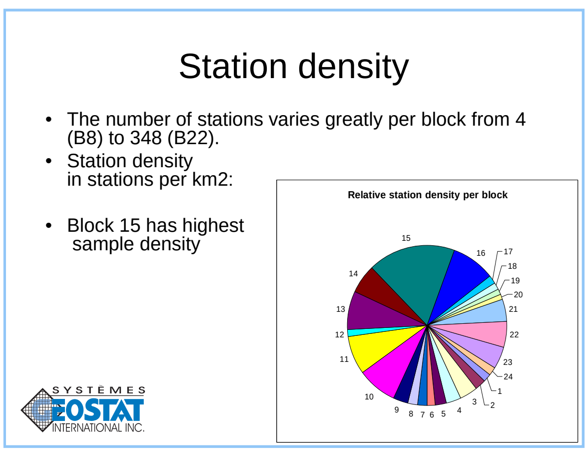


Figure 26

In addition, Mr. de L’Etoile pointed out that block 22, with a total of 348 stations covered a 19,000 sq km. area. He said that each station therefore represented an area of 216 sq. km. Using *Figure 26*, he illustrated the situation with respect to block 22.

With regard to *Figure 26*, Mr. de L’Etoile pointed out that the grid size was 12.5 x 12.5 km (a cell), the plus signs in the diagram are where the actual stations are to be found, and that on average the data comprise one station per one-and-a-half square cells. He further pointed out that the situation was equivalent to having only one sample per mine on land to work with.

Through *Figure 27*, he described station statistics. He said that these were the average depth, the content of manganese and abundance values for each block and that the statistics revealed the presence of outliner blocks, such as block 23, which had a higher average.

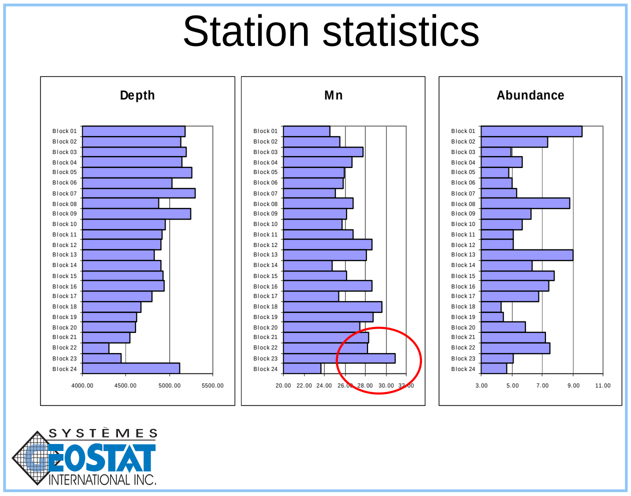


Figure 27

As an example of a means to improve resource assessment, Mr. de L'Etoile said that in the analysis of land-based prospects, samples were analysed in different laboratories. He said that the usual practice was that one in every 20 samples from a given laboratory was sent to another laboratory, to check and double check the accuracy of results. He said that this process could help to explain or attempt to explain the differences that were observed in cobalt grades. Through this process, he said, the Authority would be able to exclude lab errors as a source of the differences and concentrate on finding geological reasons for those differences.

Compatibility of data between blocks

Mr. de L'Etoile said that Mr. de Souza had mentioned that the 24 blocks of the reserved areas were different. While agreeing that there were important discrepancies, such as measurement errors (for example the abundance values associated with France's application that was later corrected), Mr. de L'Etoile said that others were due to factors such as cobalt. At this stage, however, he said that he could not state the source of those differences. Equally important, he noted, was the fact that station data in a block had no impact on neighbouring blocks; there was no significant cross-contamination across block boundaries. He said that when the resource estimate of block 22 had been undertaken, only block 22 samples had been utilized.

Mr. de L'Etoile said that what was required to sort out the issue of compatibility was the establishment of a quality control and quality assurance programme to explain and minimize potential sampling errors that he had already discussed. In that regard, he said that abundance was the principal factor contributing to the variability of the resource estimation. To address that issue, the Authority would need photos and other material relating to the geological model. These, he said, included the transparent layer that may or may not be related to abundance. If it was found to be related, it should be used to cross-check and augment the quality of the abundance data.

Model resources

In relation to the resource model, Mr. de L'Etoile showed participants its elements through *Figure 28*. He said that the cells inside each block were 12.5 x 12.5 km (156.5 km²) and that this array of cells formed the resource base. The cells contained information on abundance, tonnage of nodules, and the grade and tonnage of manganese, nickel, copper and cobalt. Cell values were estimated from surrounding station data using a technique known as geostatistics.

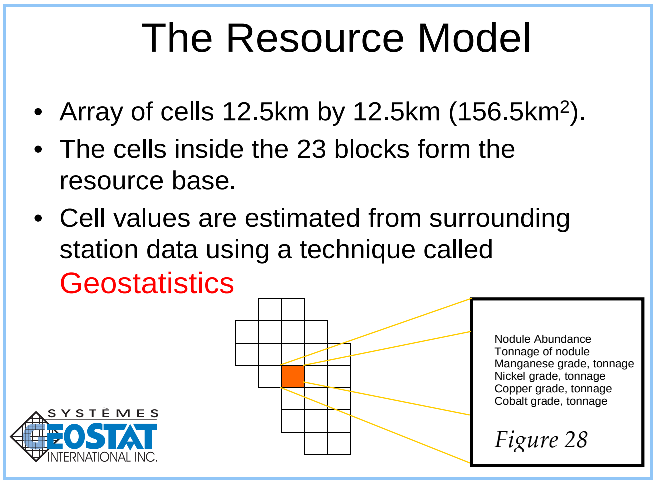


Figure 28

Mr. de L'Etoile said that the estimated resources in the reserved areas amounted to 5,400 million tonnes of nodules, with an average abundance of six kilograms per square metre based on the information available to Geostat Systems. On the basis of the metal grades that were provided, those nodules contained 1,500 million tonnes of manganese; 66 million tonnes of nickel; 54 million tons of copper; and 12 million tons of cobalt.

Mr. de L'Etoile observed that not all of the deposits that contained those resources had economic extraction potential because they had to be mined at a profit. He further observed that, at the present time, it was not known what was going to be considered economic. As an example, he said that if a minimum of six kilograms per square metre was required to be considered economic, then the resources became 3,200 million tonnes of nodules.

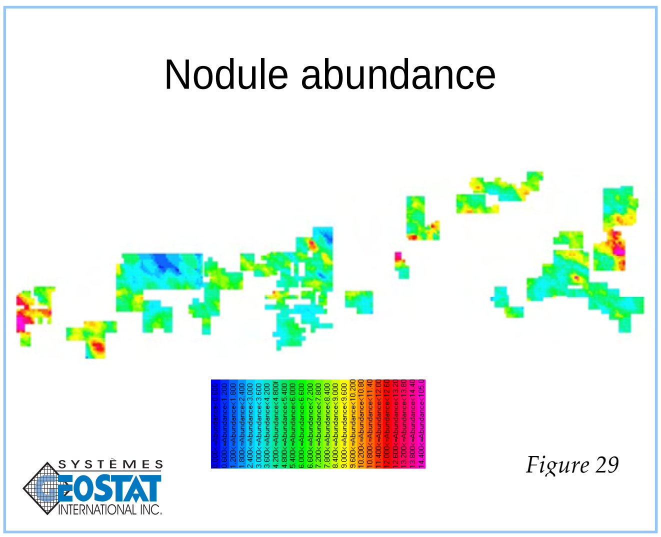
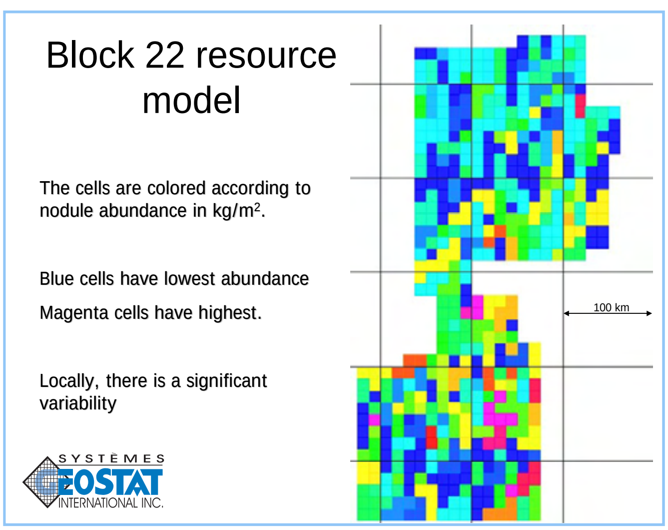


Figure 29

Nodule abundance

In relation to abundance, through *Figure 29*, Mr. de L'Etoile summarized nodule abundance data for the reserved areas in the CCZ. He said that the magenta cells in the figure had the highest abundance values, and the blue cells had the lowest abundance values.



Through *Figure 30*, he summarized the abundance values that had been determined for block 22. Noting that this block appeared good in terms of abundance, he made the observation that not all blocks were equally interesting in terms of nodule abundance. He emphasized that that was one of the main benefits of having a resource model that could serve as a guide for areas that were better than others.

Manganese grade

Through *Figure 30*, Mr. de L'Etoile summarized the data on manganese grades in the reserved areas in the CCZ. He said that the highest grades of manganese were shown in magenta, and the lowest grades were shown in blue. He noted once more that the results for block 22 were very good. He also said that the results suggested that, with regard to manganese, the blocks in the central region were better than in the other two regions (*Figure 31*).

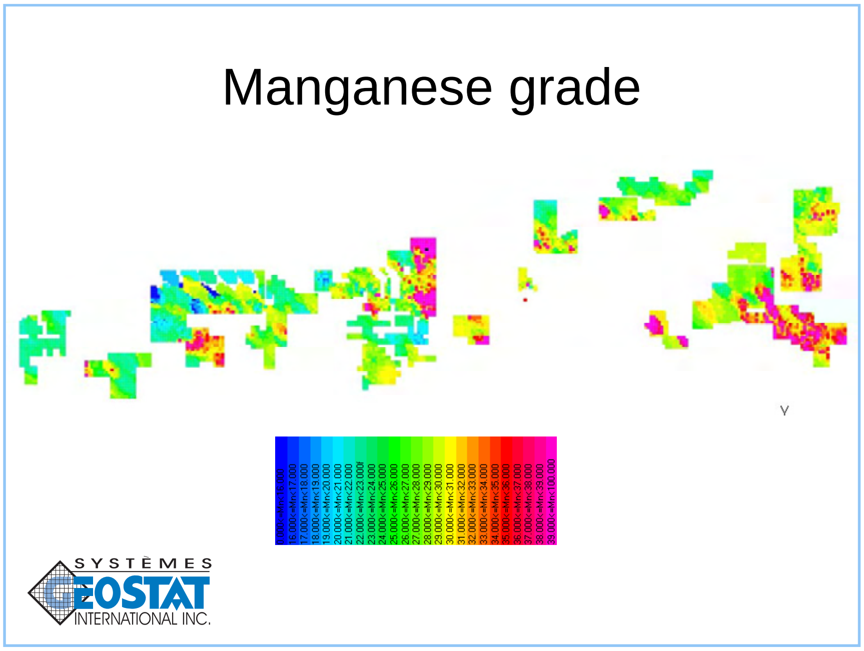


Figure 31

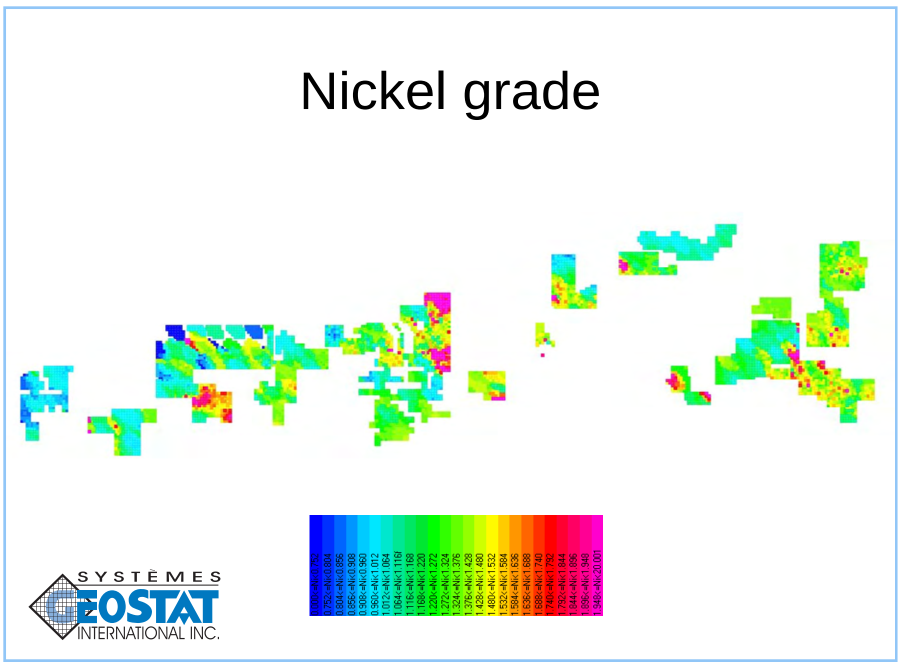


Figure 32

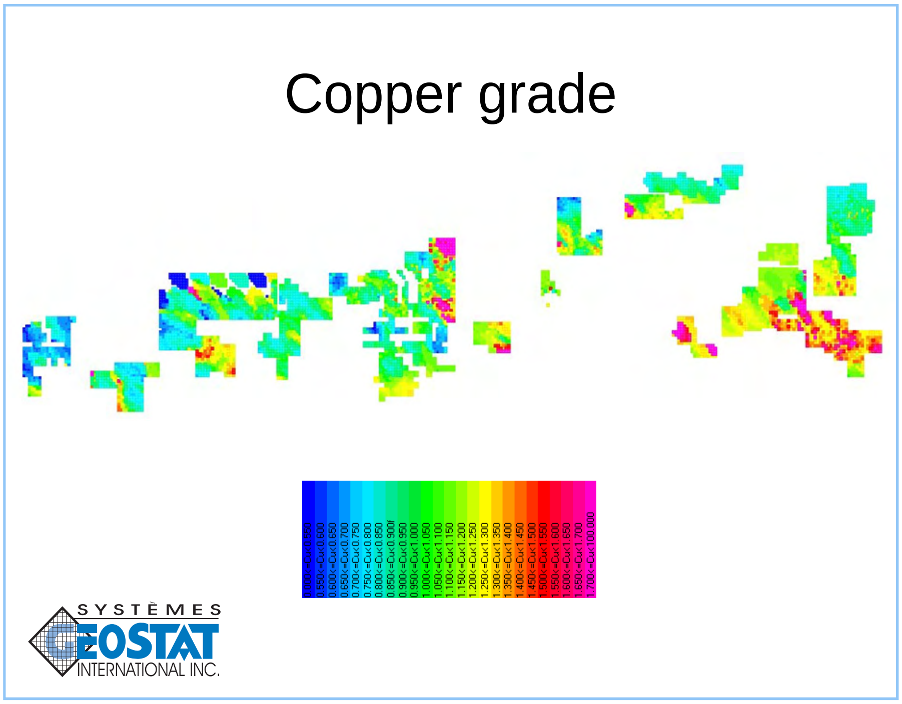


Figure 33

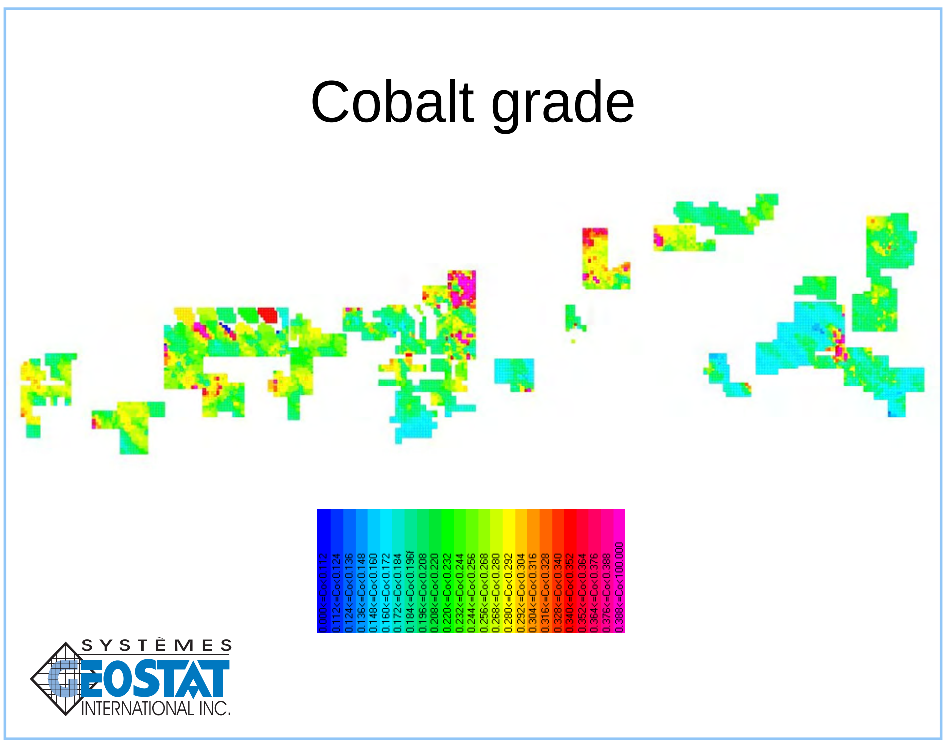


Figure 34

Through *Figures 32, 33* and *34*, Mr. de l'Etoile summarized the data with regard to the grades of nickel, copper and cobalt respectively. In general, he said that the central region appeared to be very good with respect to those three metals

In presenting a summary of this part of his presentation, Mr. de L'Etoile said that another way of looking at the situation was that each block had its specialty. He suggested that, while not very practical, one could mine block 22 for manganese and mine another block for cobalt and so on and so forth. He said that in land-base mining, these graphs were used a lot, and were called grade tonnage curve. Through *Figure 35*, he presented participants with a version of this curve for the reserved areas in the CCZ.

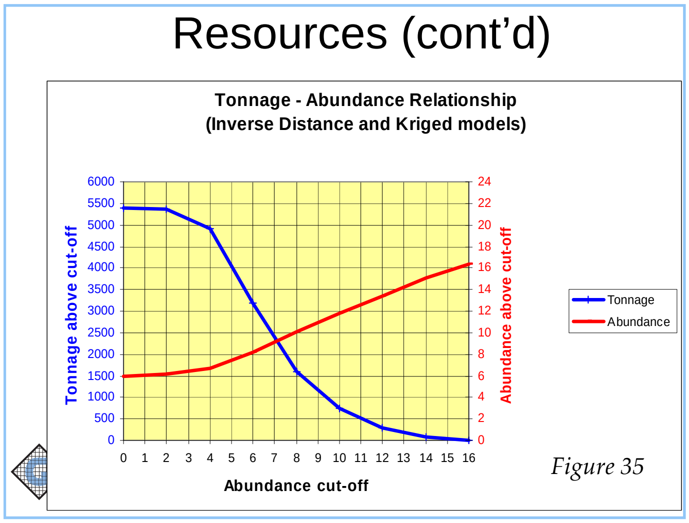


Figure 35

Explaining the contents of the figure, he said that, along the x-axis was a plot of the abundance cut-off. He said that the red line showed the abundance value above the cut-off, with the tonnage of nodules shown in blue. He observed how fast the resource decreased with the cut-off as applied to abundance and pointed out that this was a very short graph, describing the behaviour of the resource in economic terms, based on the abundance cut-off.

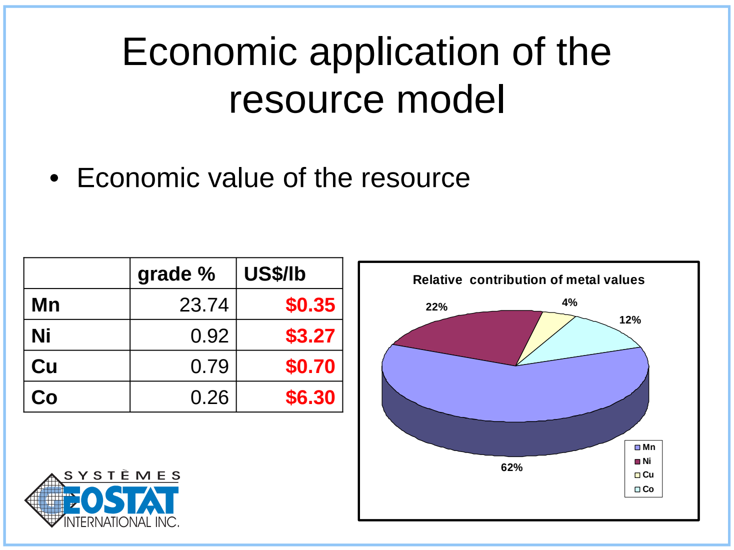
Mr. de L'Etoile said that he had done some research on the Internet on manganese, visiting the International Manganese Institute's website. He said that he had discovered that, since 1940, 400 million tonnes of manganese had been extracted from land. He said that, in the case of manganese in the reserved areas, if a cut-off of above 6 kilograms per square metre were applied, there would be 885 million tonnes of manganese. In the case of nickel, Mr. de L'Etoile said that terrestrial nickel production in 2002 had amounted to 1.2 million tonnes. At an abundance cut-off of 6 kilograms per square metre, he noted that that there would be 37 million tonnes of nickel available in the reserved areas. Turning to copper, he noted that world production of copper in 1996 exceeded 10 million tonnes. He said that the resource assessment of the reserved areas in the CCZ indicated 30 million tonnes of *in situ* copper. Similarly he noted that cobalt production in 2003 had been estimated at 27,000 tonnes; the resource assessment of the reserved areas indicated that polymetallic nodules contained 7 million tonnes of in situ cobalt.

Regarding the scale of a polymetallic nodule mining operation, Mr. de L'Etoile stated that, when one compared this with the biggest land-based nickel open-pit mining operation at Mount Keith in Western Australia, further perspectives were provided. He said that Mount Keith produced 47,000 tonnes of nickel per year, and that over its life, it was expected to produce a little less than a million tonnes. This, he said, was to be compared with 37 million tonnes of nickel in the reserved areas of the CCZ.

He further stated that the Escondida mine in Chile was one of the largest open-pit copper mines in the world, with reserves of over 23 million tonnes of copper. Based on the resource assessment, Mr. de L'Etoile said that it was fair to say that the international community had another Escondida mine in the reserved areas of the CCZ. Turning to resource classifications, Mr. de L'Etoile said that land-based miners recognize three categories: inferred resources, indicated, and measured resources. Under this scheme, polymetallic nodules of the reserved areas would fall into the inferred category. He explained his reluctance to use the term *inferred,* for the resources contained in polymetallic nodules in reserved areas, stating that he would prefer to call them a resource or mineral inventory. He was of the opinion that the traditional resource classification applied to human scale operations or exploration projects. If, for example, block 22 became an exploration project of the scale that was manageable by humans, maybe a tenth of block 22 would be eligible for classification. For that reason, he did not place much effort on trying to classify the resources contained in the reserved areas. In his opinion he concluded, it would be better to concentrate on a promising area, and to evaluate the quality of the resources in a much smaller area.

He further said that, in land-based mining, this classification was used for a very important aspect - mine financing. He said that people would invest money if the resources were measured. He informed participants that much less money would be invested if the resource were determined to be in the inferred category. With measured resources, he pointed out, the money invested would be used to start off the operation. Mr. de L'Etoile stated that the resource classification was related to the amount of data that was needed to take a mining decision. He said that with the inferred category, it was understood that a lot more data were required to bring the resource to the indicated level. He noted that even the indicated level was still not enough to make the decision to start mining. It was only when the resource was in the category of measured that a feasibility study would be undertaken, to convert the measured resources into reserves. He said that it was only after a bankable feasibility study that yielded positive results had been undertaken that resources became reserves. Before that, they remained at the resource level.

Through *Figure 36*, Mr. de L'Etoile described the economic application of the resource model. Mr. de L'Etoile said that, in the economic application, the grades of metals in percentages were converted into dollar values as the common denominator. Each pound of manganese, nickel, copper and cobalt contributed so many dollars of revenue. After making that conversion, he pointed out that the results as shown in figure 35 were that 62% of the revenue of the block came from its manganese grade; 20% from its nickel grade; 4% from its copper grade and 12% from its cobalt grade. *Figure 37* was the result of applying this to the 23 blocks.



	grade %	US$/lb
Mn	23.74	$0.35
Ni	0.92	$3.27
Cu	0.79	$0.70
Co	0.26	$6.30

Figure 36

He pointed out that, in *Figure 37*, the magenta cells reflected the highest economic values and the blue cells the lowest values in dollar terms.

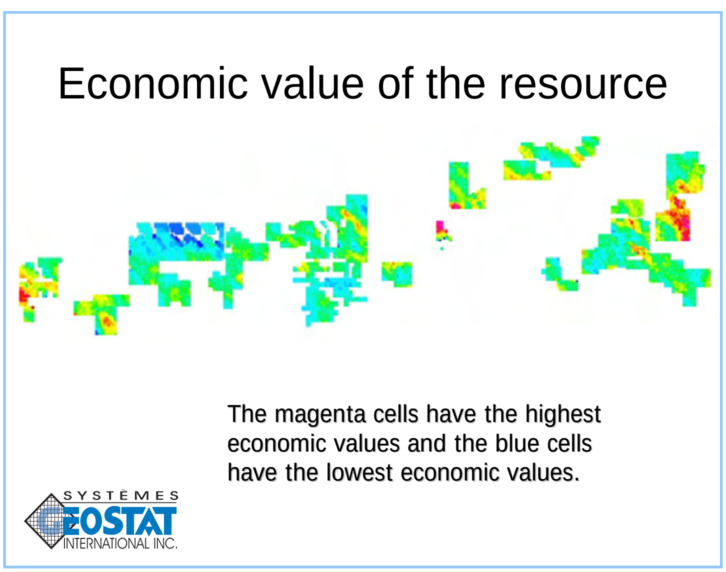


Figure 37

Mr. de L'Etoile's classification of the various blocks was presented in *Figure 38*.

Preferred Areas or blocks

Block	Value	Quality of data (sample density)	Accessibility (depth)
22	high	medium	high
13	high	high	medium
15	high	high	medium
1	high	low	low
19	medium	low	high

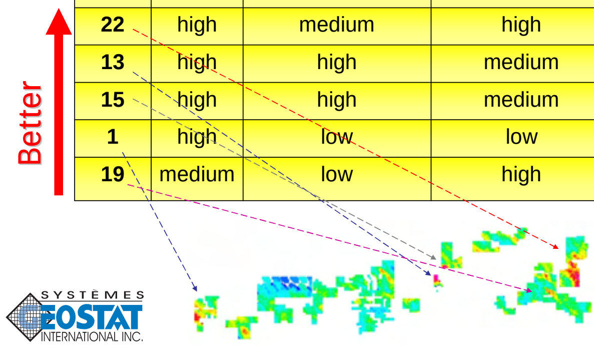


Figure 38

He explained that he had taken the liberty of classifying the blocks using three criteria. The first criterion was the value of the block, the second, the quality of data, which he had translated into the sample density, and the third criterion was accessibility to the deposits in terms of the depth. Noting that block 22 was the shallowest, and that block 1 was the deepest block, Mr. de L'Etoile said that, under his criteria, the good areas of block 22 would be the most preferred area. He said that, while block 13 had high values and high sample density, its accessibility was medium because it was deeper than block 22. Similarly, he described block 1 as containing high values, low density and quality of data, and low accessibility; and block 19 as containing medium values, low density of sampling, but high accessibility.

On the question of precision of resources, Mr. de L'Etoile said that Geostat Systems was always asked how good the results it had obtained were. The traditional way this question was posed was the range within which its results fell, that is, plus or minus how much? He used *Figures 39 and 40* to provide estimates of the precision of the resource values for each block.

Precision of the resources

block	Surface (km2)	Abundance (kg/m2)	Tonnage (Mt)	Precision on tonnage (%) (95% conf. Int.)
Block 01	46562.50	9.49	442.10	8.62%
Block 02	42656.25	7.98	340.45	7.09%
Block 03	30468.75	4.87	148.35	8.91%
Block 04	39062.50	5.52	215.72	8.11%
Block 05	123750.00	4.11	508.40	6.56%
Block 06	95156.25	5.00	475.92	6.55%
Block 07	7968.75	5.95	47.43	11.76%
Block 08	2500.00	6.11	15.27	31.27%
Block 09	15000.00	6.39	95.78	9.07%
Block 10	44843.75	6.05	271.26	5.14%
Block 11	48437.50	4.93	238.80	6.73%
Block 12	21250.00	5.24	111.26	17.86%
Block 13	5625.00	9.91	55.74	13.40%
Block 14	23593.75	6.60	155.80	6.96%
Block 15	15156.25	7.84	118.79	5.45%

SYSTÈMES GEOSTAT INTERNATIONAL INC.

Figure 39

Mr. de L'Etoile informed participants that the precision of the tonnage estimate was basically equivalent to the precision of the abundance values, since the size of the blocks were fixed and determined by property boundaries. He said that the precision of tonnage values ranged from plus or minus 5% to plus or minus 30%. That meant, for block 8, the average abundance was estimated at six (6) kilograms per square metre, plus or minus 30%. So this pre cision was fairly low, and it was directly related to the sampling density of block 8, which was one of the lowest, with only four (4) or five (5) stations.

Precision of the resources

block	Surface (km2)	Abundance (kg/m2)	Tonnage (Mt)	Precision on tonnage (%) (95% conf. Int.)
Block 16	24843.75	6.62	164.52	5.05%
Block 17	42968.75	6.77	291.09	8.96%
Block 18	18281.25	4.97	90.93	17.51%
Block 19	26093.75	4.91	128.09	16.80%
Block 20	55468.75	6.23	345.72	11.70%
Block 21	14843.75	7.08	105.02	8.60%
Block 22	90000.00	7.63	687.11	4.36%
Block 23	67812.50	5.06	343.18	5.72%
Total 1-23	**902343.75**	**5.98**	**5396.72**	**1.75%**

SYSTÈMES GEOSTAT INTERNATIONAL INC.

Figure 40

All in all, he observed, the precision of the estimates of resource values did not look too bad. For most of the blocks, it was below 10%, and if one looked at the last row in figure 40, the precision of the entire reserved area was an average of 5.98 kilograms per square metre, plus or minus 1.75%. Mr. de L'Etoile found this to be very encouraging, noting that one could say that there were enough data, because the precision was fairly good. He cautioned participants about this conclusion, pointing out that this only related to 905,400 million tonnes of material.

He further noted that if this amount of material could be mined all at once, it could be said that the tonnage was known to a level of 1.75%. Since this was not the case, and only a very small portion of it would be mined, the precision of the estimate would be significantly less than 1.75%. Again, he noted that these precision estimates were similar to the resource classification that he spoke about earlier, being somewhat irrelevant as long as the scale of the project was beyond human scale.

Finally, through *Table 4*, Mr. de L'Etoile provided the workshop with estimates of the precision of metal grades in the CCZ. At the scale of the blocks, he said that the precision of metal grades was very good. Once again however, he pointed out that they were more or less irrelevant at this stage.

Table 4
Precision of average grades of nodules per block at 95% confidence interval

Block	Manganese		Nickel		Copper		Cobalt	
	Average (%)	Precision (%)	Average (%)	Precision (%)	Average (%)	Precision (%)	Average (%)	Precision (%)
Block 01	23.81	1.40%	0.92	3.26%	0.70	6.14%	0.25	2.80%
Block 02	24.60	1.25%	1.08	2.41%	0.86	4.65%	0.24	2.08%
Block 03	27.37	0.93%	1.34	1.12%	1.03	1.75%	0.22	1.36%
Block 04	26.56	1.48%	1.26	1.75%	0.93	2.80%	0.24	2.08%
Block 05	24.60	0.93%	1.12	1.25%	0.85	1.88%	0.25	1.60%
Block 06	25.81	1.24%	1.19	1.09%	0.95	1.79%	0.22	1.82%
Block 07	24.03	4.22%	1.04	4.04%	0.86	5.00%	0.25	5.60%
Block 08	28.20	7.35%	1.31	6.34%	1.13	11.15%	0.21	4.29%
Block 09	26.81	2.91%	1.25	3.04%	0.99	4.14%	0.24	2.50%
Block 10	25.77	1.11%	1.22	1.23%	0.89	1.80%	0.22	1.36%
Block 11	27.20	1.02%	1.23	1.22%	0.95	1.68%	0.22	1.36%
Block 12	29.19	1.89%	1.35	2.44%	1.15	3.04%	0.19	5.79%
Block 13	28.51	1.32%	1.38	1.16%	1.07	1.68%	0.22	1.36%
Block 14	25.15	1.74%	1.15	2.00%	0.90	2.78%	0.28	1.79%
Block 15	27.04	1.04%	1.27	1.26%	1.00	1.70%	0.25	1.20%
Block 16	28.54	0.65%	1.27	0.55%	1.16	1.03%	0.25	0.80%
Block 17	25.57	1.49%	1.09	1.56%	0.92	3.15%	0.22	2.27%
Block 18	29.90	1.20%	1.23	1.14%	1.25	1.60%	0.17	2.94%
Block 19	27.95	1.09%	1.19	1.68%	1.21	1.49%	0.17	2.35%
Block 20	27.19	1.01%	1.16	1.55%	1.12	1.61%	0.18	2.78%
Block 21	28.67	0.97%	1.32	1.06%	1.15	1.39%	0.22	1.82%
Block 22	28.13	0.66%	1.27	0.63%	0.99	1.31%	0.21	0.95%
Block 23	30.64	0.56%	1.25	0.64	1.26	0.87%	0.18	1.67%
Block 1-23	**26.61**	**0.29%**	**1.18**	**0.34%**	**0.97**	**0.52%**	**0.22**	**0.45%**

SUMMARY OF THE DISCUSSIONS

The discussions that followed Mr. de L'Etoile's presentation focused on the "identified discrepancies" contained in the datasets, the role of bathymetry in resource assessment, and the comparability of the areas reserved for the Authority with those that were allocated as contractor areas.

In relation to whether or not differences in metal content between blocks were due to analytical errors or due to real geological differences between the blocks, a participant pointed out that it was important to take into account, not only the elements in which differences appear, but also other elements that suggested some irregularity. That participant further pointed out that in the three blocks where cobalt was assumed to be unjustifiably low, copper was enriched. Stating that it was well known that there was a negative relationship between copper and cobalt grades in manganese nodules, the participant suggested that if it had been decided that low cobalt values were as a result of analytical errors, then the associated high copper values should also be taken as analytical errors. He further stated that the fact that both metal values were anomalous, would suggest that perhaps it was really a geological difference between the blocks and had not been caused by analytical errors. The participant concluded his statement by pointing out that, in assessing the quality or the reliability of the data, one ought to consider not only the element that one might think could be in error, but also other elements geologically associated with it

While generally agreeing with the statement, Mr. de L'Etoile pointed out that reassessing nodules was about the easiest way to clear up the matter. He said that reassessing a subset of the nodules at different laboratories would quickly show whether the cobalt grade obtained was due to an error from the originating laboratory. He said that the laboratory test was very, very easy, and probably the least expensive method to eliminate this problem.

Another participant wanted to know the role of bathymetry in the determination of average nodule grade and tonnage in the CCZ. Mr. de L'Etoile responded that, in terms of resource assessment, the bathymetric values did not come into play in calculating tonnes and average grades. He said that bathymetry would be used to assess the mineability of the resource, but that it did not affect the in situ tonnage and average grade. He said that the data on bathymetry available in POLYDAT were sufficient to qualify the depth and general accessibility of deposits, but were not adequate for any mining engineering studies.

Finally, in response to a question on how the resource assessment of the reserved areas compared with resource assessments of the areas allocated to contractors, based on the data available to Geostat Systems International, Mr. De L'Etoile said that the only data that were made available to him were data for the reserved areas. Geostat Systems International was therefore not in a position to make the comparison.

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CHAPTER 4 REQUIREMENTS FOR DATA SUBMISSION TO THE AUTHORITY

Baïdy Diène, Special Advisor to the Minister, Ministry of Mining and Energy, Dakar, Senegal

The International Seabed Authority (ISA) is organizing a workshop to elaborate a geological model which will facilitate resource assessments of deep seabed polymetallic nodules in the Clarion-Clipperton Zone. To do so, it is essential to have a good set of data.

* The Area and its resources are the Common Heritage of all mankind. All the resources referred to in Article 136 should benefit all mankind (Article 140).

*The Convention needs to be read with "The Agreement relating to the Implementation of Part IX of the United Nations Convention on the Law of the Sea of 10 December1982. This Agreement entered into force on 28 July 1996.

For the implementation of Part XI and the Convention this Agreement shall be interpreted and applied as a single instrument.

Background

1. United Nations Convention on the Law of the Sea

All this needs to be looked at on the basis of The United Nations Convention on the Law of the Sea.

This Convention:

- Establishes different spaces on the Ocean (territorial sea, continental Shelf), exclusive economic zone … with the appropriate jurisdiction (national – non-national) in relation to the management of resources (living- non living)in these areas, the conduct of marine scientific research, and the protection and preservation of the maritime environment.
- Defines "The Seabed and Ocean Floor and the subsoil beyond the Limits of National Jurisdiction (The Area), as well as its resources, as the Common Heritage Of Mankind"

The Area and its resources are the Common Heritage of all mankind. All the resources referred to in Article 136 should benefit all mankind (Article 140**).**

The Convention needs to be read with "The Agreement for the Implementation of Part IX of the United Nations Convention on the Law of the Sea of 10 December 1982. This Agreement entered into force on July 28th, 1996.

For the implementation of Part XI and the Convention, this Agreement shall be interpreted and applied as a single instrument.

2. International Seabed Authority

Article 157: "The Authority is the organization through which States Parties shall, in accordance with this part, organize and control activities in the area, particularly with a view to administering the resources of the Area."

The International Seabed Authority:

- Administers the resources of the Area for the benefit of mankind;
- Takes all the necessary measures to promote and encourage the activities of exploration, research and exploitation of the resources of the Area, including marine scientific research;
- Adopts rules, regulations and procedures for the conduct of activities in the Area;
- Takes all necessary measures to protect the marine environment;
- Administers the reserved areas

In this respect, the activities in the Area are governed by:

(a) A mining code
(b) Environmental guidelines

3. Manganese nodules

The exploitation of manganese nodules will start only after a feasibility study proves its profitability and viability. This will depend basically on the quality and quantity of polymetallic nodules, the technology, the tax regime, the legal framework and the price of metals.

For this reason, it is of paramount importance to try to assess the resources of the Area and to do so, one needs to elaborate a geological model.

Legal framework

The activities in the Area are governed by the Mining Code. This Mining Code provides for prospecting and exploration of polymetallic nodules

Prospecting

The conduct of prospecting for polymetallic nodules requires only a notification to the Secretary-General of the International Seabed Authority and registration by the International Seabed Authority. The prospector doesn't have any rights over the resources but can collect enough material for analysis and study. The Prospector shall present a report and information about the area, every year. The prospector has no limitation on how much area it can prospect nor does it have a time limit.

Exploration

The second activity covered by the Mining Code is the exploration for polymetallic nodules. It starts with an application for approval of a plan of work for exploration.

After its approval by the Council, the work programme for exploration becomes a contract, signed between the International Seabed Authority and the applicant with duration of 15 years, and the possibility of extension for an additional five-year period.

An exploration contract contains a number of obligations; to relinquish a part of the allocated area (20% after three years, 10% after five years, and 20% after eight years), to conduct the programme of work, to train a number of personnel for the future Enterprise, to submit annual reports on the progress of work, and to protect and preserve the marine environment.

Data requirements

The Authority receives data during
- prospecting,
- Upon submission of an application of a plan of work for exploration;
- After signing a contract for exploration, and
- After the termination of a contract.

1. Prospecting

Data requirements for prospecting for manganese nodules are to be provided in annual reports. Under regulation 5(Annual Reports) of the Regulations on prospecting and exploration for polymetallic nodules in the Area, this data is of a general nature: A prospector for manganese nodules is required to submit a report to International Seabed Authority that contains "a general description of the status of prospecting and of the results obtained". In addition the prospector is to include in its annual report, "information on compliance with the undertakings referred to in regulation 3, paragraph (4) (d)". These are:

- Compliance with the Convention and the relevant rules, regulations, and procedures of the Authority concerning:
- Cooperation in the training programme (marine scientific research, transfer of technology),
- Environmental protection;, and
- Accept verification by the Authority.

2. Exploration

The content of an application for approval of a plan of work is outlined in section II of Annex 2 of the Mining Code and regulations 10, 11, 12, 13, 14, 15, 16, 17 and 18. Under these regulations, the information to be submitted are:

(a) Data on the location (coordinates, physical (topography, bottom currents), Geology of nodule samples;

(b) Data on the quality and quantity of polymetallic nodules and results of the survey:
- Abundance of nodules (average density, map showing the sampling sites);
- Metal content of economic interest (grade);
- Technology used for the recovery of the nodules;
- Estimation of the commercial value of the two parts (economic data);
- Description of all techniques used by the applicant.

Environmental data

(a) Physical data
- Water (salinity, temperature);
- Waves (periods, height, direction, frequency) ;
- Current (duration, speed)

(b) Biological
Different communities (lateral and vertical distribution…)

Data required in the annual report

The Contractor shall, within 90 days of the end of each calendar year, submit a report to the Secretary-General of the Authority covering its programme of activities in the exploration area and containing applicable information in sufficient details (annex IV, section 10, para. 10.1) on:

(a) Work done during the year: The exploration work carried out during the calendar year, including maps, charts and graphs illustrating the work that has been done and the results obtained

(b) Equipment/technology used: The equipment used to carry out the exploration work, including the results of tests conducted on proposed mining technologies, but not equipment design data

(c) Training: training done – revision or development
- Revision of the programme of work
- Details on any proposed adjustments to the programme of activities and the reasons for such adjustments.

Environmental studies

Results obtained from environmental monitoring programs including observations, measurements, evaluation and analysis of environmental parameters.

Expenditure

A statement of the contractor's exploration expenditure during the year (audited).

Data to be submitted after the termination or expiration of a contract

Paragraph 11.2 states: "Upon expiration or termination of a contract, the Contractor, if he has not already done so, shall submit the following data and information to the International Seabed Authority's Secretary General." The following data are transmitted to the Authority after the termination of a contact:

(a) "Copies of geological, environmental, geochemical and geophysical data acquired by the contractor in the course of carrying out the programme of activities that are necessary for and relevant to the effective exercise of the power and function of the Authority in respect of the exploration area;"

(b) "Estimation of mineable areas, when such areas have been identified which shall include details of the grade and quantity of the proven, probable and possible polymetallic nodule reserves and the anticipated mining conditions;"

(c) "Copies of geological, technical, financial, and economic reports prepared by or for the Contractor that are necessary for and relevant to the effective exercise of the powers and functions of the Authority in respect of the exploration area." A statement of the quantity of polymetallic nodules recovered as samples or for the purpose of testing;

(d) "Information in sufficient detail on the equipment used to carry out the exploration work, including the results of tests conducted on proposed mining technologies, but not equipment design data;"

(e) "A statement of the quantity of polymetallic nodules recovered as samples or for the purpose of testing."

Quality of data to be submitted to the International Seabed Authority

The data to be submitted to the Authority should be of a certain quality and quantity. This data should be:

- Sufficient
- Representative
- Reliable
- Compatible

The quality and quantity of data are very critical for:

- The geometry of the deposit
- The assessment of the resources
- The optimum and suitable technology to mine it
- The characteristics of the deposit
- The optimum and suitable technologies for the processing and extraction of metals
- The requirements for the protection and preservation of the environment

Quantity of data

A minimum amount of data is necessary for geostatistical extrapolation.

Reliability of the data parameters

Occurrence information is derived from both sediment samplers and deep-sea photographs. Nodules presence or absence is recorded as indicator of occurrence. Abundance is usually a direct measurement. Element assays are used to express grade. Each set of information has a different degree of reliability associated with it. It is impossible to quantify the reliability of the data

Representativeness

- A certain number of questions can be asked regarding the representativeness of the data parameter:
- Is the value of the parameter distributed in such a way over an area that it can be considered as random?
- Does the portion of sample which has been analysed represent the whole?
- Does the sample analysed represent the location from which it was taken**?**

Compatibility of different data submitted to the International Seabed Authority

- Different contractors;
- Different areas with different grids;
- All data submitted to the Authority emanate from:
- Different methods of sampling;
- Different time;
- Different operators: (RPIs or contractors)
- Different procedures

Minimum compatibility of the data submitted to the Authority (harmonization-homogenization standardization) is a necessity in the assessment of the resources, in particular in the reserved areas.

Use of the data by International Seabed Authority

The ISA secretariat does not collect data and information from the pioneer investors, the prospectors, the applicants or the contactors just for the sake of gathering data but, rather, to organize and manage the data, build up databases and to provide public access to data that are not confidential, to manage the confidential data with security of access and make them available to the Legal and Technical Commission to work with the aim of designating the reserved area and the one to be considered for the contract after approval by the Council

** evaluating areas reserved for the Authority, until the Enterprise is in operation

*** transferring to the Enterprise or to any joint-ventures the information or data related to the area

**** To carry out any required work with the data of a specific or general nature.

Standardization

In order to use data or information from the different contractors, or from other sources, the International Seabed Authority needs to harmonize such data if they are not standardized. This will offer a guarantee of compatibility, accuracy and will also facilitate its task.

Data and information are entered in the ISA database using specific formats. It will be absolutely necessary to define procedures for acquisition and treatment before processing and formatting those data and information.

How to achieve standardization

- By establishing a list of parameters to be measured;
- By defining units for each parameter with the required or desired precision;
- By selecting a format to record the data (number of decimal places symbols to be used, etc.)

Standardization of procedures

Standardization of procedures is more difficult because it depends on the methods and equipment used for measuring.

Imposing methods and equipments on operators unrealistic and will kill all the inspiration or the poetry inherent to any research.

Recommendation

- A recommendation should be based on standardization of formats.
- Standardization of procedures should be of general recommendations, taking care of previous experiences and mistakes that can be avoided or other additional data to be submitted in the future.
- Cooperation between ISA and operators is necessary and the LTC should provide recommendations for standardization.

SUMMARY OF PRESENTATION

Mr. Diène said that the Authority organized the workshop to find a reasonable approach to establishing a geological model of polymetallic nodule deposits in the CCZ. He said that in order for the Authority to do so, it was essential for it to have a good set of data. Mr. Diène started his presentation with a digression to provide a context for the "*Mining Code*".

He said that all of the provisions contained in the code, are derived from the United Nations Convention on the Law of the Sea. He said that the Convention establishes different jurisdictions for ocean space, such as the territorial sea, the continental Shelf, the exclusive economic zone in relation to the management of living and non-living resources, the conduct of marine scientific research, and the protection of the marine environment. He stressed that the Convention delineates the seabed and ocean floor and the subsoil beyond the limits of national jurisdiction (which is called by the Convention - the Area), as well as its resources, and these together constitute *the common heritage of mankind.*

Mr. Diène referred to Article 136 of the Convention, which requires that the Area and its resources should benefit all mankind, and Article 157 of the Convention that provides the Authority with the mandate through which States Parties organize and control activities in the Area, particularly with a view to administering the resources of the Area. Mr. Diène reminded participants that the Convention needs to be read with the agreement for the implementation of Part XI of the United Nations Convention on the Law of the Sea. He also reminded participants that the Implementation Agreement entered into force on 28 July 1996, and that by its article 2, paragraph 1, the Agreement and Part XI of the Convention shall be interpreted and applied as a single instrument.

Mr. Diène said that the main goal of the International Seabed Authority is to administer the resources of the Area, for the benefit of all mankind. To do so, Mr. Diène stated that the Authority has to utilize all necessary measures to promote and encourage mineral exploration and exploitation in the Area, including the promotion of marine scientific research for this purpose. Mr. Diène said that the Authority adopts rules, regulations and procedures for the conduct of activities in the Area, takes all necessary measures to protect the marine environment, and administers the reserved areas. He noted that during the past few years, the Authority has developed an exploration code for polymetallic nodule deposits, and environmental guidelines for exploration contractors for these mineral resources.

Manganese nodules

Mr. Diène observed that the exploitation of manganese nodules would only start when a feasibility study proves nodule mining to be profitable. In this regard, Mr. Diène remarked that technology aids the political side. Defining the political side as being the legal framework and the price of metal, he said it was of paramount importance to undertake assessments of the resources of the area, utilizing means such as geological models.

Legal framework

Mr. Diène pointed out that all activities for polymetallic nodules in the Area are governed by the mining code, which provides for prospecting and exploration for polymetallic nodules.

Prospecting

With regard to the content of the provisions on prospecting for polymetallic nodules, Mr. Diène said that all an interested party had to do was to notify the International Seabed Authority. He noted that prospectors have no rights to the nodules in the areas they investigate but can get enough material for analysis and study. He further noted that prospectors were required to submit annual reports, have no time limit to conduct their activities, and could prospect as many areas as they wished.

Exploration

Mr. Diène said that after approval of an application to the Authority for approval of a plan of work for exploration, such activities start when a contract is signed between the contractor and the Authority. He said that the contract was for a duration of fifteen years, with a possibility of extension of five years. The signing of an exploration contract goes with the obligation to relinquish some parts of the Area, to conduct the programme of work, to attend to training programmes, to deliver to the Authority an annual report, and to protect and preserve the marine environment.

Data requirements

Mr. Diène summarized the data requirements of the regulations as follows: The Authority receives data during the prospecting phase (the annual report); an application for approval of a plan of work for the exploration phase; when the exploration contract is signed, and at the termination of a contract.

He said that during prospecting all data are of a general nature. A prospector is required to give to the Authority an annual report where it provides a general description of the state of prospecting along with the results it has obtained. It also has to provide information in compliance with undertakings referred to in the Convention. These undertakings include cooperation in training programmes, environmental protection and acceptance of verification by the Authority. To undertake exploration, however, Mr. Diène said that the data to be submitted to the Authority are the following: the proposed exploration area (coordinates of the area, physical topography, bottom currents, the geology etc.), the results of surveys, an evaluation of the quality and quantity of polymetallic nodules found in the area, environmental data, as well as financial data.

With regard to data specific to the quality and quantity of polymetallic nodules and the results of surveys, Mr. Diène informed participants that the applicant has to provide information on, inter alia, the abundance of nodules, their metal content, the technology used for the recovery of the nodules, estimation of the commercial value of the two parts of the application area (economic data), and descriptions of all techniques used by the applicants.

Environmental data

Mr. Diène described environmental data as, inter alia, water salinity and wave direction at sea, as well as geological data/biological data.

Mr. Diène said that a year after signature of the contract, the contractor has to submit a report to the International Seabed Authority on the execution of its programme of activities in the exploration area. He said the report should contain sufficient information and provide:

- Data on the work done during the year; exploration work carried out during the calendar year, including, maps, charts, and graphs, illustrating the work that has been done and the results obtained.
- The equipment and technology used by the contractor - including the results of tests conducted on proposed mining technologies.
- If any training was imparted, what kind of training.

- The programme of work and any change which needs to be made in the course of implementing this programme; if it is to be adjusted or if it has been adjusted; this is to be reported to the Authority.
- Environmental studies, environmental monitoring, and all related programmes including, observations, measurements, evaluations and analysis of environmental parameters.
- All expenditure incurred during that calendar year for exploration should be provided.

Data to be submitted after the termination or expiration of a contract

In relation to data requirements following termination of a contract, Mr Diène said that the contractor, if it had not already done so, is required to submit the following data and information to the Secretary General of the International Seabed Authority:

- A copy of the geological, environmental, geochemical and geophysical data acquired by the contractor. Mr. Diène suggested that this requirement should be omitted, because upon termination of the contract, the contractor's work is complete.
- Estimation of mineable areas - when such areas have been identified - which shall include details of the grade and quantity of the proven, probable, and possible polymetallic nodule reserves, even the anticipated mining conditions.
- Copies of geological, technical, financial, and economic reports necessary for the effective exercise of the powers and functions of the Authority.
- A statement of the quantity of polymetallic nodules recovered as samples or for the purpose of testing.
- Information in sufficient detail on the equipment used to carry out the exploration work, including the results of tests conducted on proposed mining technologies, but not equipment design data.

Quality of data to be submitted to the International Seabed Authority

Mr .Diène said that data submitted to the ISA should be of a certain quality and quantity; and should be sufficient, representative, reliable, and compatible. Recalling the presentation of Kaiser De Souza, Marine Geologist of the Authority, in particular the difficulties of the comparability of data from the different contractors, Mr Deine reiterated the importance of standardization for future applicants. He pointed out the need to minimize these types of problems. He said that the quality and quantity of data are critical for: the characteristics of the deposit; the geometry of the deposit; the assessment of resources; and the selection of optimum and suitable technology to mine it.

Mr. Diène pointed out that a minimum quantity of data is necessary for resource assessment in such large areas. He noted that these data would form the basis for any extrapolation that was required. Given the size of the areas in question, Mr. Diène said a large quantity of data are required for extrapolation or interpolation to work.

Mr. Diène also said the data should be representative. In this regard, he pointed out that a number of questions could be asked regarding the representativeness of a data parameter: Is the value of the parameter distributed in such way over an area that it can be considered random? Does the portion of sample, which has been analysed, represent the whole? Does the sample analysed represent the location from which it was taken?

Compatibility of the different data sets submitted to the International Seabed Authority

Mr. Diène stated that the data submitted to ISA were from different contractors who have prospected different areas using different grids, different methods of sampling, and different procedures. He said that a minimum compatibility of the data submitted to the ISA (harmonization) was a necessity to enable assessment of the resources, in particular in the reserved areas. He noted that these data need to be organized and standardized.

He informed participants that the data were managed and stored in databases by the Authority. He said that the normal procedure is for the Authority to make data submitted by contractors, available to the Legal and Technical Commission for its work that ranged from the designation of an area for the applicant, the reserved area for the Authority, and the evaluation of the data for interests that may exist for any joint ventures with the Enterprise.

In order to facilitate the establishment of databases and to ensure the integration and comparability of data, Mr. Diène emphasized the need for standardization in acquiring, processing and formatting data. He concluded his presentation with a recommendation that data required of contractors in the regulations should be standardized. He said that this could be achieved by introducing guidelines on data collection, processing and formatting to the code. He said subsequent data received by the Authority could then be utilized to improve the model and future models.

SUMMARY OF THE DISCUSSIONS

There were no discussions after the presentation.

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CHAPTER 5 GEOLOGICAL MODEL INPUTS

Dr. Charles Morgan, Environmental Planner, Planning Solutions, Inc.; Honolulu, Hawaii, United States of America

Introduction

One of the primary responsibilities of the International Seabed Authority (the Authority) is to assess the quantities of metals present in seabed polymetallic nodules. To carry out this responsibility, the Authority undertakes an assessment of the reserved areas in the Clarion-Clipperton region of the northeastern Pacific (CCZ) using the data submitted by the registered contractors and maintained in the Authority's POLYDAT database. The results of its most recent assessment demonstrated that the information submitted by the contractors, although satisfactory for some purposes, does not permit the exploitable quantities of metals in these areas to be estimated with a degree of confidence that is comparable to many land-based mineral resource estimates.

During a meeting between the Authority and the registered pioneer investors (RPIs) in March 2001, some of the RPIs suggested that the future work of the Secretariat on resource assessment of the reserved areas in the CCZ would be enhanced through the development of a geological model for this region of the international seabed. At the ninth session of the Authority in 2003 (see ISBA/9/C/4), the members of the Authority's Legal and Technical Commission (LTC) recognized that such a model could directly benefit the contractors working in the CCZ by improving the resource assessment for the area and could also contribute to a better general understanding of how economically interesting deposits are formed. This workshop has been convened to examine the potential methods that can be used to develop such a geological model. This presentation:

1. Examines the criteria that should be set for data inputs into the model*;*
2. Suggests specific input variables that might be considered for inclusion in the model*;*
3. Suggests a procedure for developing the model that separates the process into two closely related efforts, one (the geological model) which includes the construction of quantitative predictions of the spatial distributions or ore grade and abundance and one (the Prospector's Guide) which includes qualitative principles for guiding mineral exploration for deep seabed polymetallic nodules; and
4. Presents an example of one potential method for geological modelling that may be useful in the effort.

Criteria for model inputs

The geological model should be capable of improving and extending the presently available resource assessments for the Clarion-Clipperton Zone and should be designed to permit efficient updating as new input data become available. It should be constructed using proxy data variables that are postulated or known to be correlated with the grade and/or abundance of nodule deposits in the CCZ and that can be used in geostatistical routines (co-kriging) to predict grade and/or abundance where data are not available. Input proxy data for the model should have the following characteristics:

- Be available in formats that will require little or no processing for their use;
- Be available for a significant portion of the CCZ; and
- Be clearly linked to the postulated formation processes that are believed by the participants to cause the formation of polymetallic nodules.

Candidate model input variables

The variables described in the following sections may be appropriate to consider for use as proxy variables in the model development.

Regional **s**eafloor **t**opography*:*

Regional topography in the deep North Pacific and other areas is directly related to the tectonic history of the area.

As shown in *Figure 1*, the primary characteristics of the CCZ seafloor clearly show the major fracture zones emanating from the East Pacific Rise (EPR), the progressive deepening of the seafloor to the west (shown by Sclater[5] to be caused by the cooling of the crust as it moves away from its origin at the EPR), and the groups of seamounts that dominate in the extreme west of the CCZ. when interpreted within the context of plate tectonic theory, these regional features provide basic constraints on the time that the CCZ deposits have had to form and the environmental variables to which the growing deposits have been subjected.

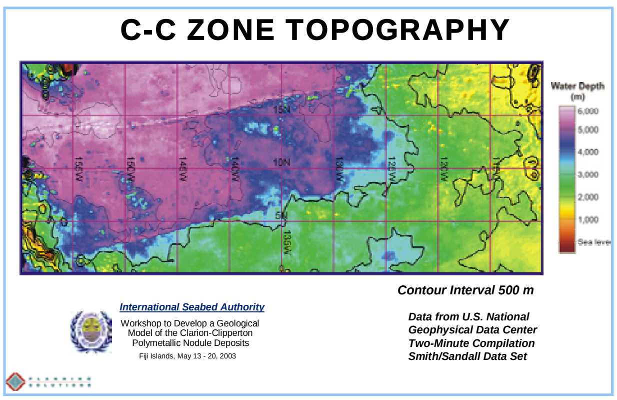

Figure 1: Regional seafloor topography in the Clarion-Clipperton Zone (CCZ)

Nodule morphology: Extensive research has been done in various attempts[6] to correlate the intriguing external morphology and internal stratigraphy of the CCZ nodule deposits with external environmental variables (e.g. sedimentation rate, glaciation history, surface primary productivity). To date, these efforts have not established quantitative relationships between nodule grade and abundance and nodule morphology.

As shown in *Figure 2*, there is an apparent weak relationship in at least some data sets[7] between nodule size and nodule abundance. Further examination of this possible set of candidate variables may be productive.

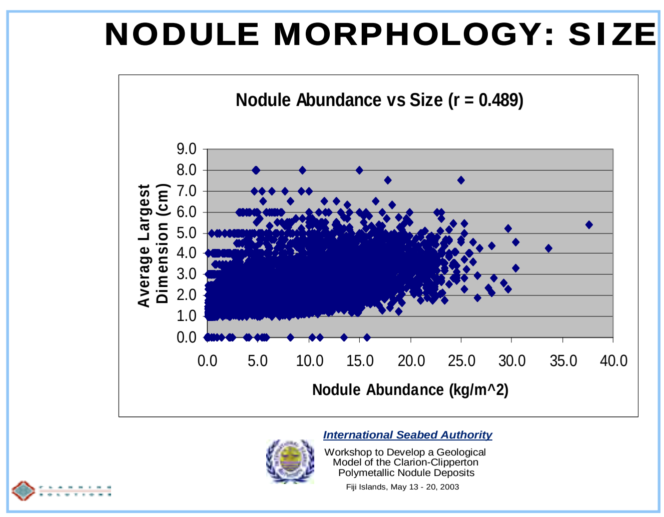

Figure 2: Nodule abundances vs size

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5 Sclater, J.S. 1972. "Heat Flow and Elevation of the Marginal Basins of the Western Pacific." *Journal of Geophysical Research*. 77(29): 5688-5696.

6 For example, Sorem, R. K. and Foster, A. R., in *Ferromanganese Deposits on the Ocean Floor* (ed. Horn, D. R.), LDGO, NY, NSF/IDOE, Washington D.C., 1972, pp. 167–181.

7 Proprietary data from Ocean Minerals Company

__Total sediment thickness.__

Growth of substantial polymetallic nodule deposits in the CCZ is believed to be a balance between too much sedimentation, which will bury the deposits, and too little sedimentation, which will result in small deposits or no deposits at all if the primary sources of the metals in the deposits are associated with sediment sources.

Thus, sedimentation rate, and the resultant sediment thickness, should be related to nodule abundance and grade, except for those deposits that form from hydrothermal or other non-sediment sources. As suggested by *Figure 3*, sediment thickness is related both to the distance from the high-productivity zone found at equatorial latitudes and the age of the crust, with sediment thickness increasing to the west with increasing crustal age and to the south with increasing primary productivity. Thus, it is possible that the optimum region for the generation of high-grade, high-abundance deposits occurs at a particular total sediment thickness that reflects the balance between burial of the deposits and supply of metals to the deposits.

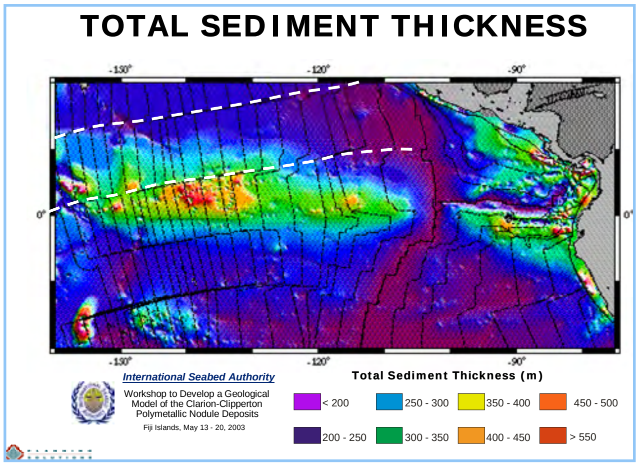

Figure 3: Total sediment thickness

<u>Tectonic constraints</u>

As noted earlier, the regional topography is an important variable in the effort to constrain the predicted occurrence of polymetallic deposits, because it is related to crustal age. More generally, the tectonic setting, which includes crustal age, as well as the history of plate motion, places both temporal and geometric constraints on the formation of the CCZ deposits.

As shown in *Figure 4*, the CCZ has been moving during the past 40 million years generally to the west-northwest. While the CCZ polymetallic deposits have been forming, the sedimentation rate has been steadily dropping, and the water depth has been increasing. These and probably other trends associated with the plate motion are likely to be directly related to the formation of nodule deposits for the reasons discussed elsewhere in this presentation. Because the tectonics comprise basic influences on many environmental variables known to be relevant to the formation of the CCZ deposits, it is important to include a thorough evaluation of the tectonic history of the region in the modeling efforts.

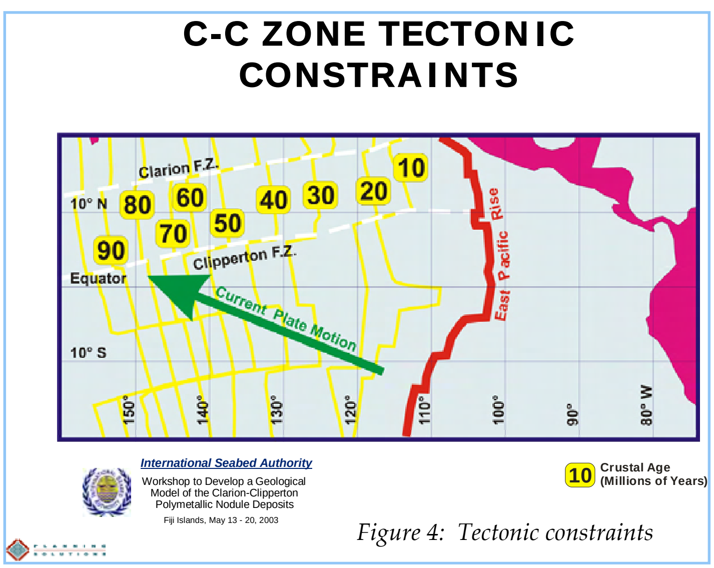

Figure 4: Tectonic constraints

Benthic currents:

Physical oceanographers have believed for many years that the CCZ seafloor experiences flows of deep-water currents that are caused by cold water that sinks to the seafloor near the Antarctic continent and then flows northward into the CCZ (see *Figure 5*).[8]

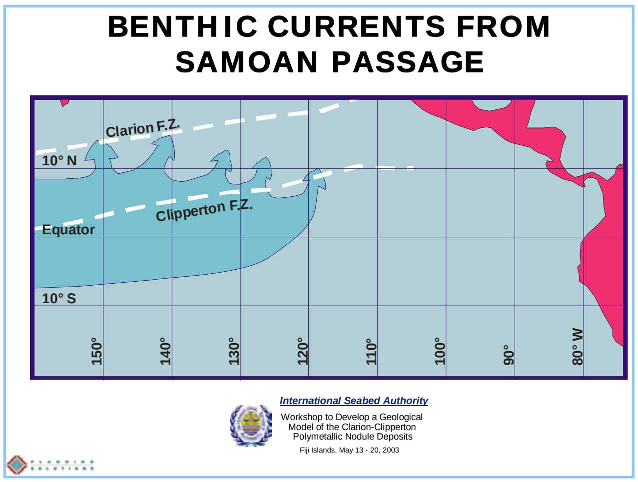

Figure 5: Benthic currents

Researchers have postulated that these currents may influence the occurrence and abundance of polymetallic nodule deposits.[9] However, to date, there are very few measurements of these currents and even fewer studies of the relationships that may exist between these currents and nodule grade and abundance. Thus, it might not be productive to attempt to include this variable in the development of the geological model.

Surface currents:

In contrast to benthic currents, the structure of surface currents in the CCZ region is fairly well understood. They include (see *Figure 6*):

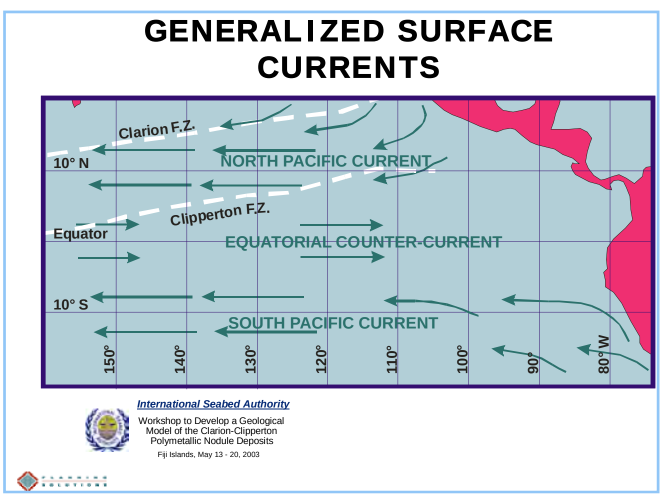

Figure 6: Surface currents

- The North Equatorial Current, which occurs north of about 10˚ N and flows from the northeast to the southwest; and
- The Equatorial counter-current, that flows eastward against the prevailing North Equatorial current.

As discussed in the following section, we believe that these currents are related to the abundance and grade of polymetallic nodule deposits in the region because they carry fine-grained sediments from the North American continent that may contain much of the metal content that ends up in the nodule deposits.

Using surface-water chlorophyll as a proxy variable

The following sections describe a potential methodology that might be useful in the development of the geological model. The exercise examines the potential utility of using one particular variable, surface-

[8] Stommel, H. and A.B. Arons. 1960. "On the abyssal circulation of the world ocean" *Deep Sea Research*. 6:140-154.
[9] For example, see Demidova, T.A., E.A.Kontar, and V.M. Yubko 1996, Benthic current dynamics and some features of manganese nodule location in the Clarion-Clipperton Province*, Oceanology*, v. 36, No. 1, 94-101.

water chlorophyll concentrations as measured by satellite colour scanners, as a proxy for polymetallic nodule abundance. The exercise demonstrates one example of the general concept of using proxy variables and geostatistics to enhance resource assessment and some of the methodology that might be employed.

Rationale Researchers have for several years postulated that the deep Pacific Ocean polymetallic nodule deposits are composed primarily of metals that settle with sediments from surface waters. The theory, developed most completely for the South Pacific by D.S. Cronan,[10] and by P. Verlaan[11] is that the fine-grained materials (too small to sediment out of the water column) in the deep ocean are carried to the region by surface currents, ingested by plankton, and then settle to the ocean floor in the form of larger fecal particles. Benthic organisms ingest these materials and then oxidize the organic matter for nutrition and excrete chemically reduced wastes. These wastes include chemically active metals (in reduced oxidation states) that can be efficiently scavenged (by surface adsorption) onto the manganese oxide surfaces of the polymetallic nodules. If this theory is correct, and if it also applies to the North Pacific nodule deposits, then the growth rate of polymetallic nodules in the CCZ should be proportional to the flux of these fine-grained sediments to the seafloor. This flux is directly proportional to the concentrations of sediments in the surface waters and the density of plankton that ingest the sediments.

Oceanographers have shown in other studies that plankton density is directly proportional to primary productivity (the rate at which photosynthetic plankton convert sunlight and nutrients into organic matter) and that chlorophyll concentration in surface waters (which can be measured through colour measurements collected by satellites) is directly proportional to primary productivity.[12] Thus, if surface-water primary productivity has maintained a similar spatial distribution over the CCZ during the past few million years, then the theory predicts that chlorophyll concentrations in surface waters will be correlated with the abundance of polymetallic nodules and thus can be used as a proxy variable for resource assessment.

Datasets

Surface chlorophyll concentrations.

The absorption of blue and blue-green wavelengths by photosynthetic pigments enables phytoplankton biomass to be quantified through measurements of ocean colour obtained by satellite.[13]

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10 Cronan, D.S. 1997. "Some controls on the geochemical variability of manganese nodules with particular reference to the tropical South Pacific" In K. Nicholson, J.R. Hein, B. Buehn, & S. Dasgupta, *Manganese Mineralization: Geochemistry and Mineralogy of Terrestrial and Marine Deposits* (pp. 139-151). Boulder, Co.: Geological Society Special Publication 119.

11 Verlaan, P.A., D.S. Cronan and C.L. Morgan. 2004. "A comparative analysis of compositional variations in and between marine ferromanganese nodules and crusts in the South Pacific and their environmental controls" *Progress in Oceanography* 63(3):125-158.

12 Bidigare, R.R., & M.E. Ondrusek. 1996. "Spatial and temporal variability of phytoplankton pigment distributions in the central and equatorial Pacific Ocean" *Deep-Sea Research II*, 43, 809-833.

13 Falkowski, P.G, Barber R.T & Smetacek. V. 1998. "Biogeochemical controls and feedbacks on ocean primary production" *Science*, 281, 200-206.

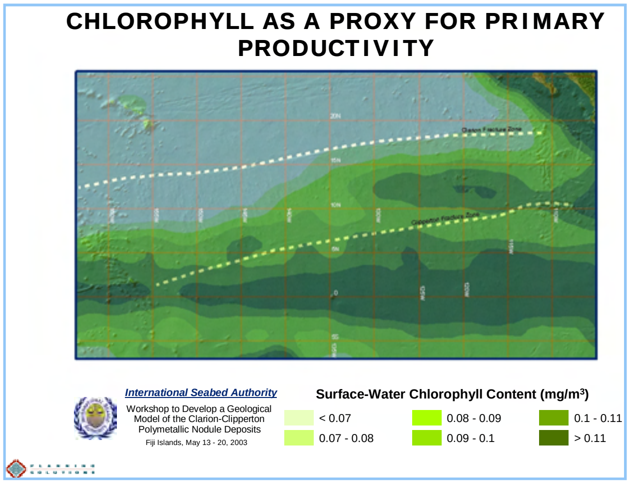

Figure 7: Contoured map of chlorophyll content

The 7.5 year average of concentrations of chlorophyll obtained by the Coastal Zone Colour Scanner program operated on the *Nimbus 7* satellite by the US National Aeronautical and Space Administration from November 1978 to June 1986[14] was used to generate chlorophyll values (at a density of 1 value per degree of longitude and latitude) that include the area of interest within the CCZ. *Figure 7* shows the contoured map of these data. Note the extension of relatively high values into the central, eastern part of the CCZ to the north of the equatorial maximum. We believe that this feature represents the enhanced primary productivity caused by the nutrients carried to the region by the North Equatorial Current.

Polymetallic nodule abundance and grade

Co-kriging consists of augmenting existing data on the variables of interest (in this case nodule abundance and grade) through the incorporation of proxy variables. The existing grade and abundance data used in this exercise come from a private data set (Ocean Minerals Company, OMCO) with the addition of available published data. We have obtained permission from Lockheed-Martin Corporation (the successor of OMCO) to use the OMCO exploration in this work, with the condition that the original data are not disclosed. The spatial distribution of the sample stations used is shown in *Figure 8*.

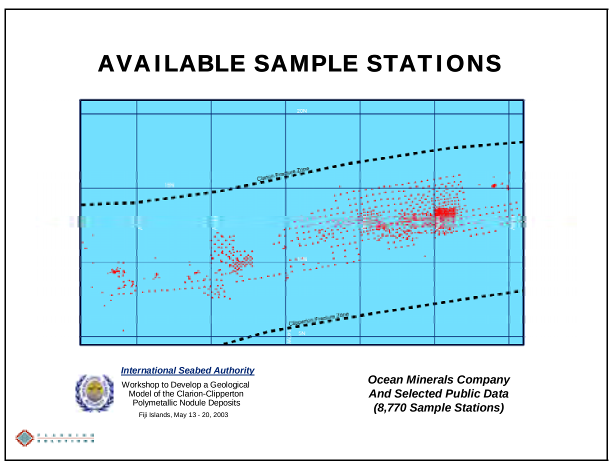

Figure 8: Available abundance and grade sample stations

Kriging methods

Kriging is a statistical tool developed by Matheron[15] and named in honour of D.G. Krige, a South African mining engineer. Although originally developed specifically for ore reserve estimation, kriging has

[14] Hovis, W.A., D.K. Clark, F. Anderson, R.W. Austin, W.H. Wilson, E.T. Baker, D. Ball, H.R. Gordon, J.L. Mueller, S.Z. El-Sayed, B. Sturm, R.C. Wrigley, & C.S. Yentsch. 1980. "Nimbus-7 Coastal Zone Color Scanner system description and initial imagery" *Science*, 210, 60-63.

[15] Matheron, G., 1962, *Traité de Géostatistique Appliquée:* Mém. Bur. Rech. Géol. Minières, 14, 333 p.

been used for other spatial estimation applications, such as analysing and modelling environmental data. At its simplest, kriging can be thought of as a way to interpolate spatial data much as an automatic contouring program would. Mathematically, kriging can be defined as a best linear unbiased estimator of a spatial variable at a particular site or geographic area. Co-kriging is an interpolation technique that allows one to better estimate map values if the distribution of secondary variables, correlated to the primary variable, are sampled more densely than the primary variables. If the primary variables are difficult or expensive to measure, then co-kriging can greatly improve interpolation estimates available only from the primary variables. In this exercise, we used kriging to establish first order maps of ore grade and abundance using available data, and then used co-kriging techniques that employ the original grade and abundance data with the chlorophyll proxy variable. We used the ESRI® ArcGIS® Geostatistical Analyst Extension as the primary software tool for implementation of these geostatistical techniques.[16]

Results

Figure 9 shows the results of applying ordinary kriging to predict the distribution of nodule abundance, using the OMCO/published data set alone.

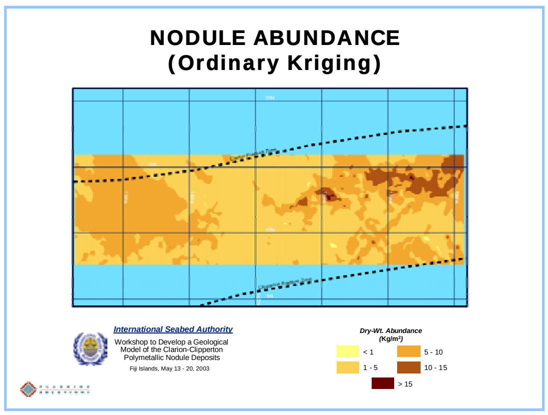

Figure 9: Nodule abundance (ordinary kriging)

Because nodule abundance has a relatively high variability, even at very local scales, it is important to determine the estimation error associated with each kriging prediction. The capability of kriging to provide adequate, spatially dependent error estimation is one of the key reasons why it is used for mineral resource assessment. When we limit the predictions to those where the estimated error is less than the median value of the variable (in this case 6.5 kg of nodules per square meter of seafloor area), we obtain the plot shown in *Figure 10*.

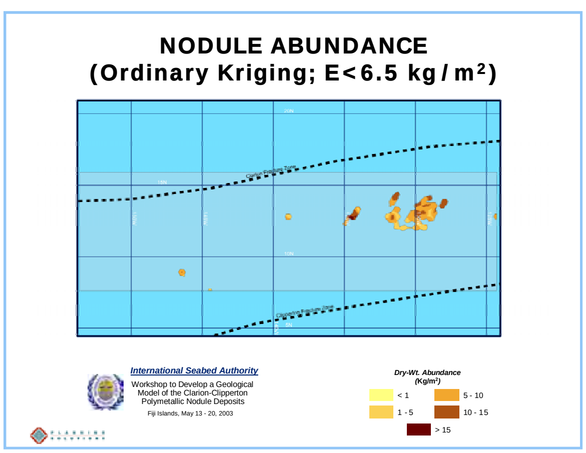

Figure 10: Nodule abundance (ordinary Kriging; E<6.5 kg/m²)

[16] Johnston, K, J. M. Ver Hoef, K Krivoruchko, and N. Lucas 2001. *Using ArcGIS Geostatistical Analyst*. ESRI, Redlands, California. 300 p.

When we use co-kriging to generate estimated abundance and similarly limit the plotted values to those with error estimates less than 6.5 kg/m^2, we get a distribution which appears to be a distinct improvement in the resource assessment.

Summary of major points

The primary points raised in this presentation are the following:

1. The objectives of the project to be developed from this workshop should include:
   (a) The completion of a *Geological Model* that includes quantitative improvements in the available resource assessment of the polymetallic nodule deposits in the CCZ, and
   (b) The completion of a *Prospector's Guide* that provides documentation of the methods used to develop the *Geological Model* and also includes semi-quantitative and qualitative observations useful for the guiding prospectors and explorers for polymetallic nodule deposits in the CCZ and, hopefully worldwide.
2. A candidate method to use for development of the *Geological Model* involves the application of geostatistical methods to existing nodule abundance and grade data combined with other variables ("proxy" variables).
3. A number of candidate proxy variables should be considered, including regional bathymetry and tectonic history, nodule morphology, sediment thickness, and surface-water properties, particularly primary productivity.
4. Any proxy variable used in the project should be available for a substantial portion of the CCZ and should be known or believed to be correlated with abundance and/or grade.

SUMMARY OF THE PRESENTATION

Mr. Alf Simpson introduced Dr. Charles Morgan of Planning Solutions Inc., based in Honolulu, Hawaii, USA, to present his paper on geological model inputs. Mr. Simpson informed participants that Dr. Morgan, who had a long history of working in this area, had a previous association with one of the United States consortia, the Ocean Minerals Company (OMCO) and its successor, Lockheed-Martin, in polymetallic nodule development.

Dr. Morgan expressed his delight that most of what he had to say had been touched upon by previous speakers. He said that a number of the points that he had intended to raise with regard to the modelling effort had been brought up by some of the speakers, which he felt boded well for the productivity of the workshop.

Dr. Morgan said that his presentation would focus on following topics:

(a) The International Seabed Authority's (ISA) objectives for model development;
(b) The crireria for model inputs;
(c) Candidate input variables to model;
(d) Considerations for model development, and
(e) An illustration of a potential method for model development..

In relation to the ISA's objectives for model development he recalled the presentation of Mr. Odunton and the results of the meeting of scientists in January 2003 for model development. In short, Dr Morgan said that these objectives require clarifying the formation processes of nodule deposits to serve as a guide for prospectors, who can then provide inputs for a dynamic model that assists the Authority to improve its resource assessments for the CCZ over time. He described the objectives as distinct but interrelated.

With regard to the data to be incorporated in the model, Dr. Morgan proposed two criteria; namely, (a) the data have to be updateable without huge expenditures of time and/or money; and (b) the data have to be clearly linked to the key variables of the resource, i.e., abundance and grade.

Dr. Morgan then proceeded to discuss the variables identified for model development at the January 2003 meeting of scientists. These were topography, nodule morphology, nodule size, sedimentation, tectonic constraints, currents, and primary productivity. He suggested that, participants should decide whether these variables should be incorporated in the model and whether data are available in each case.

Topography

As regards topography, Dr. Morgan said that over the years there had been a lot of discussion on this topic. Using *Figure 12* (Figure 1 of his paper), which depicts the topography of the CCZ, he explained that it had been constructed using the United States National Geophysical Data Center Two-Minute Compilation dataset as distinguished from the one-minute dataset that is currently available.

Dr. Morgan informed participants that the two-minute topographic grid data were determined from track lines and interpolated using satellite altimetry. He said that these data are not really useful when one talks about local problems with respect to nodule deposits. He also said that these data could not be used when looking for a mine site because they were absolutely too general for that. However, he pointed out that they were very useful when looking at the regional issues involved. Among other things, he said that they clearly showed the basic tectonics of the region, including the offset between the fracture zones, and the strike-slip motion that has taken place over the last few million years in this region. Dr. Morgan noted that, while much of the focus was on how bad these data were, for regional purposes, they were good data.

Nodule morphology

Dr. Morgan informed participants that much had been said in the past about nodule morphology, and that there was a huge publication record of different kinds of nodule morphology. He said that in the past, if you pulled up a dredge and the nodules looked discoloured and large, some people would say that those nodules came from a good deposit. If nodules came up looking round and smooth, others would say that those nodules were from a bad deposit. He suggested that there were clearly qualitative factors that were of great importance and quite relevant, but that to include them in a quantitative model would be very difficult. Because of that, he suggested that there may be a need to think about establishing more than one model, so that important clues on grade and abundance that may be gleaned from nodule morphology are not discarded. He also said that just because how to incorporate them in some sort of numerical model was not presently available, this was not a sufficient reason to discard them.

Nodule size

Utilizing *Figure 13* (Figure 2 of his paper), Dr. Morgan showed the possible relationship between nodule size and abundance.

He pointed out that to generate this chart he had taken nodule size data available from free fall grabs in their database and averaged them with the abundance in the area. Describing the end product as a not-so-pretty map, he pointed out that nodule size would appear to have a very significant positive correlation with abundance. He suggested that nodule size was the kind of variable that could be examined as part of the development of the geological model because something of a quantitative nature between size and abundance would appear to exist.

Sedimentation

Dr. Morgan said that sedimentation had been talked about more than any other parameter in relation to the grade and abundance of nodules. He said that nodules had a love-hate relationship with sediments. Nodules, he continued, needed the minerals that were brought in through sedimentation in order to grow. They did not grow in places where there was no sedimentation; there was no input of metals. In the Clarion-Clipperton Zone, Dr. Morgan said, there probably were no obvious volcanic sources. On the other hand, if there was too much sediment, nodules got buried. When developing the model, Dr. Morgan said that this balance must be kept in mind. Using *Figure 14* (Figure 3 of his paper), he showed areas with a high thickness of sediment, which he said could be predicted by their proximity to the equator. He said that as the crust got older and farther out, not surprisingly, the sediments became thicker. He described the situation as valuable for clues as to nodule abundance in a regional sense.

Tectonic constraints

Dr. Morgan informed participants that tectonic constraints provided certain clues that would be useful in developing the geological model. He said that the plates had been moving pretty much in the direction of 292^{o}, and at about 7 centimetres per year for the last 40 million years. He used *Figure 15* (Figure 4 in his paper) to illustrate the point.

As a result, Dr. Morgan said that it didn't make a lot of sense to look at processes between the Clarion and Clipperton Zones which take longer than 20 million years. He said that the crustal age of the large abundances of nodules found at about 120^{o}, is about 20 million years old. He said that this type of information provides a good constraint on what has to be looked at in developing the model

Currents

Dr. Morgan said that many researchers believed that currents were very important to nodule formation. He expressed his appreciation that Dr. Allen Clarke would address the importance of benthic currents in the formation of some polymetallic nodule deposits in the South Pacific. While there is a lot of research being done in the North Pacific, Dr Morgan said that the data are insufficient for determining how strong these currents are, and what the fluxes are in different areas along the CCZ. He said that what was generally known was that most of the benthic water came up through the Samoan Passage, which was about 10^{o} south, and 170^{o} west (*Figure 16*). In addition, he said, it was known that the benthic water filters through the Clarion-Clipperton Zone and upwells in the northeastern Pacific. He therefore suggested that benthic currents should not be one of the variables used in model development.

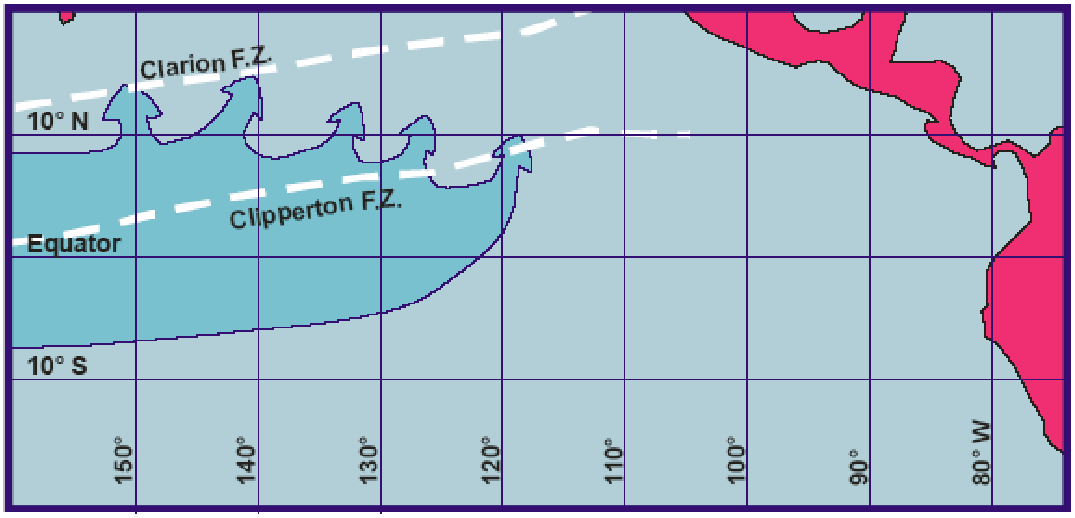

Figure 16: Benthic currents from the Samoan passage

Surface currents

In contrast, Dr. Morgan said that surface currents that are well characterized and well known provided the main horizontal vector that brought materials in from the North American continent and that led to the production of the polymetallic nodules (*Figure 17*). He said that the surface currents were major currents that had probably been similar for at least several million years. He said that their implication as a source of metals for nodules would serve as an important guiding principle for the development of the model.

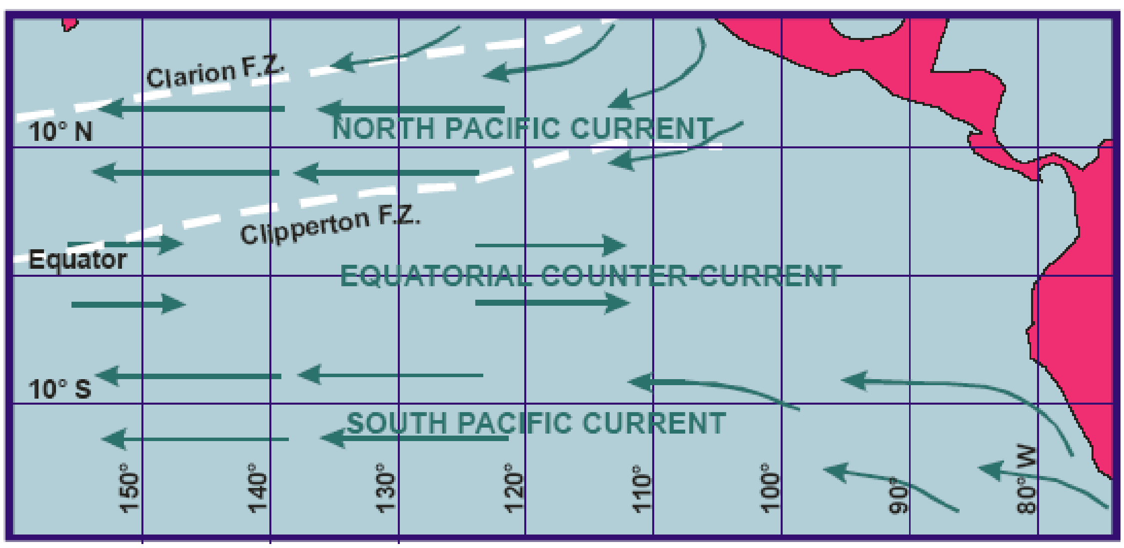

Figure 17: Generalized surface currents

Primary productivity

Dr. Morgan described primary productivity as his favourite variable. He said that the *Nimbus 7* satellite had measured the surface-water content of chlorophyll between 1979 and 1985. He said that this integrated chlorophyll database was a fairly good snapshot of current levels of chlorophyll, which was directly proportional to the fundamental primary productivity in the region. He provided a snapshot of chlorophyll as a proxy for primary productivity in the CCZ using *Figure 18* (Figure 7 in his paper).

Dr. Morgan said that, while most researchers thought that currents were the horizontal vector that brought materials into the CCZ, the vertical factor was the very fine materials that were too fine-grained to settle when it got to the oligotrophic Pacific Ocean. He said that one way that this material settled was through the guts of zooplankton that ate the phytoplankton and produced the faecal matter that was large enough to settle.

Dr. Morgan said that the greater proportion of them was along the equator, which, he added, was exactly like the sedimentation that was also at a maximum along the equator. Dr. Morgan informed participants that the sediments within this region were directly proportional to primary productivity. He also said that he would expect that this variable when integrated with the climatic changes that had taken place over the past twenty million years would very likely change this gradient; in particular, since the Pacific plate had moved in this area. He stated that he would expect the chlorophyll data set to be a very important input to the geological model.

Table 1
Candidate variables key points

- Topography
  - Deeper to NW;
  - Express tectonics regionally
- Nodule morphology
  - Qualitatively important
  - Abundance ≈ F (size)?
- Sediments
  - Bring metals and bury nodules
- Tectonics and volcanic activity
  - Constrain age and potential sources of metals
- Currents
  - Surface; vectors for metals to surface above deposits
  - Benthic; poorly known
- Water column characteristics
  - Vertical vectors to deposits

Introducing candidate proxy variables as presented in Table 1, and as identified at the meeting of scientists, Dr. Morgan said that topography was not all that great, certainly not at a local scale, but that it certainly expressed the tectonics regionally. He said that topography was important in the dissolution of carbonates, which he also said varied proportionally with depth.

With regard to nodule morphology, Dr. Morgan noted that it is extremely important qualitatively, but that it may or may not be something that could be used in a quantitative sense. Stating that this qualitative sense should not be lost, he recalled his suggestion about the prospector’s guide.

In relation to sediments/sedimentation, Dr. Morgan recalled that sediments brought metals to the nodules and that when too much sediment accumulated in an area, they buried the nodules.

Dr. Morgan said that tectonic constraints provided, inter alia, an age limit and information on the direction and speed of the plate for at least the past 40 million years. He recalled his earlier statement that twenty million years was the limit for nodule formation in this region and noted that abundant nodules are found at about 120^{o}. He said that crustal age at 120^{o} is about twenty million years, suggesting that this was the constraint brought about by tectonics.

Finally, in relation to surface and benthic currents, Dr. Morgan said that surface currents were the horizontal vectors that brought materials in from the North American continent and that good data were available on them. With regard to benthic currents which he described as the vertical vectors, Dr Morgan said most of the benthic water come up through the Samoan passage (10^{o} degrees South and 170^{o} West) and though the currents are probably important, data are insufficient for use in the model. He recommended that the model should not include currents.

Dr Morgan said that chlorophyll is a very good proxy variable for primary productivity. He said that sediments along the region vary with primary productivity. His expectations were that when this variable is integrated over the past twenty million years, as the Pacific Plate has moved under this area, the data set on chlorophyll would be a very important input into the model.

Dr. Morgan said that, based on the variables to be considered for model development, he had two approaches, as follows:

(a) A rigorous and iterative statistically based quantitative model, and

(b) A prospector's guide or narrative, which would take advantage of the experience gained on the formation of nodule deposits and the expertise of some of the workshop participants. He said the prospector's guide would ensure that qualitative clues are retained.

He also said that it would be critical to ensure that the effort is iterative. He said that this would require some inputs from all involved in developing the model, including changes and modifications as different data sets are tried out, and model developers improve their understanding of how their data impact the model and make it more effective.

In regards to the prospector's guide, Dr Morgan suggested a narrative that assembled all the relevant factors that were important for prospecting. It would take advantage of all the experience available, and provide a framework for the integration of qualitative experience-based information with the results of the model. In some ways, he said, it would be a reality check for the model. He suggested that if the model produced results that did not make sense to workshop participants, many of whom have significant experience in the formation of nodule deposits, then there was probably something wrong with the model and not the experience.

With regard to the geological model, he said he expected the end product to be a set of maps and tables that describe abundance and grade in the CCZ. He said that the model would have to be iterative; the application of different kinds of proxy data, perhaps in different ways, perhaps in combination. He also said that he had no doubt, that this effort, whether or not it turned out to be the best thing ever made, was definitely going to improve the international community's understanding of the polymetallic nodule resources of the region.

Finally, Dr Morgan presented an illustration of the quantitative effort that could be applied in model development. He informed participants that his illustration contained a lot of shortcuts that should not be used in the development of a real model. He stated that the proxy variable that he used for illustrative purposes was chlorophyll, his favourite variable. He also said that he had rotated the Pacific plate backwards for 42 million years until the deposits lined up under the equatorial maximum *(Figure 19).*

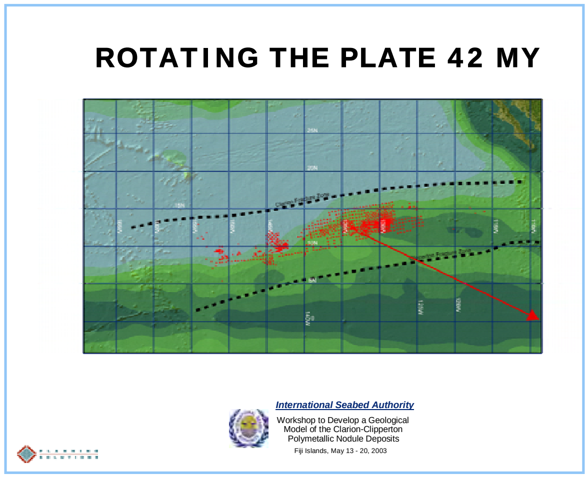

Figure 19: Rotate the Pacific plate backwards until deposits line up under equatorial maximum

Dr. Morgan said that he used this approach because he did not have enough time to do an actual time integration of what the real net primary productivity would have been over the past 20 million years. He described this approach as a quick way to embark on the proposed methodology. He said that he had completed the values for abundance using standard kriging methods, and then had compiled *Figure 19*. Dr. Morgan used *Figure 20* to show participants the database that he used, pointing out that it was the Ocean Minerals Company database, plus selected public data.

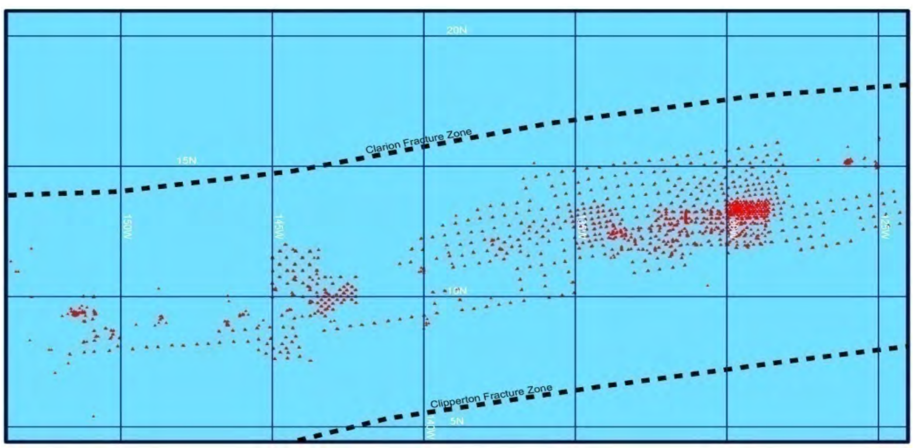

Figure 20: Available sample stations

He said that, because what is required for the illustration could be inferred throughout the whole CCZ, this was the dataset that he used. He said that normally, the data were clustered close to the station, because they were collected in that way, to eliminate a lot of the local variability, but that he did not do that because he wanted it to be simple. He said that through kriging, he then eliminated each point successively, and measured the distance between the kriged surface and the actual data. He then calculated another error surface, and picked as a threshold the median value of the data which, in this dataset, happened to be six and a half (6.5) kilograms per square metre. He said that if the uncertainty in the error estimate was larger than the median, then the data were probably not worth very much.

Dr. Morgan said that one would not know that much about abundance based on this dataset. He pointed out that he cheated a bit, because the data are clustered, and a lot of the local variants were eliminated, allowing one to get a much better picture. He pointed out that this was for the purpose of comparing the raw data with the co-kriging value. He described the process as a cheap proxy for actually integrating what the productivity would be if the Pacific plate were moved back about 20 million years, then moved forward slowly, and then integrated into every area in the region. He said that if afterwards co-kriging is performed with chlorophyll, a very similar map would be obtained, and that the key difference was that one obtained a much prettier picture because, using the proxy variable, one had a lot more data over the whole area. He said that because the data were correlated significantly with the primary productivity using chlorophyll , one found a great improvement in the knowledge of the area.

Dr. Morgan said that he was very optimistic that some progress would be made in developing the geological model using proxy variables. In summary, he said that to get a useful model, it would have to contain both quantitative and qualitative aspects. With regard to the qualitative aspect, he said that this was to ensure that those variables that are not utilized quantitatively, but have qualitative value are retained. He concluded his presentation saying that the workshop had several viable candidates for variables, and that efforts should be spent in identifying those to be used in the model and providing a method through which they could be developed into proxy variables.

SUMMARY OF THE DISCUSSIONS

Following Dr Morgan's presentation, the discussions focussed on the meaning of iterative, whether Dr Morgan had attempted to use chlorophyll concentration to verify grade and abundance estimates in the South Pacific Ocean, and whether he had used other variables for these estimates.

With regard to the meaning of "iterative", Dr Morgan said that it meant repetition. For the model, he said it would be involve running the model using a dataset, obtaining a set of results, modifying the model to improve it as appropriate, and repeating the process with another dataset. He emphasized the repetitive nature of the process and said that the model could not be established in one or two simple steps.

In relation to efforts that he might have undertaken using chlorophyll concentrations to verify nodule grade and abundance in the South Pacific Ocean, and whether he had used other variables, Dr Morgan said that the Clarion-Clipperton nodules are by no means unique. He pointed out there are other nodule deposits in the Central Pacific of similar composition, likely to have been formed by similar processes, and from which lessons may be learnt that would help in understanding the Clarion-Clipperton Zone nodules. Furthermore, in order to develop a model for projecting CCZ nodule characteristics, he said CCZ nodules have to be examined in terms of Central Pacific or grade-nodule-forming processes as a whole. He described potentially economic nodules as those enriched in nickel and copper, and said that it is those kind of nodules that are being sought in the CCZ He said that for the model, he would concentrate on these elements and Central Pacific nodules as a whole.

Dr Morgan informed participants that nodules enriched in nickel and copper, are generally restricted to areas in the Central Pacific basin, the Penryhn Basin, the Tiki Basin, and the Peru Basin. He said that all of these areas have nodules similar to those in the Clarion-Clipperton Zone. He noted however that there were subtle differences between them. He said that for model development it would be suitable to restrict comparisons to the areas in the Central Pacific basin.

With regard to nodule deposits in the Central Pacific basin, Dr Morgan pointed to their similar characteristics – that they were all on the flanks of the high productivity zone; they were separated longitudinally by island groups, or plateaus, in particular the Line Islands and some other topographic elevations; they all occurred at areas where nodules are most abundant and with the highest grades, and they all occurred at sea floor depths near the Calcium Carbonate Compensation Depth. Dr Morgan discussed each of these factors starting with known conditions in the Penrhyn Basin, where he had participated in a cruise. He said that he would try to extrapolate the conclusions from his work in the Penrhyn Basin to the other areas, and to see what it might offer in the CCZ.

With a map showing the Penrhyn Basin, Dr Morgan showed a transect of the cruise called the Aitutaki-Jarvis transect. He said that the cruise was designed to transect the Calcium Carbonate Compensation Depth, and take samples, as well as to traverse the high productivity zone, from low productivity zone in the South, to high productivity here in the North, at the Equator.

He showed dots, each of which represented a group of stations, providing data on nodules in relation to productivity variations, and nodules in relation to the calcium carbonate compensation depth. He said that several hundred samples were recovered, and he also provided copies of the analysed and unprocessed data. He said that the results indicate that manganese, nickel, copper and zinc tend to co-vary to the greatest extent. He also said that to understand this variability, other factors, which might influence the composition of the nodules throughout the region needed to be examined.

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CHAPTER 6 INTEGRATION OF GEOPHYSICAL/GEOLOGICAL DATA FOR THE RESERVED AREAS OF THE CLARION-CLIPPERTON ZONE: NEW PERSPECTIVES FROM CURRENT COMPILATION TECHNIQUES

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Introduction

This paper has been prepared to illustrate the range of data types and considerations required when preparing a data synthesis appropriate to the development of a geological model for the Clarion-Clipperton Region (CCR). It is not exhaustive, but by way of an introduction, it points the way forward to a methodology and strategy for obtaining the base geological context within which a model of deep seabed polymetallic nodule resources could be readily developed.

Integration of data types

We offer a review of the first order, that is, directly applicable datasets to the development of a geological model. Additional and equally relevant data and compilations will be considered below, but in less detail. Some general comments would be useful which apply to all datasets to be considered:

Analogue and/or digital data

It should be recognized that, in practice, it will be necessary to review the importance and suitability of both analogue as well as digital data. In many cases, older records provide the only control on our understanding of this enormous study area. Providing certain parameters to the data are acceptable in quality (such as navigation accuracy, for example), these data should be considered. There is no reason why paper record data, for instance, if appropriately quality controlled, should not contribute to the synthesis. A chart or even an interpretation figure from a publication can be scanned and geo-referenced so that it can be integrated into a data synthesis/analysis. We should be aware that much of the highly relevant early data which we know to have existed (such as from enterprises in the 1970s) may be effectively 'lost'.

It is also essential that any model developed remain flexible and adaptable. The very nature of the research process will dictate that the model will have to be organic. It is necessary for the result to be flexible in approach. Several iterations of the model or synthesis will be expected; for instance, the distinguished group of scientists gathered at the Authority from 13 to 17 January 2003 will not get it completely right, nor is it likely that the May 2003 workshop will achieve a final product, so adaptability is an important character of the model to be considered.

The model will have to be multi-scalar. The area we are dealing with is huge - in excess of 10 million square kilometres - so an approach should be arrived at on different scales. As elegantly demonstrated by Dr. Kodagali in his accompanying paper on nested scale investigations in the Central Indian Basin, we should recognize that different data type inputs relate to different scale of the processes we wish to consider within the model (e.g., multi-channel seismic reflection seismic profiler data is applicable to aspects of the model related to scales of tens to thousands of kilometres, in contrast with bottom photography's relevance to around 0.01 kilometre process). The model will also have to consider temporal/spatial variability and related parameters.

The model will have to be easy to use and accessible. The ability to operate, update and modify the synthesis/model is paramount, along with the need for ease of interrogation of the model. It cannot be only for a computer nerd to drive the bus - and it should be accessible to as wide a community as possible, in order that people feel a sense of ownership to it. I shall return to some ideas on this later - but we should consider the possibility of web-based access, and the implications of this for support of the work of the Authority. The model will have to merge as seamlessly as possible with current programs. Clearly the model needs to retain as high a level of compatibility with what exists - the countless hours of effort and significant expense invested in the current databases set up and presently run by the International Seabed Authority needs to be a high consideration.

Relevant aspects and results of the development of the model will have to be publishable and published. This is a requirement, not just as a laudable concept, but also to be presented as a requirement. The model will also have to be readily refined and a timetable set for revisiting and possible overhaul. The last two points are critical. Scientists will provide their input, effort and commitment, provided they could publish in peer-reviewed international literature and not internal reports. The one sure way to turn off the motivation tap is to restrict publication.

Definition of model objectives

- Requirements of community
- Fulfillment of the present goals
- Geological model for the International Seabed Authority and contractor exploration
- Scientific model for the wider community
- Base for development of holistic, multidisciplinary model(s)
- Models will be tested and revised
- Needs to have capability to fulfil future goals
- Needs to recognize its limitations

The community is at least twofold - this is very important - one that relates directly to the CCZ itself, that includes the International Seabed Authority and the marine scientific research community as a whole (which concerns itself with the evolution of deep ocean basins). The Authority has an opportunity to progress on both fronts, and to gain international support for its status as a technical initiating/support/championing body.

Generic data integration: studies for article 76 of the United Nations Convention on the Law of the Sea

In addition to maintaining an interest in the Authority's technical work, for at least the past six years, the Law of the Sea Geosciences Group at Southampton Oceanography Centre has been involved full time in work on a parallel section of the United Nations Convention on the Law of the Sea. Part 6 of the Convention, dealing with maritime jurisdiction, concerns itself with the continental shelf, its legal definition and a strategy for coastal States to claim their rights. In this capacity, we have worked closely with the Government of the United Kingdom and a range of coastal States in a technical advisory capacity.

Article 76 has a range of technical criteria that need to be addressed and combined into a legal framework. The potential for incorrect interpretation is large and, of course, costly. Sourcing and consistent interpretation of data is needed to determine case, existence or need to acquire additional data – itself a costly exercise. Development of data baselines for this work provides an excellent corollary for our present task.

A number of aspects have to be considered: resource evaluation; cost-benefit analyses; and evaluation of the potential financial return. The cost-benefit analysis is to help a coastal State to decide on its strategy/time considerations, in the case of nodules and the extended continental shelf the long look, but a clock ticking for the continental shelf.

Figure 1 presents a summary chart of extended continental shelf areas that have been identified as potentially claimable by coastal states as continental shelf under article 76 of the Convention.

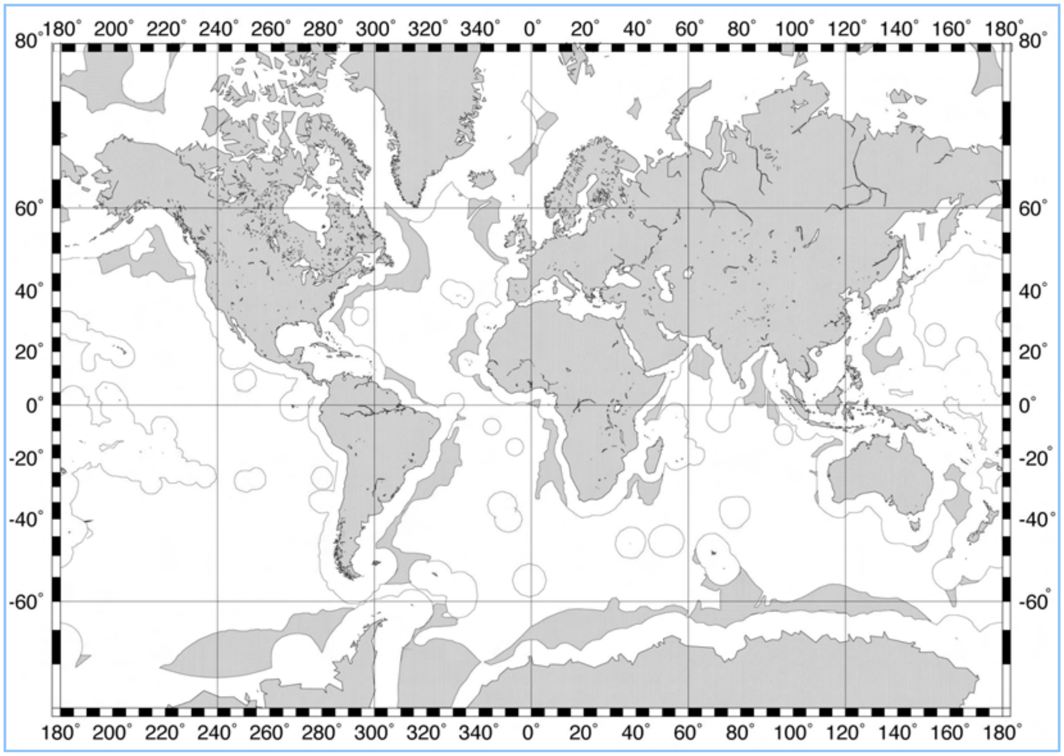

Figure 1: A generalized summary chart of the areas that have been identified as potentially claimable as continental shelf under article 76 of the United Nations Convention on the Law of the Sea.

All 50 or so coastal States involved need to make a fully substantiated territorial claim, supported by data they have compiled and/or collected. The process of synthesizing these various types of data is one, which the Southampton Oceanography Centre (SOC) has been through with a significant number of States with intentions of claims. Issues we have here that are relevant are key seafloor bathymetric features associated with conventional shelf morphology, data sources which will provide understanding of sediment thickness variations, and resource types and parameters - not nodules in this case, but critical input to the model.

Inputs to a broad/generic geological model

- Maximum access to data negotiated, exchanged, filtered, metadata;
- As early as possible, to acquire data on prior knowledge of the potential/realized data in advance of the May 2003 workshop;
- Estimation of shortfalls and remedial strategies;
- Scales of the model -spatial and temporal;
- Definition of the area - consistency of dimensions/parameters
- (or, maybe, access to maximum data – possibly the same);

In order to make the model meaningful, we need to support it with everything we can. We need to hope that the basic aspects of the model, such as bathymetry and morphology, are not considered as commercially sensitive by those in that field holding data.

We will need to address this at an early stage; delegates and attendees to the May 2003 workshop should be invited to bring data and to allow the data to be merged. I would propose that a notice to that effect be sent out to potential attendees, encouraging this and to strive to build up the compilation during the workshop. The meeting should have some form of a base understanding set up and ready to accept data. It would be a natural opening to the proceedings

This will itself highlight data gaps and requirements and allow development of a plan for addressing shortfalls.

Definition of the area

It is statistically important to constrain the lateral limits of the CCZ, since the two fracture zones deal with North and South. We need to normalize observations to a set area. I suggest 115 and 160 degrees West as longitudinal limits.

Data types for the geological context

- Bathymetry (E/S, M/B, analogue and digital compilation, satellite predicted);
- Gravity (marine compilation and satellite altimeter);
- Magnetics;
- Other geophysical - heat flow;
- Seismic (high resolution 3.5, SCS and MCS, reflection and refraction);
- Sample locations, including deep drill data;
- Backscatter and side scan (reflectivity and seafloor response/SRP);
- Bottom photography, including submersible and ROV results;
- Sediment type, reworking pathways and distribution, 2- and 3-D;
- Nodule analyses, variability and genesis;
- Miscellaneous oceanographic and biological;
- No data is too humble;
- No data should be assumed useless, (no navigation might be an exception) in an area where there is nothing else, one has to consider the analysis of the most unlikely of source;
- We have to recognize that we may not secure the ship time to address gaps in our knowledge base.

Extant databases – bathymetry

Digital bathymetric compilation, the GEBCO one-minute grid.
Use of control tracks;
Predicted bathymetry;
Comparison and cross-correlation of these and other sources;
Control and reliability - geostatistical análisis;

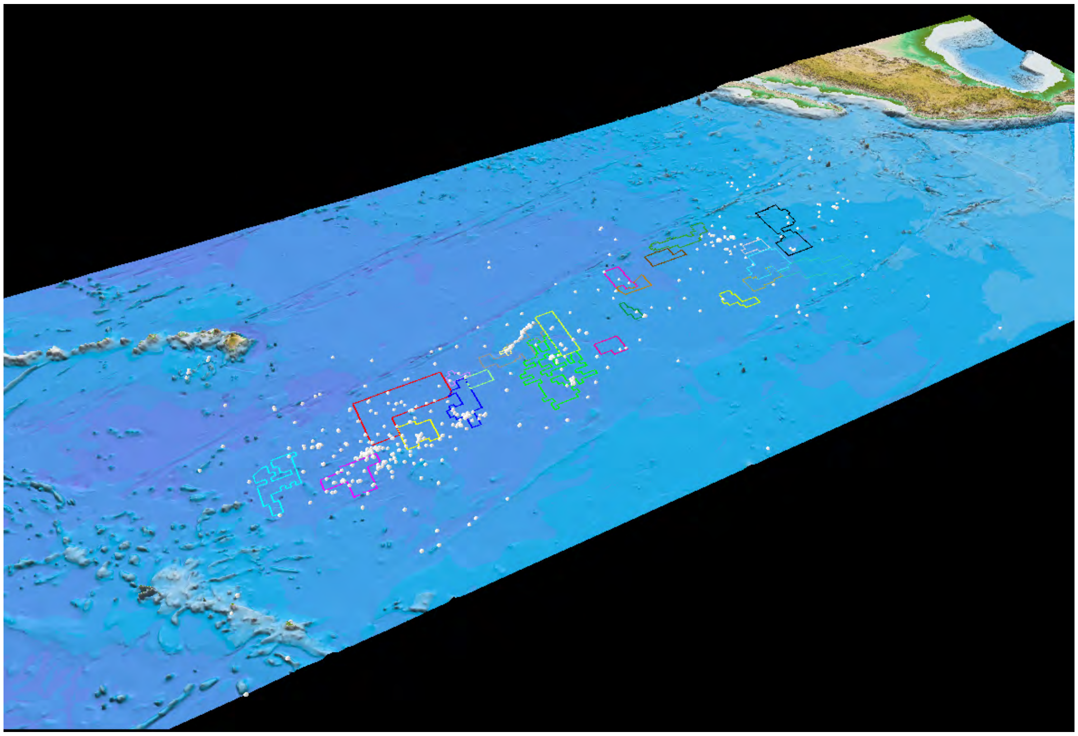

Figure 2: This perspective view is made up of a section of the unpublished digital bathymetry generated by GEBCO as a one-minute grid. It is overlain by the reserved area boxes for reference, and superposed with location points of the National Geophysical Data Centre's Global mineral sample database. (The scene is not meant to be definitive, and is provided purely to demonstrate a vehicle by which we might be able to synthesize data input to derive and refine our geological model).

This part of the global ocean database, which was completed by Mike Carron based at SACLANT, is derived from interpolation between proprietary data, as well as military and public domain tracks. Of course there will be areas where we can add swath control. We should consider this as an option to GEBCO. Involve them in what they do best - generating a background internally consistent bathymetric compilation.

I have added some of the control lines used to generate this chart to *Figure 3.*

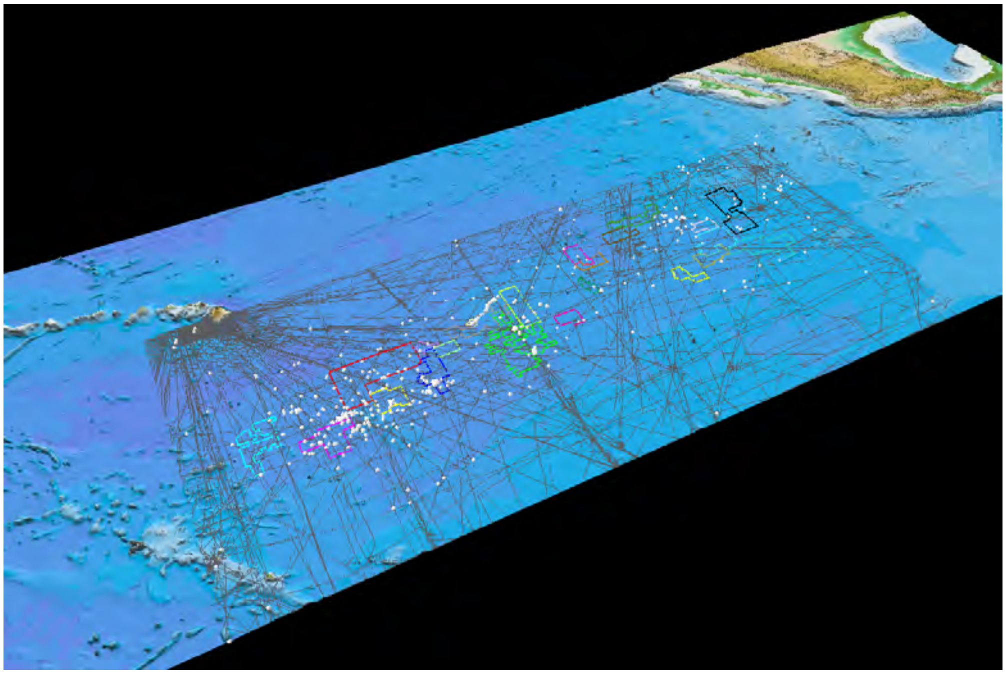

Figure 3: Addition of the navigation of control tracks (these are in the public domain taken and are taken from the GEODAS geophysical digital atlas source) complicates the view, but demonstrates the variance in density of data tracks.

Interrogation of the database can provide alternate overlays comprising solely bathymetry, or magnetics, or gravity, or seismic data locations - or any combination of these.

Not shown here is the predicted five-minute satellite altimetry derived predicted bathymetry of Sandwell and Smith (1995 and subsequent publications), or any other of the compiled public geophysical or geological datasets (some of which have already been referred to by other speakers). I shall come back to these datasets when I conclude the presentation with a short demonstration of a software package, which I think the Authority might find useful in its effort to develop a geological model for the CCR.

Calibration of the data/synthesis

- Groundtruthing
- Sites, distribution
- Control
- Track spacing, data Quality Assurance (QA)
- Confidence
- Semi-quantitative

Other geophysical data

- Satellite derived
- US National Geophysical Data Center (NGDC)
- Contractors
- Consortia
- Published and unpublished academia

- (Strategy to access)

Parameters derived from bathymetry

- Topographic -slope, variability, scaled roughness, bottom water current pathways
- Structural features -basement fabrics, different order crustal discontinuities, phases of crustal accretion
- Controls of sediment reworking

Samples

- Location and attribute databases (POLYDAT, US, NGDC, consortia and contractors)
- Biological

Integrated datasets

- Physical oceanography
- Fluid dynamics, water column/recharge
- Geotechnical
- Biological
- Geochemical
- Environmental
- Published interpretations/models

Methodology

- Fledermaus–demonstration of examples
- ArcView
- GMT
- VistaPro

Function of this part of the model

- Catalyst to initiative
- Frame to build from
- Provide means to inform and readily update
- Demonstrate compatibility of GIS
- Establish data shortfalls and priorities
- Publicise to ISA, LTC, leverage to government funding authorities
- Use W/S to consolidate data sources/access
- Post W/S implement integrated data frame
- Model is distributed to community, plus browser for use (and review/refinement)
- Model updated and new version distributed at intervals

Proposal

Issues

- Money

- Heroes/heroines
- Structure/umbrella
- Software browsers
- Willing contractors (and other commercial entities)

Summary and recommendations

- Four-stage framework model process
- Component of future thematic workshops
- Clear publication strategy
- Visibility through International Seabed Authority web –mpegs?

SUMMARY OF THE PRESENTATION

Dr. Parson began his presentation saying that he would combine bits of other presentations into one presentation, because most of it was derived from the presentation made in January at the meeting of experts. He also acknowledged that he had used the services of Allan Evans of the Southampton Oceanography Centre, as he was much more adept at merging datasets together than he was. Utilizing *Table 1*, he started his presentation on data integration.

Table 1:
The model 'frame'–data integration

- Analogue
- Digital -GIS
- Organic
- Multi-scalar
- Temporal/spatial
- Ease of use/Accessible
- Compatible
- Published
- Initiated and Refined

Dr. Parson said that for the purposes of the model, we were probably at the stage where most of the data had been acquired. He also said that one should not delude oneself by thinking that a lot more data was coming in; the odd research cruise might be managed, but what was in hand was what had to be worked with to achieve the product requested by the International Seabed Authority. He said this meant that the available data had to be used, provided they were the right quality. He noted that while analogue data that met the required quality were acceptable, digital data was preferable. He noted that some of the analogue data would be available, but the majority was not going to be up-to-date. Dr. Parson said the model had to be organic. Whatever was going to be built and however the data were going to be put together, the model had to be flexible enough to adjust to new data, or rather, old data that might not come until a couple years down the line. He said that the model had to be multi-scalar and capable of receiving multi-channel seismic data, which really had a resolution of a few hundred kilometers.

Dr Parson was of the view that the model should have both spatial and temporal appreciation. He said that in addition, the model had to be understood by a wide range of people, easier to use and to be visible and accessible to everyone. It also had to be compatible with the sort of stuff that had been developed before.

Dr. Parson suggested that since the scientists who were going to help to build this model would have to be compensated, the derivatives from building the model should be published. He said that this would assist in obtaining the support of national expertise and experts. He noted that the geological model would be useful for the Seabed Authority, exploration contractors and the wider scientific community. In this regard, he said that its benefits would not be restricted to the Clarion-Clipperton Fracture Zone but would find application to, inter alia, the Indian and the Atlantic Oceans. He said that this is because some of the processes to be examined would be generic.

Dr. Parson said that he was trying to show in a few slides the basic development of a multidisciplinary effort. He reiterated that with access to the reserved areas data, the model would be a good one, but that a way had to be found to access the additional data, whether through consortia, or through the contractors. He said that a relationship had to be developed between the Authority and scientists building the model, and contractors, or consortia to the extent possible.

Dr. Parson also spoke about metadata, which he explained as an understanding of where data existed. He said it wasn't necessary to have data *per se*, but to know where they were available. He said that in case gaps were found in the datasets acquired for the model, a way of remedying that situation would have to be found. He suggested that a new cruise to acquire the data would be highly unlikely.

Dr. Parson said that the geological model would be the earth model of the Clarion-Clipperton Zone. As far as bathymetry was concerned, he said there were different types and different resolutions. He referred to direct inputs from soundings and predictions from satellite altimetry data.

With regard to gravity and magnetics, Dr. Parson said that Dr. Yuri Kazmin had a tremendous compilation based on Yuzhmorgeologiya data and other of interpretations of how seafloor structure might affect the control of the sea-water-recharged minerals. He stressed the need to address all these factors in model development.

Dr. Parson was of the opinion that to calibrate what was seen in the predicted dataset, the new data needed to be calibrated, if possible, with the newest data. He said that this could be done using small portions of the contractor areas. He suggested to the Secretary-General that this might be a process that might start immediately, adding that the contractors would have to be reassured that the process was not a hijacking of their data.

Just as statistics were used for other data, Dr. Parson said he would also like to put colour on the bathymetry map as a way of indicating the reliability of the database. With the help of a clear figure, Dr. Parson showed the new one-minute grid of the bathymetry in the CCZ overlaid with maps of the reserved areas. Using a visualization process, he showed how best the data could be viewed.

Dr. Parson reminded the group about the scale factor in parameters relevant to the evolutionary process of manganese nodule formation. He pointed out that for example, topography was related to slopes; not just a slope relevant to the formation of manganese nodules, but slopes that were mineable. Another example provided by Dr Parson related to the roughness on the sea for scaling. In this regard, he asked **h**ow this affected the distribution of manganese nodule accumulation. In the same vein, he asked how topography controlled or affected current distribution. He pointed out that current pathways are important in terms of feeding or redistributing mineral resources via dissolved elements to the final site, producing deposition as a nodule deposit.

Dr Parson said that the model was not going to be focused on the plains but that it had to go up to the water column. He said the model would have to capture processes at the seafloor as well as the sea surface. He also said the model should also indicate where the delivery to the Clarion-Clipperton Zone is initiated.

He showed some examples of the fly-by visualization of the bathymetric data on which several parameters were superimposed. He said there were many ways to visualize data, and that he was only going to show one, because in his opinion, it was a very smart way of looking at three dimensions in a relatively straightforward way.

Dr. Parsons showed some generic datasets. On the seafloor, he overlaid several other datasets. He thought this would be a good way to start putting the model together. Starting from the coast, he indicated the part of the seafloor on which data tracks were laid. He showed how the resolution could be changed and how it would depend on the density and reliability of the datasets. He incorporated the predicted bathymetry from satellite gravity, the 2x2 minute grid data, and others. However, he said that this was only good for a general impression.

He also showed a visualization of the Clarion-Clipperton Zone with the reserved areas and the contractor areas. Then Dr. Parson showed how through visualization, issues such as non-repeatability, cross-errors, etc., could be solved.

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CHAPTER 7 GEOLOGY OF THE CLARION-CLIPPERTON ZONE: EXISTING GEOLOGICAL INFORMATION IN RESPECT OF POLYMETALLIC NODULES

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Introduction

The development of a geological model of the Clarion-Clipperton Fracture Zone (CCZ) is proposed to establish the spatial trends in nodule distribution and grades due to reasons of natural factors along the CCZ and to facilitate a better understanding of the interrelationship between geological processes and formation of nodule deposits. The model should help to facilitate nodule assessment in the areas with scarce data by means of analogy or mathematical simulations (by conventional or geostatistical methods) on the basis of interpolation of available data. Moreover, the geological model of the CCZ will be important, not only for the purpose of establishing the interaction between geological and related parameters and nodules resources in the reserved areas in the CCZ, but also for the purpose of understanding the geological processes and environment which has led to the development of the most prominent polymetallic nodules province on a global scale.

A concept of a geological model of the Clarion-Clipperton Zone is to be considered in connection with nodule resource assessment of the CCZ on a global scale. The concept may be understood through the analysis of factors influencing such nodule parameters as growth of nodules, supply and concentration of manganese, nickel, copper, cobalt and other economic metals, and accumulation of high-grade and high-abundance nodules which leads to the formation of deposits.

Therefore, as a first step the required polymetallic nodule parameters for the zone as a whole (not only for the reserved sites) shall be derived from the data and information for both reserved and other areas as a result of analysis and processing of the existing database which should include the available data in the public domain as well as unpublished information accumulated in the Secretariat and by contractors.

As a next step, a review of the known relevant factors shall be carried out in order to establish their interrelationship with the above parameters to select the factors which have influenced the formation of the nodule resources of the CCZ.

Once such a relationship is established, it will serve as a basis for different variations of mathematic models which may be constructed with the purpose of possible quantitative and numerical evaluations of the controlling role of various factors.

Mathematical simulation may be constructed for the areas with different density of information in order to understand the predominant trends in the CCZ as a whole and to facilitate the resource comparison of various reserved sites.

The components of a geological model will be primarily defined by the Authority's task of assessing the polymetallic nodules potential of the CCZ as a part of the Area in general and of the reserved sites in particular. They should include natural factors which influence such nodule parameters as growth of nodules, supply and concentration of manganese, nickel, copper, cobalt and other economic metals, and accumulation of high-grade and high-abundance nodules which leads to the formation of deposits.

The basic parameters of polymetallic nodules in the CCZ shall constitute an integral part of a geological model. They include primarily:

- Nodules population, nodules abundance and their spatial distribution;
- Contents of metals of economic interest (nickel, copper, cobalt and manganese) in nodules;
- Types of nodules, nodule facies;
- Existence and spatial distribution of nodules deposits with high-grade and high- abundance nodules.

The most important components of the geological model for the above-mentioned purposes will be factors relevant to formation of nodule deposits. A low rate of sedimentation was considered to be one the major factors controlling the process of nodule growth. Other important factors include climatic zonality; bathymetry and seabed topography; the supply of nuclei, their size and composition; seawater composition physical parameters and geochemistry of the seawater column; existence of such oceanographic layers as the oxygen minimum zone and the carbonate compensation depth; paleo-currents and bottom currents; biological productivity in the water column; composition of underlying sediments; the proximity to volcanic activity and to discharge sources of terrestrial material from landmass into the ocean; age of underlying sediments and oceanic crust. It was noted that high Ni, Co and Co concentrations in nodules are generally associated with siliceous surface sediments, and less with red pelagic clays.

These factors were discussed during the meeting of scientists convened by the International Seabed Authority in Kingston from 13 to 18 January 2003. Although arguing on the importance and the role of various factors the participants of the meeting agreed that the following factors are relevant to nodules formation and their grade:

- Water depth and seafloor topography ;
- Crustal history including plate motion; tectonics and volcanic activity;
- Paleo-environment and sedimentation history (including composition and thickness of sediments, rates of sedimentation, existence of upper transparent layer, sediment digenesis, biological paleo-productivity);
- Water column characteristics (chemical and physical structure, currents, benthic activity, etc) ;
- Nodule genesis and other theoretical aspects of nodule formation and metals accumulation nodule growth, accumulation of metals, source of material, etc).

It should be pointed out that those factors are different in nature and scale. No common view exists with respect to the role of such factors and their relationship. It is obvious that many factors belong to various disciplines. Some of them are purely geological. However, many factors belong to the nodule formation processes which were considered as part of oceanography since the basic environment of nodule formation is the water column. For the polymetallic nodules, which have been growing for a million years as a result of sedimentary processes, the oceanic water column represents a key geological aqueous environment. Therefore, all oceanographic factors relevant to the formation of the polymetallic nodules shall constitute the integral part of a geological model of the CCZ and are to be considered together with other geological parameters.

One very important condition is to have a common understanding on a scale of a geological model of the CCZ to be developed. The Clarion-Clipperton Zone itself is a global geographical and geological province of the ocean floor in the Pacific. The length of the zone is about 5,000 km; its width reaches up to 1,000 km. By its dimensions, it certainly should be considered as an area of a global nature and scale. Geologically, the CCZ crosses important planetary features of the Earth's crust: the East Pacific Rise and the Pacific crystal plate. The oceanic crust of the CCZ dates from 65 in the west to 10-20 million years in the east. Geologically, the CCZ is also an important global structure of the ocean floor. Therefore, it is suggested that a geological model for the CCZ as whole be considered as a model on a global scale and be called a global geological model of the CCZ. Some researchers have subdivided the CCZ into several parts or regions. For the sake of consistency, it is proposed to follow such a subdivision and to consider a geological model for each part or the region of the CCZ as a model on a regional scale or a regional geological model, which is typical for several reserved areas. With regard to single reserved areas or blocks, it is suggested that a scale of a geological model be considered as subregional or local, depending on the dimensions of reserved blocks. The term "geological model on a local scale" could be used for single reserved blocks, limited areas with certain geological environment, and for a single nodule deposit.

Since the main objective of the project is the assessment of nodule potential of all reserved sites, we shall speak about a geological model of the Clarion-Clipperton Zone on a global scale, since the reserved sites are located within the total extension of the zone (*Figure 1*).

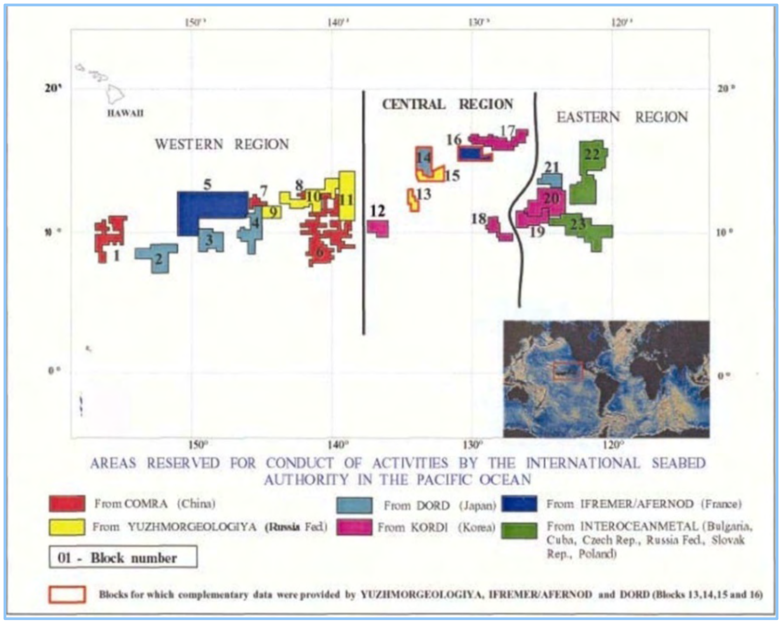


Figure 1: Location of the reserved areas (from the ISBA Secretariat Background Paper for Meeting of the RPIs, 26-30 March, Kingston)

At the same time, it has been indicated that the important factors, which will be the components of the model, are different in nature and scale. Some of them have a planetary or global effect; many are regional or local and can be better investigated and understood within certain areas limited in size. It is therefore suggested that the development of a global geological model of the CCZ might be a process of examining certain parameters and factors on a global scale in parallel to the development of geological models of nodule formation on a local scale with further interpolation of their results throughout the CCZ as a whole. That could be achieved through case studies on nodule deposits and components of a geological model of nodule deposits on a local scale in selected areas of the CCZ.

In this paper the author presents a brief review of some basic parameters related to nodule population and abundance, as well as to spatial distribution of nodule concentration of metals of economic interest (nickel, copper, cobalt and manganese). The existence and spatial distribution of nodule deposits with high-grade and high- abundance nodules in the reserved areas is also considered.

Due to a global scale of the review and lack of sufficient data and information, many considerations and conclusions contained in the paper should be considered as suggestions or assumptions, rather than proved or established factors and parameters. But the aim of the paper is to draw attention to the existence of certain trends and their importance. Their further research and establishment will be the task of a future geological model of the CCZ on a global scale, which is to be developed under the Authority's aegis.

Historical background

Substantial literature and published data are available with respect to polymetallic nodules, including those in the Clarion-Clipperton Fracture Zone. There have been attempts to analyse various factors in order to establish relevant trends on a general and regional level, which can be considered as valuable inputs to a CCZ geological model.

In 1967, Wyrtki studied the circulation of water masses in the eastern equatorial Pacific and established special trends of an oxygen minimum layer in the region covering the CCZ.

In 1973, Tjeerd H. van Andel and G.Ross Heath summarized the geological results of Leg 16 of the Deep-Sea Drilling Project in the Central Equatorial Pacific Ocean, including the CCZ. Five drill sites (DSDP 159 – DSDP 163) are located within the CCZ. The DSDP helped to clarify the tectonic and depositional history of the region and to establish basement ages. The authors were the first to compile a tectonic sketch of the region, including the CCZ, which showed (together with the location of drill sites) magnetic anomaly patterns, position of fracture zones and extinct spreading centres (Mathematicians Ridge).

P. Halbach *et al*. (1977) studied the morphology, size and composition of manganese nodules in the CCZ and distinguished three groups of nodules: *Group A* - large nodules of regular shape with a cumulative content of Mn + Cu +Co averaging 2.5-3.5% (Mn/Fe >4); *Group B* – smaller aggregated nodules of irregular form with cumulative content of Mn + Cu +Co less then 2.5 (Mn/Fe<2.5) and *Group AB* - transitional type nodules with Mn + Cu +Co content 2-3% (Mn/Fe =2.5-5.00). These groupings have been used since most researchers of the CCZ use a genetic and morphological classification of the CCZ nodules in relation to hydrogenous and diagenetic processes of nodule formation. It should be noted however that various scientists used different names for the groupings.

Diamond *et al.* (1982) produced a model, establishing a correlation between manganese nodule composition in the CCZ with hydrogenous precipitation, and oxic and suboxic diagenesis. A similar model was developed later by Knoop, Owen and Morgan (1998) on the basis of a geochemical analysis of more than 5,000 manganese nodule samples from the CCZ.

The work of Krishnaswami *et al*. (1976, 1982) contributed to the understanding of the growth rates of the nodules, including those in various parts of the CCZ.

Martin (1980, 1985) conducted studies to explain the metal sources and suggested substantial manganese fluxes to the CCZ, moving with the surface currents to the west from the continent.

Reigh and von Graftenstein (1987) carried out research in order to establish sedimentological and geochemical trends in deep-sea sedimentation of a part of the CCZ.

A considerable amount of data on the CCZ was collected and analysed by the Russian enterprise Yuzhmorgeologia in 1980-1990. This work was used for geological and other related models of the Russian pioneer area. Much information had been used to obtain an understanding of nodule formation processes and geological considerations of the CCZ as a whole (Kazmin *et al*., 1984; Kazmin (ed.) 1984; Korsakov (ed.), 1987; Yubko et al., 1987, 1992).

Important research to establish the interrelationship of nodule formation and grades in the CCZ was undertaken in 1987 by O. Korsakov, V. Yubko *et al*. (Russian scientists) in their publication on the trends of nodule distribution in the World Ocean (Korsakov, ed., 1987). In fact, it may be considered as one of the first attempts to develop a geological model of the area and to understand nodule parameters of the zone on the basis of geological and oceanographic environment and anomalies. In 1990, V. Yubko *et al*. reviewed and analysed nodules distribution and grades in the CCZ in relation to its geological structure and environment.

In 1988, French scientists undertook the study of three small nodule areas in the Central region of the CCZ during the *Naudinaut* diving cruise with the submersible *Nautile*. The results of the study, which were presented by M. Hoffert (who participated in the dive) at the International Seabed Authority meeting of scientists in January 2003 in Kingston, contribute much to the understanding of nodule genesis and sedimentary environment.

A kind of a geological model for four reserved sites in the central part of the CCZ (blocks 13, 14, 15, and 16) was presented in the study "Preparatory work in the International Seabed Authority's reserved area by the three pioneer investors IFREMER/AFERNOD (France), Yuzhmorgeologiya (Russian Federation) and DORD (Japan) which was compiled in 1991. The study described oceanographic, biological characteristics of, bottom geomorphology, geology, and nodule types and discussed factors related to the nodule formation and metal grades.

In 1991, Von Stackelberg and Beiersdorf developed a geological model of nodule formation for some small sectors southeast of Hawaii, having analysed various geological and oceanographic factors related to nodule genesis. They established a correlation between acoustic and nodule facies, as well as sedimentation anomalies in the CCZ that are characterized by the existence of "hiatus" between Early Miocene and Late Pliocene due to the intrusion of the Antarctic Bottom Currents.

An attempt to create a geological model of the CCZ on the basis of a multifactor and interdisciplinary approach was undertaken by S. Andreev (1994) in his comprehensive publication. He analysed and summarized some data and information on manganese nodules in the CCZ, which had been received during research and prospecting activities of the Russian institutions (Sevmogeologiya and VNiioceangeologiya) in that area before 1982. A geological scheme of the CCZ as a whole had been proposed and was later reproduced in "Explanatory note to the Metallogenic map of the World Ocean published in 1998 by the Russian VNIIoceangeologia and Interoceanmetal Joint Organization.

The model attempts to establish trends in nodule population and metal concentrations in the CCZ in connection with factors such as: the age and type of the underlying crust; fracture and fault systems; age, thickness and composition of underlying sediments; seabed topography and landscape; the interrelationship between nodule types (with respect to their metal contents) and the location of the carbonate compensation depth in various parts of the CCZ. Andreev pointed out that in the eastern part (east of 123°W), a latitudinal spatial variability of morphological-genetic types of nodules is observed, which is probably connected with volcanic activities in the transitional zone to the East-Pacific Rise the eastern part of the CCZ.

One of the major contributions to the geological model of the CCZ was made by C. Morgan (2000) in his publication on resource estimates of the CCZ nodule deposits. The author analysed some basic factors in relation to nodule distribution and formation. Nodule growth and metals supply processes were considered. The author presented a genetic model that connected manganese concentrations in the CCZ with chlorophyll concentrations in the surface waters of the zone. The overall resource calculations were produced from kriging analysis. The publication contains schematic charts for spatial distribution of nodule abundance, the metal contents of manganese, nickel, copper and cobalt, as well as chlorophyll concentrations within the CCZ.

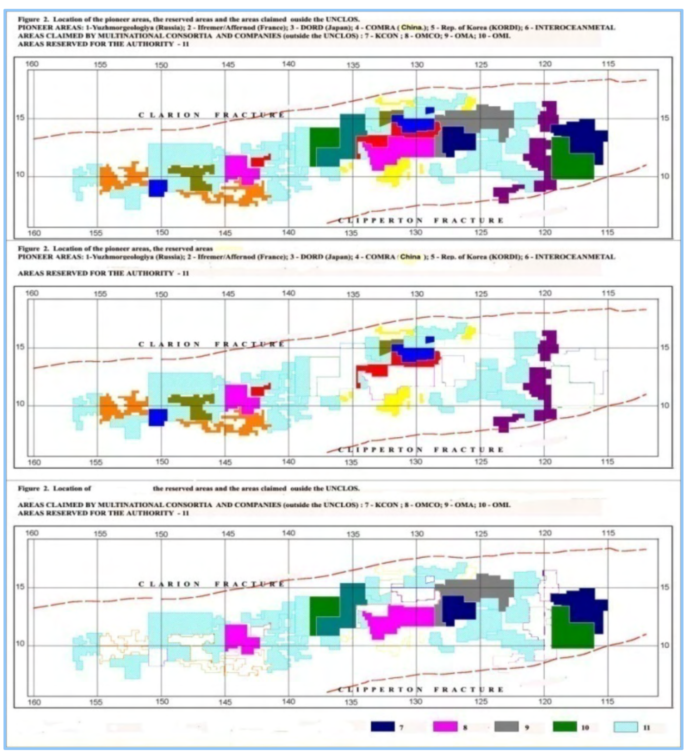
Morgan's publications (1993, 2000) will be of high value for a geological model of the CCZ, since his analysis and compilations are based on a scientific study of the large unpublished data from the database of Ocean Mining Company (OMCO), which, together with three other multinational consortia, carried out intensive research and prospecting activity across vast areas of the CCZ. That allowed the author to provide some valuable information on a rather large area in the central part of the CCZ, which otherwise is unavailable for the Authority and the scientific community. Most of the data collected by those entities are still considered to be of a proprietary nature.

The French research institute IFREMER developed some numerical models for its pioneer area for reconstruction of the mining environment and possible mining fields within a hypothetical nodule deposit (Lenoble, 1996). The model was based on factors such as topography, nodule facies and mining requirements (based on selected mining technology). It is useful for resource assessment of nodule fields and deposits on a local scale. In 1997, the Secretariat of the International Seabed Authority (ISA) reviewed and analysed the data submitted by the pioneer investors for the reserved areas (23 blocks) in the CCZ, as contained in their applications. The available site-specific data on nodule abundance and metal content of Manganese (Mn), Nickel (Ni), Copper (Cu) and Cobalt (Co) were incorporated into the ISA's database POLYDAT, which allowed for the production of associated maps showing the location of sampling sites, nodule abundance, and metal content of the four metals separately. A map showing the spatial distribution of nodule deposits of various grades has been also compiled.

This work of the ISA Secretariat was continued on the basis of geostatistical analysis. The study revealed some anomalies in variations of nodule abundance and metal grades in various reserved blocks which might be either attributed to natural factors, or considered as discrepancies between data the data submitted by the pioneer investors due to differences in sampling and analytical methods and techniques. Discussion of the problem revealed the need to consider various geological and oceanographic features in order to understand the nature of such variations. The method suggested was through the development of a geological model of the zone as whole on the basis of available information.

Data sources

The first step to developing a geological model is to identify the availability of necessary data and information and their possible sources. Although some data may be found in academic institutions and in the public domain, the main sources of data for a geological model are still the registered pioneer investors, contractors and other industrial entities, which were previously engaged actively in nodule research and prospecting within the CCZ (*Figure 2*).



These include the six registered pioneer investors (IFREMER/AFERNOD of France; DORD of Japan; Yuzhmorgeologiya of the Russian Federation; COMRA of the People's Republic of China; the Interoceanmetal Joint Organization of Bulgaria, the Czech Republic, Cuba, Poland, the Slovak Republic, Russia; and KORDI of the Republic of Korea), which started and are continuing nodule projects under the framework established by the United Nations Convention on the Law of the Sea.

The other entities possessing appropriate data are four multinational consortia which claimed their sites for nodule development in the CCZ under the unilateral legislation of the United States of

Figure 2: Location of sites in the CCZ

America: the Ocean Minerals Company (OMCO), Ocean Management Incorporated (OMI), Ocean Mining Associates (OMA) and the Kennecott consortium (KCON)[1].

The first kind of data that should be used for the project for the CCZ is that of the six pioneer investors, which were submitted for the reserved areas at the time of their registration (*Figures 1 and 2*). This is the most important dataset at the disposal of the Authority.

In addition, for the reserved areas in the Central region (blocks 13, 15, and 16), some additional information was provided by IFREMER/AFERNOD, DORD and Yuzhmorgeologiya in 1991 in their report on the preparatory work in these blocks.

In 2001, additional data and information were provided by IFREMER/AFERNOD at the request of the Secretariat, which represented a 20% increase in the Authority's database for the reserved areas.

At present, the Authority's database POLYDAT contains a total of 2,785 sample stations which have been used in the Secretariat's geostatistical evaluation of nodule resources in the reserved areas. In general, the POLYDAT data for the reserved areas does not present a total picture of the CCZ, although it provides certain orientations for establishing trends along the CCZ on a global scale. It should be noted that the number of sample stations varies greatly from one block to another. The sampling grid for different blocks varies from 12.5 x 12.5 to 60 x 60 km. The difference in sampling density in various blocks is well illustrated in *Figure 3*.

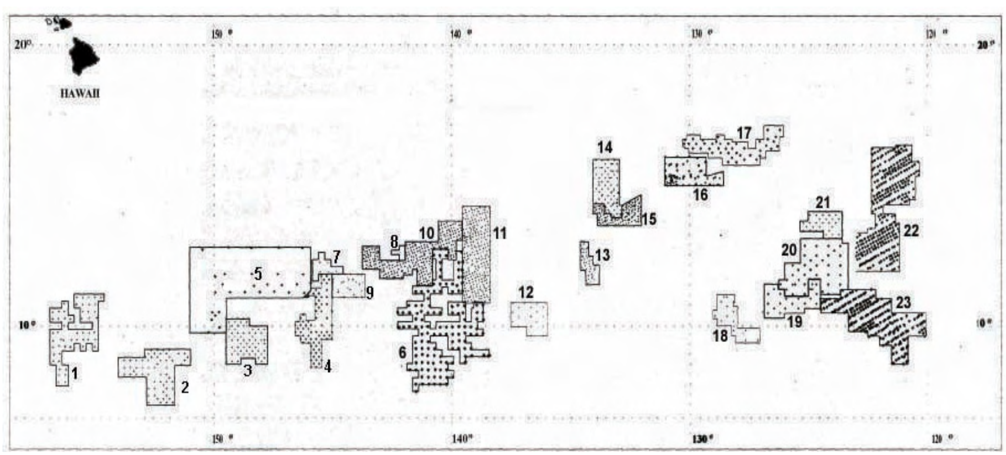


Figure 3: Density and location of sampling stations in the reserved blocks (modified from the background paper of the ISA Secretariat "Analysis of Discrepancies Between the Data Sets Submitted by the Pioneer Investors" submitted to the RPIs meeting (28-30 March 2001, Kingston)).

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1. Ocean Minerals Company, formed in November 1977 with Amoco Ocan Minerals Company (Standard Oil of Indiana), Lockheed Systems Company, Inc., (Lockheed Aircraft Corporation) and Ocean Minerals Inc., (Royal Dutch/Shell Group).

Ocean Management Incorporated (OMI), formed in February 1975 with Inco Ltd of Canada. A,R (Metallge-sellschaft AG), AMR (Preussag AG and Salzgitter of the Federal Republic of Germany), Sadco Inc of the USA and Deep Ocean Mining Company Ltd (DOMCO) of Japan

Ocean Mining Associates (OMA), formed in May 1974 with Essex Minerals Company of US Steel Corporation, Union Seas Inc of Union Minière SA of Belgium, Sun Ocean Ventures of Sun Company Inc., and Samin Ocean Inc of Ente Nazionale Idrocarburi (ENT) of Italy.

Kennecott Consortium (KCON), formed in January 1974 with Kennecott Corporation of Sohio, RTE DeepSea Enterprises Ltd of Rio Tinto-Zinc Corporation Ltd, Consolidated Gold Fields PLC of the UK, BP Petroleum Development Ltd of British Petroleum Company Ltd, Noranda Exploration Inc of Noranda Mines Ltd of Canada and the Mitsubishi Group comprising Mitsubishi Corporation, Mitsubishi Metal Corporatin and Mitsubish Heavy Industries Ltd; all of Japan.

The second important dataset that could be used for the development of a geological model of the CCZ is the data for the allocated pioneer areas which were submitted by the same six pioneer investors in their original applications at the time of their registration and the allocation of their pioneer sites. This database is in the possession of the ISA Secretariat, but is still treated as confidential proprietary information. Therefore, it cannot be used without the consent of the contractors; but the possibilities and modalities for utilizing these data for the geological model should be explored and negotiated. However, this dataset should be used for the analysis of seabed bathymetry and topography, since such information is not of a proprietary nature and its use for the project cannot harm the commercial interests of the pioneer investors.

The area covered by this kind of data is illustrated in *Figure 2*. It may be assumed that the quality and density of these data will be similar to those for the reserved areas because of the procedure outlined in the United Nations Convention on the Law of the Sea for the selection of reserved sites by the Authority. The exception may be sites in the central zone which were selected by IFREMER/AFERNOD, DORD and Yuzhmorgeologiya.

The third type of data, are those possessed by multinational consortia such as OMCO, OMI, OMA and KCON that are important and numerous. Their claim sites are large in size (*Figure 2*). The OMCO database alone includes more than 8,000 sample stations. Although these entities have discontinued their nodule activities in the CCZ due to the market situation, their data are still treated as confidential and proprietary and the possibility of their use in the Authority's project on a geological model of the CCZ is speculative.

A precedent for utilising these kinds of data was established by Charles L. Morgan, who was allowed to use the OMCO database for scientific study in 1991 and who published his results in some publications. More than 8,000 sample stations of that database were used by the author for the scientific study of nodule deposits in the CCZ.

In total, the data concentrated in the hands of these former industrial entities are very valuable, since their claim sites are large in size and constitute vast areas in the central and eastern regions of the CCZ (Figure 3). In any case, an attempt should be made to find a way to use such data for scientific purposes, provided that it is not possible to use the published material to derive the original dataset.

The fourth type of data are those that were collected by the pioneer investors for other areas within the CCZ, but which were not part of their applications for pioneer areas. It is obvious that, in order to select their application sites, the pioneer investors had to investigate and prospect areas within the CCZ that were much larger than their application sites. Since the obligation of the pioneer investors under the Convention on the Law of the Sea regime was to present to the Authority only the data for the designation of pioneer and reserved sites, the data for the areas outside those areas were not submitted to the Authority and might still be in the possession of the contractors.

It may be the case that some domestic data classification regulations are still an obstacle for the release of such data to the Authority. It is suggested that the appropriate consultations be held with the contractors to find out the type and amount of data that they possess for the areas outside their pioneer sites and to negotiate the terms and conditions for the possible use of their data, if any exist, for developing a geological model. The same approach may be applied for such data to be used for scientific purposes, provided that it is not possible to use the published material to derive the original dataset. For instance, some important maps and other relevant material on nodule abundance and grade of nodules within the CCZ on a global scale were compiled by Yuzhmorgeologiya as a result of the processing and analysis of the Yuzhmorgeologiya dataset for the CCZ. They may constitute a valuable contribution to the geological model of the CCZ as a whole.

Another source of data may be the information and data of national academic institutions and various national and international data centres. Substantive study should be undertaken to identify the data and information necessary for the development of certain parameters and components of the model and to identify scientific and public data sources for acquiring available data and information.

For the purposes of this study, we used the ISA Secretariat's POLYDAT data, Morgan's publication on the CCZ nodule deposits (*Figure 4*) and some of Yuzhmorgeologiya's analytic material on nodule distribution and grade (*Figure 5*) in the CCZ (courtesy of Yuhzmorgeologiya, 2002).

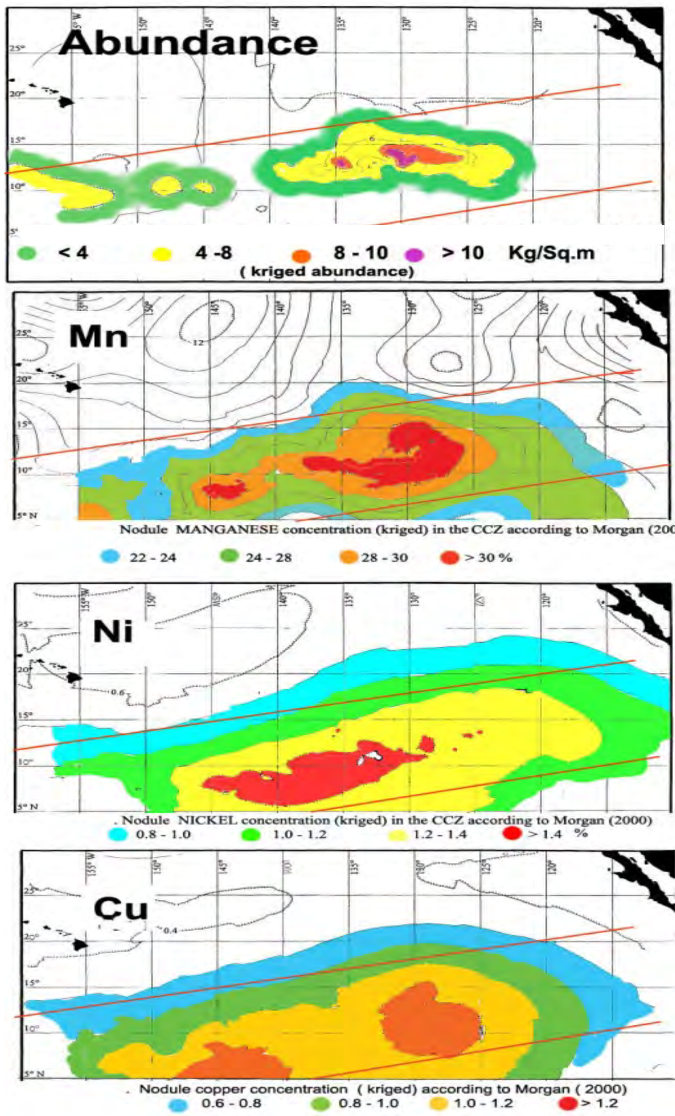


Figure 4: (at left) Nodule ABUNDANCE and MANGANESE, NICKEL and COPPER concentration in the CCZ according to Charles Morgan (2000)

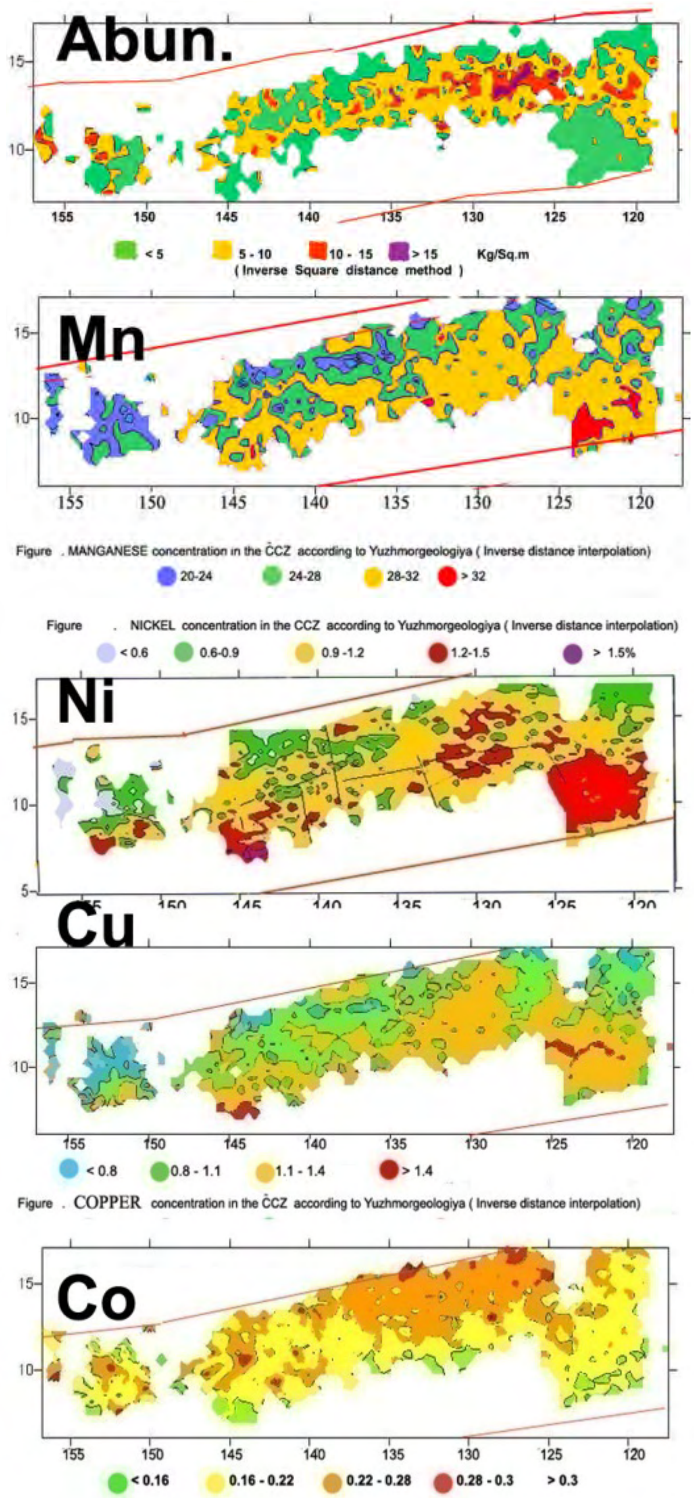


Figure 5: (at right) Nodule Abundance and Concentration of Mn, Ni, Cu and Co according to Yuzmorgeologiya

Ocean floor morphology

The CCZ is an abyssal basin with a length of 4,000 km and a width of up to 800 km. The water depth varies from 3.5 km in the east to 5.5 km in the western part. The westward increase of the depth is related to subsiding of the earth's crust due to the increase in the density of the lithosphere as a result of the plate spreading away from the spreading centre and cooling of the upper mantle

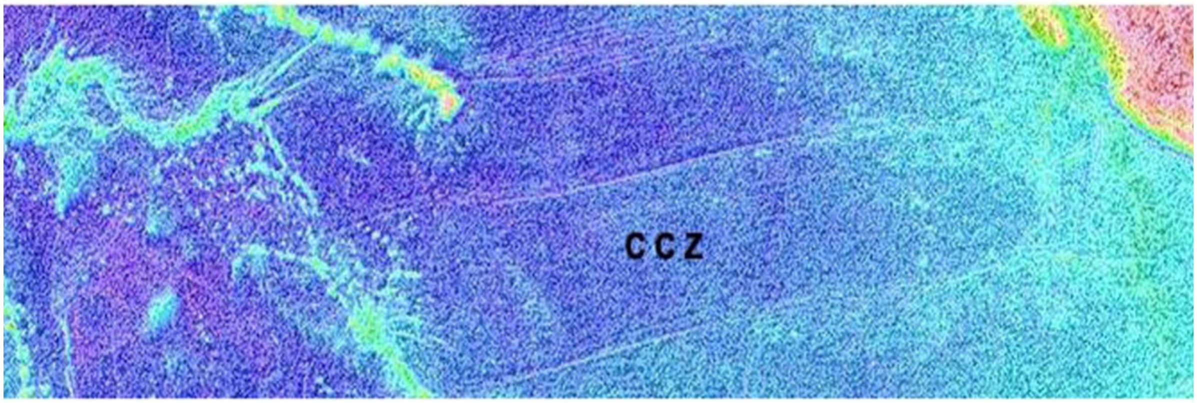


Figure 6: Satellite altimetry image of the CCZ (from W. Smith and D. Sandall "Global Seafloor Topography from Satellite Altimetry", NOAA Satellite & Information Services, National Geophysical Data Center)

According to the prevailing concept, the bathymetric interval of the CCZ on a planetary scale is favourable for nodule formation and accumulation of metals from the point of view of the geochemical structure of the ocean water column and the existence of a critical layer – the carbonate compensation depth. Thus far, it has been established that nodule population on a regional scale is continuously spread over the entire seafloor of the CCZ at various depths. Bottom relief is predominantly abyssal hilly plain with lows and highs of variable size and elevation. It is generally defined by the topography of the volcanic substratum. The latter was formed as a result of volcanic activity and fracturing by various fault systems. Therefore, the seafloor morphology is important in understanding the geology of the CCZ in general and nodule geology in particular.

The only existing data source on the topography of the CCZ on a global scale is the General Bathymetric Chart of the Oceans (GEBCO). The map as represented in *Figure 4* is a GEBCO bathymetry map modified by Yuhzmorgeologiya in 1990 on the basis of additional bathymetric data collected from various sources in the public domain, as well as from their own hydrographic surveys during various cruises conducted in the 1970s and 1980s.

In addition, the topographic structure of the CCZ on a global scale may be also imaged from satellite altimetry (*Figure 6*).

As a result of the analysis of all available information, we compiled a sketch map showing the topography of the CCZ on a global scale, which allowed for a better understanding of trends and correlations that are important for interpretating the nodule geology of the CCZ (*Figure 7*).

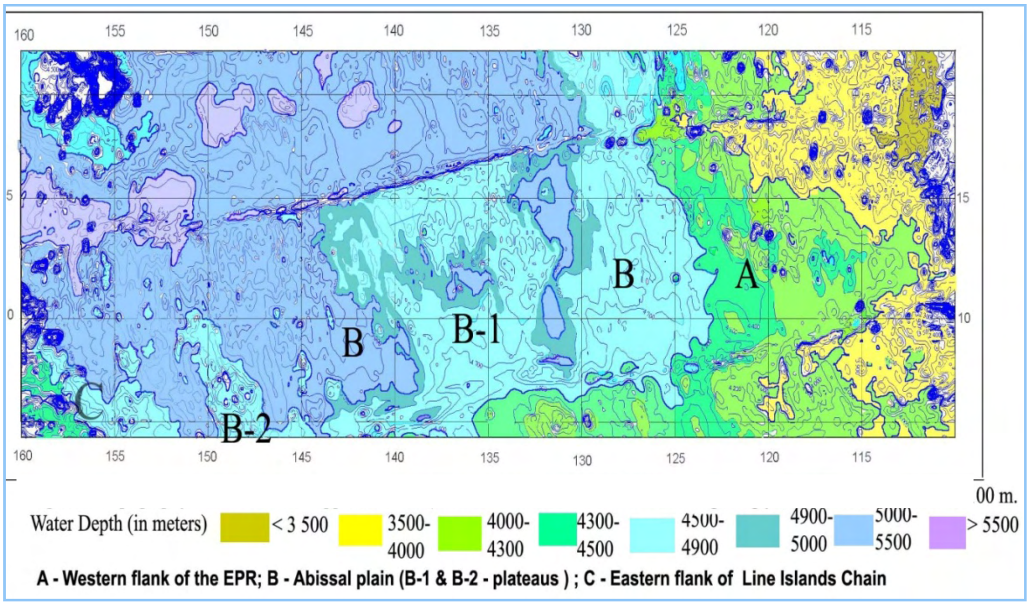


Figure 7: Topography of the Clarion-Clipperton Zone (modified from GEBCO & Yuzmorgeologiya, 1990)

Geologically the CCZ is located within (westward): (1) the western flank of the East Pacific Rise; (2) the abyssal plain; and (3) the eastern flank of the volcanic Line Islands Chain).

Many researches consider that bottom relief has a strong influence on nodule abundance and grade. There is a general concept that the highest abundance of nodules is generally associated with high relief. It is explained by the availability of more nucleating material originating from volcanic activity or by the weathering process of basaltic rock. On the other hand, in many parts of the CCZ, no correlation was observed between nodule occurrence and the depths of the ocean floor or with its morphology.

One of the first objectives of the geological model is to establish within the CCZ the relationship between nodule abundance and grade and the depths of the sea bottom and its morphology on a global and regional scale.

Nodule abundance

A natural phenomenon of the CCZ is that polymetallic nodules are continuously distributed over large areas throughout its entire length (from longitudes 110° W to 160° W) between the Clarion and Clipperton transform faults. They cover the entire ocean floor surface of the CCZ abyssal plain with its highs and lows. Of course, the continuity of nodule coverage is interrupted by certain gaps, but nodules still populate large fields, generally of a longitudinal or sub-longitudinal extension. Nodule abundance varies from 1-2 to 20-30 kg/m^2 but in general, it averages 5-10 kg/m^2, although nodule concentrations of more then 15-20 kg/m^2 are found in all parts of the CCZ.

According to the ISA Secretariat's statistical analysis of the POLYDAT database, the abundance within the reserved areas has a wide range of values from 0 kg/m^2 to 30.19 kg/m^2 with an average of 6.12 kg/m^2. The histogram of abundance indicates that over 7.5 per cent of the stations have abundance values of 0.0 kg/m^2 and that over 14 per cent of all stations have very low abundance values.

According to the Geostat analysis (R. de l'Etoile, 2003), the abundance average values per block show two clear plateaux, one at around 4.8 kg/m^2, and another, less clear, at around 7 kg/m^2 . The map of nodule abundance by sampling stations from the POLYDAT database is presented in *Figure 8*.

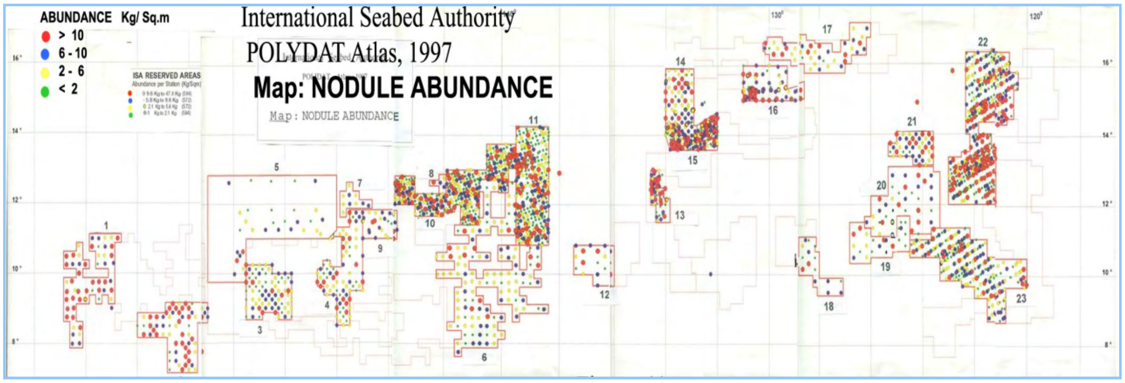


Figure 8: Nodule abundance by sampling stations from the POLYDAT database

The map of kriged nodule abundance compiled by Geostat is shown in *Figure 9*. Although varying in some detail for some the blocks within the reserved areas, both maps show a certain consistency in reflecting the general trend of nodule abundance throughout the CCZ on a global scale.

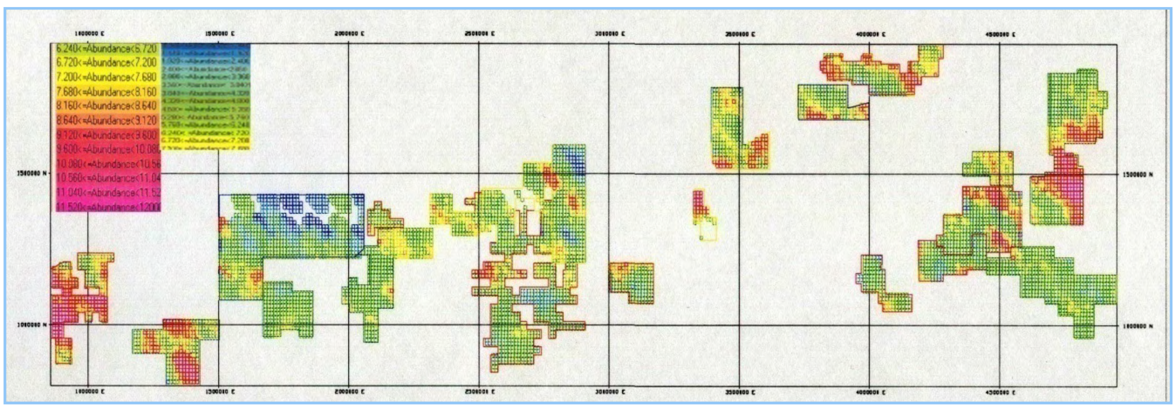


Figure 9: Kriged nodule abundance in the reserved blocks (modified from ISA Secretariat's report" Resource assessment of polymetallic nodules in the Authority's reserved areas". ISA Meeting of scientists, Kingston, January 2003)

The spatial distribution of nodule abundance in *Figure 8* indicates that nodules with abundance of more than 10 kg/m^2 are concentrated in areas in the remote east of the CCZ (block 23), in the central region (blocks 13, 14, 15 and 16; to a lesser extent in blocks 10 and 11) and in the remote west of the CCZ (blocks 1 and 2). The highest average abundance levels are typical for the areas located between longitudes 128^{o} W and 135^{o} W and between longitudes 118^{o} W and 124^{o} W. Even in the areas with high average abundance, there is local variability.

The kriged abundance for the reserved blocks by Geostat (*Figure 10*) indicates the same general trend on a global scale, except for blocks 10 and 11, in which the kriged abundance shows lower values.

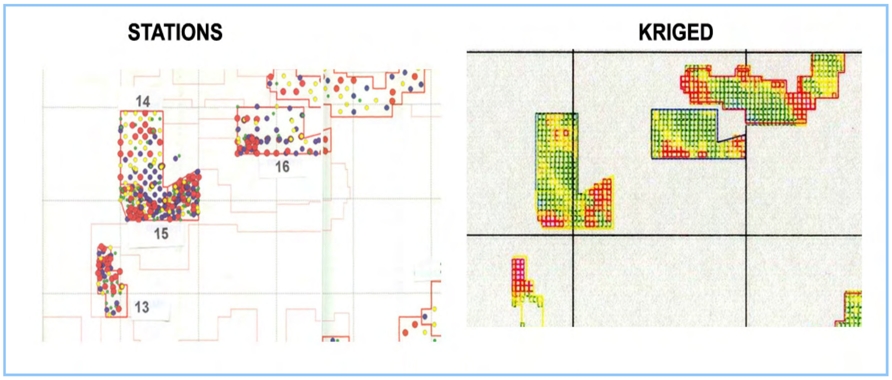


Figure 10: Comparison – Blocks 13-17

The comparison of these two maps for the CCZ on a global level is presented in *Figure 11*.

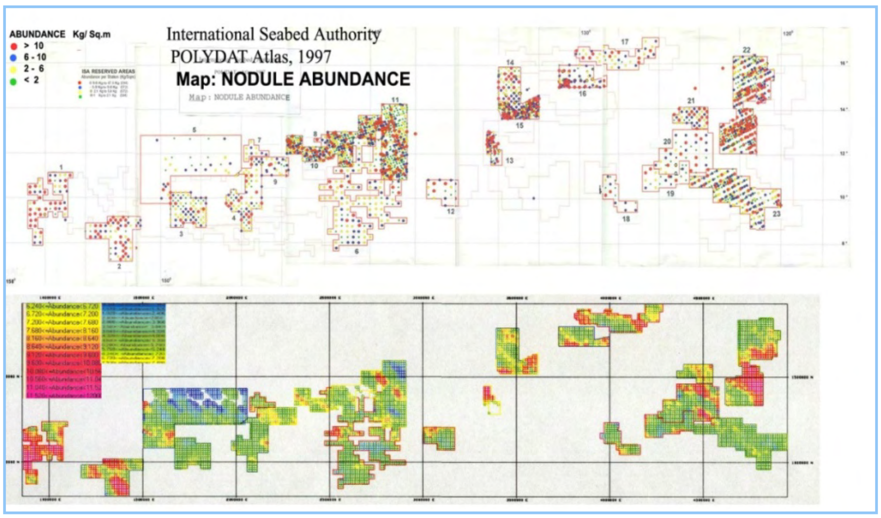


Figure 11: Comparison of the reserved blocks nodule abundance by sampling stations (POLYDAT 1997) with the kriged abundance (POLYDAT/Geostat, 2003)

Any analysis of nodule abundance in different parts of the reserved areas should take into account the fact that sampling density varies greatly from one block to another. For blocks 1 and 2 in the west, the sampling density (expressed in the size of seabed surface per one station) is about 650-750 km^2.

In the areas of high sampling density (blocks 10, 11, 13, 14, 15 and 16), it is less then 200 km^2. Blocks 22 and 23 in the remote east are characterized by a sampling density of 250-300 km^2 per station. This is important to consider in any comparative analysis of nodule abundance among various blocks, especially by applying geostatistical methods, which may extrapolate the values of one given sampling station over a large neighbouring area. The achieved results for different blocks have to be looked at from the point of view of a confidence factor, that is, the reliability of statistical calculations due to the density of the original data.

The above is well illustrated by the comparative analysis of nodule abundance by stations with kriged abundance for various areas, which is presented in *Figures 12-14*.

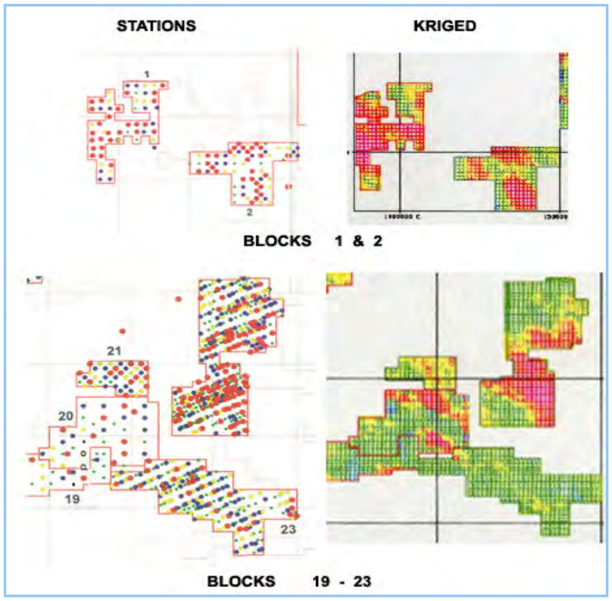


Figure 12: Comparison of the reserved blocks

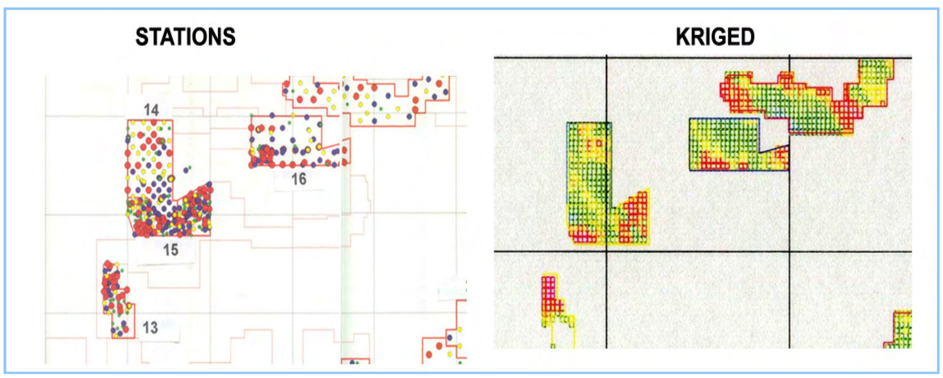


Figure 13: Comparison – Blocks 13-17

Figure 14: Comparison – Blocks 6, 8, 10 and 11

From the comparison of blocks 1, 2 and 23, one may assume that, for the areas with lower density of stations, the kriging method shows higher abundance values. The comparison of blocks 10 and 11 indicates that, for the areas with higher density of stations, the kriging method shows lower abundance values.

According to C.L. Morgan (*Figure 15*), nodules with kriged abundance more than 10 kg/m^2 are located in two zones, at latitude 13^{o}N and longitude 135^o W, and at latitudes 13-14^{o}N and longitudes 129-131^{o}W. Most of the CCZ is characterized by abundance of less than 2-4 kg/m^2. It is unclear whether this is due to the lack of data or whether it reflects low values in the OMCO sample collection.

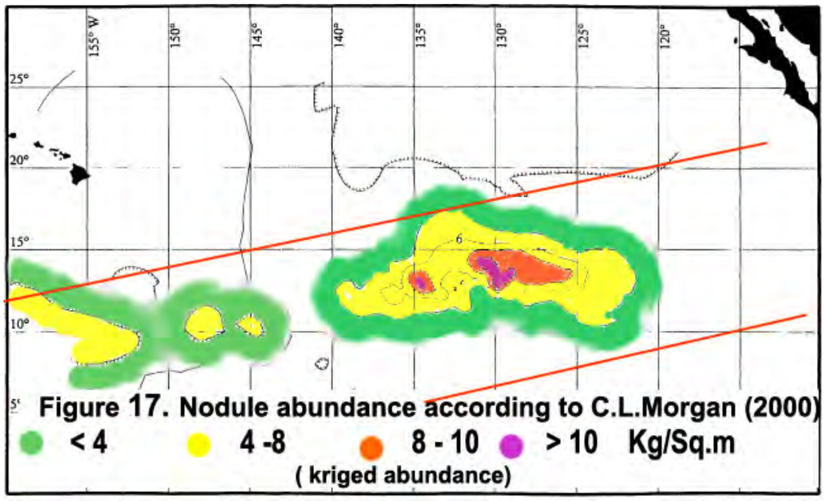


Figure 15: Nodule abundance according to C.L. Morgan (2000)

The schematic map of nodule abundance in the CCZ as compiled by Yuzhmorgeologiya (*Figure 16*) represents, to date, the most elaborate attempt to analyse the spatial distribution of nodule parameters in the CCZ on a global scale. The map covers most of the CCZ and is based on the analysis of a database established with more than 8,000 samples. Moreover, the map attempts to indicate the spatial distribution of nodule deposits with high abundance with rather detailed intervals (10-15; 15-20; and more than 20 kg/m^2). The interpolation of nodule abundance is done by the Inverse Square Distance method.

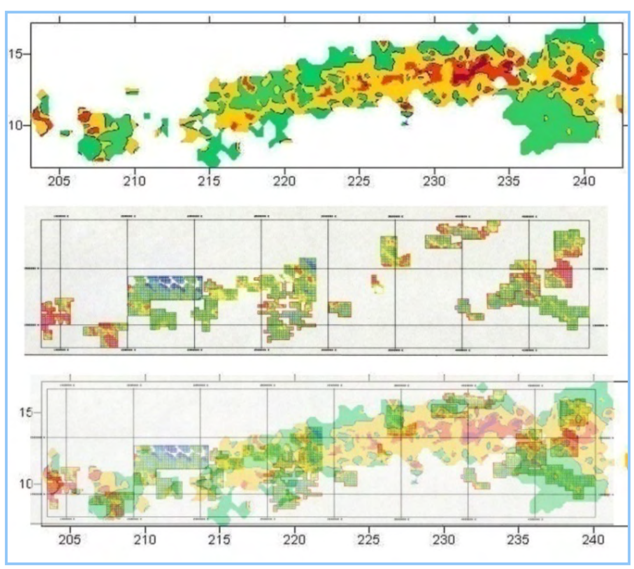


Figure 16: Comparison of the abundance of the reserved blocks by POLYDAT/GEOSTAT (ISA, 2003) with the abundance by Yuzmorgeologiya (2002)

This map is the first to emphasize a linear spatial distribution of nodule fields above the 5 kg/m^2 abundance level in the "axial" belt of the CCZ, approximately in the middle part between the Clarion and Clipperton fractures that can be clearly visualized west of longitude 125^o W. The belt extends throughout the entire CCZ in a NW-N direction parallel to the Clarion-Clipperton fractures. According to the Yuhzmorgeologiya map, the highest abundance in that zone is confined to the nodule population between longitudes 125-133^o W.

As can be seen in *Figure 17*, the Yuzhmorgeologiya map is consistent with

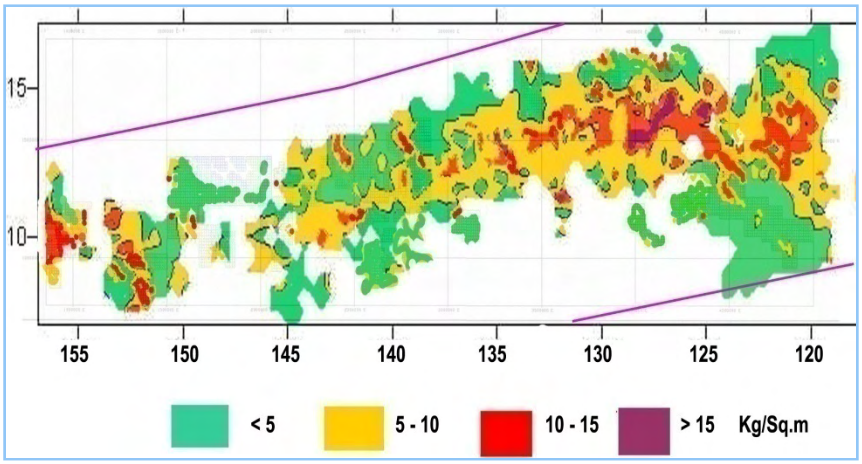


Figure 17: Nodule abundance of the CCZ (modified from Yuzmorgeologiya, 2002; ISA POLYDAT/GEOSTAT 2003; and C. Morgan 2000).

Morgan's sketch and shows striking similarity in the location of high value anomalies in nodule abundance within the CCZ at the global level.

A comparison of the Yuzhmorgeologiya map with the ISA POLYDAT/Geostat map for the reserved areas (*Figure 16*) indicates that these maps share general features of spatial distribution of nodule abundance along the entire extension of the CCZ.

Having analysed nodule abundance within the CCZ scale as presented in the above-mentioned map, we tried to compile a sketch map of the spatial distribution of nodule abundance of the CCZ on a global scale, as presented in *Figure 17*. The map indicates the following abundance values: less than 5 kg/m^2 - in green; 5-10 kg/m^2 - in yellow; 10-15 kg/m^2 - in red; more than 15 kg/m^2 - in brown. Within the vast extension of the CCZ, the spatial distribution of nodule abundance above 5 kg/m^2 shows a striking confinement to the linear "axial belt with a sub-latitudinal direction parallel to the Clarion and Clipperton fractures. The entire extension of this zone is more than 4,000 km, with a 300-600 km width.

Within this global belt, there are several isolated huge fields or sub-zones of nodules with an abundance level above 10 kg/m^2. The largest one is located in the central-eastern region between latitudes 12-14^o N and longitudes 123-129^o W. The length of this sub-zone is more than 600 km, and its width varies from 100-250 km. Within this sub-zone, there is a field structure of the second order with the highest abundance values (more than 15 kg/m^2) of linear configuration, which extends in a N-W direction.

On a global scale, the "axial" belt changes its direction to sub-latitudinal to the east of longitude 125^o W. That can be clearly visualized by the spatial distribution of high values above 10 kg/m^2. The configuration of the nodule zone with values of 5-10 kg/m^2 to the east of longitude 125^o W indicates the rather obvious NE trend of a nodule population of such abundance. That correlates with the general trend in the direction of the western flank of the East Pacific Rise and its volcanic mountain ridges. In the far west of the CCZ, to the west of longitude 152° W, the general trend of high abundance nodule fields on a global scale changes also from sub-latitudinal to the NW. This part is located in the eastern flank of the Line Mountain Chain with a NW trend of global and regional volcanic structures.

Seabed morphology and nodule abundance

It is difficult at this stage to establish any correlation between nodule accumulation and the topography of the CCZ on a global scale. Thus far, it has been noted that nodule population on a global scale is continuously spread at the various depths and in all morphological elements of the CCZ (*Figure 18*).

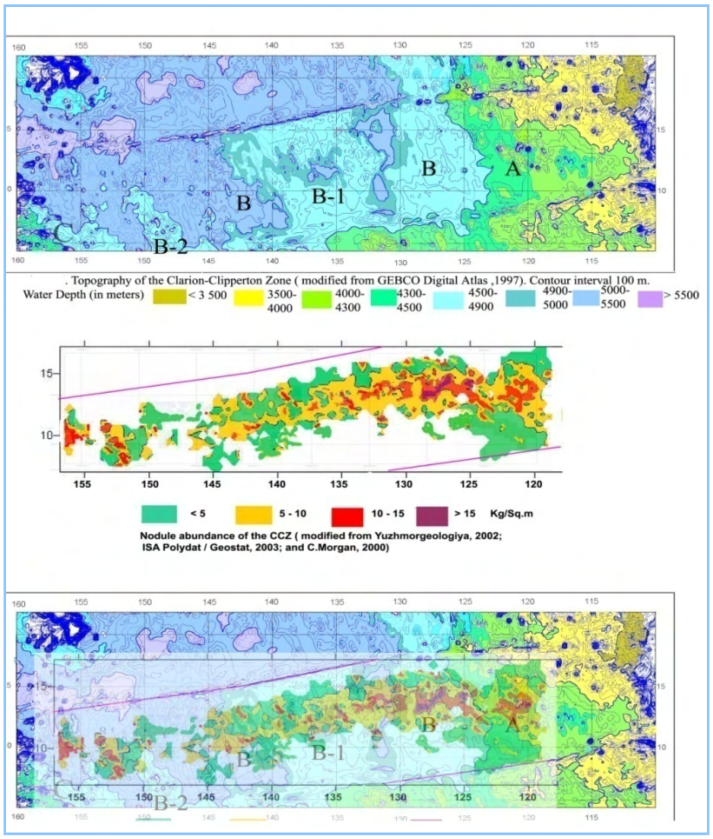


Figure 18: The CCZ topography and nodule abundance

At the same time, the high abundance at the remote western part of the CCZ has a clear connection with the eastern flank of the Line Islands Chain. There are indications that the highest abundance is confined to the mountain areas (5,000 m), as compared with the deeper parts of the seafloor (5,300-5,400 m). The correlation of the abundance values with the global topography in this part shall be further checked in order to establish whether the high abundance sub-zones and fields are interrelated with relief forms. Another option may be that high abundance of nodules has a interrelationship with intensive volcanic activity in this mountainous area.

A similar consideration shall apply to the remote east of the CCZ confined to the western flank of the East Pacific Rise. The NW trend of regional order relief forms in this part (volcanic mountain chains and ridges) are consistent with a general trend of spatial distribution of high abundance values.

For most of the extent of the CCZ between longitudes 125° W and 152° W, no correlation between nodule abundance and the depths of the ocean floor and its morphology can be observed in the “axial” belt of high values.

Sediments and nodule abundance

The relationship between nodule abundance and sediments is important, since the latter reflect the rate of sedimentation, the biological productivity and the location of carbonates, where carbonate material is dissolved. Many researchers consider sediments as a major factor which controls nodule population and grade. It has been established that polymetallic nodules are influenced by sediment composition and are associated with siliceous ooze and deep-sea clays. The thickness of sediments also influences nodule population.

From the earlier stages of sedimentation, Eocene, the Line Formation is found in the west of the CCZ. During Late Oligocene-Lower Pliocene when the seafloor of most of the CCZ was above the carbonate compensation depth, the Marquesa Formation accumulated massive carbonate layers. Since the Lower Pliocene – Holocene, when the depth increased and reached the carbonate compensation depth, sediments have become predominantly red deep-sea clays and siliceous radiolarian oozes (Clipperton Formation).

The present regime of sedimentation of the CCZ is characterized by the formation of sediments rich in siliceous material at or below the carbonate compensation depth. This trend is established all over the Clarion-Clipperton Zone. The polymetallic nodules are associated with siliceous ooze and clays because of the location of the carbonate compensation depth, which is also one of the controlling factors for nodule formation.

The CCZ is characterized by latitudinal distribution of sediment types in relation to climatic and biological zonation at the time of deposition (*Figure 19*). From the north to south there are red deep-sea clays, then argillaceous radiolarian ooze (siliceous clay), and then carbonaceous ooze (in the remote south).

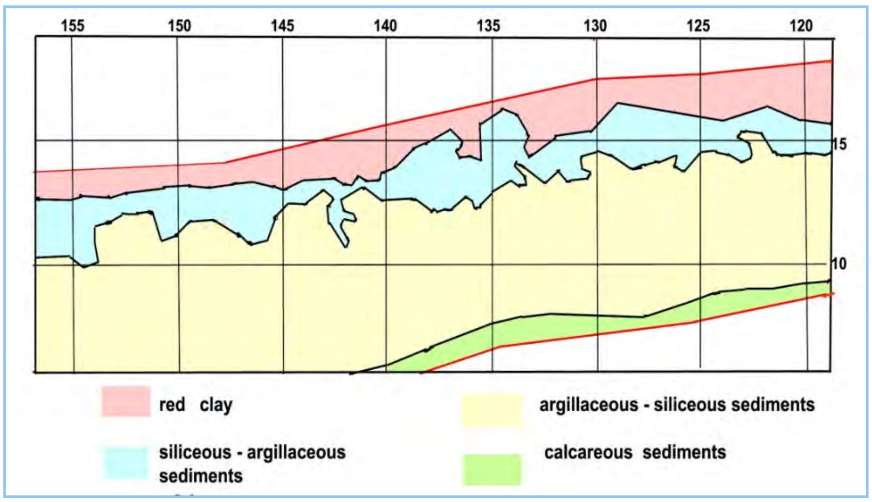


Figure 19: The CCZ sediment types according to Yuzmorgeologiya (2002)

As can be seen in *Figure 20* the high abundance belt in the CCZ is confined entirely to the area of siliceous clays and radiolarian ooze. That confirms the general concept that most favourable sedimentation environment for the genesis of nodules and their abundance is the formation of siliceous sediments.

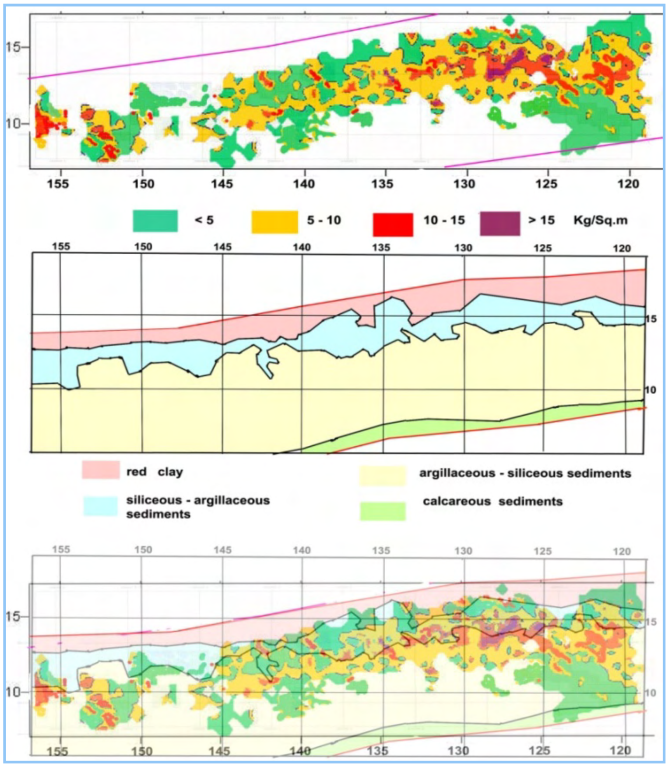


Figure 20: CCZ sediments and nodule abundance

Metal content

Manganese

In the areas reserved for the Authority, the manganese content of nodules varies between 4.14 and 33.5 per cent of dry weight with an average content of 26.83 per cent. The low values are recorded in block 11 (4.14 per cent), block 15 (10.3 per cent), block 14 (12.77 per cent), block 22 (12.84 per cent), block 9 (14.7 per cent) and block 4 (12.97 per cent), most of which are confined to the north of the CCZ near the Clarion fracture. High values of Mn (more than 30 per cent) are typical for almost all blocks in the reserved areas.

The map of manganese content in blocks of the reserved areas, in the Authority's POLYDAT database is shown in *Figure 21* (top part) as values per sampling stations). The spatial distribution of the manganese content in this figure shows that manganese anomalies with metal content more than 30 per cent are confined to the remote east of the CCZ (blocks 22 and 23) and to the centre of the CCZ between longitudes 137^{o}W and 142^{o}W (blocks 10 and 11).

Yuzhmorgeologiya's results, shown in *Figure 21* (middle part) indicates the location of the highest manganese content in the remote east of the CCZ east of longitude 125^{o} W, while values of 28-32 per cent are typical for most of the CCZ from longitude120^{o} W to 140^{o} W. The lower values (< 28 per cent) are confined to the western part (west of longitude 148^{o} W) and to the areas, which form an extensional belt along the northern part of the zone close to the Clarion fracture.

In his figures, Dr. Morgan distinguishes a large manganese concentration anomaly with values in excess of 30 per cent in the central part of the CCZ between longitude 120 and 138^{o}W, which may be consistent with the Yuzhmorgeologiya map.

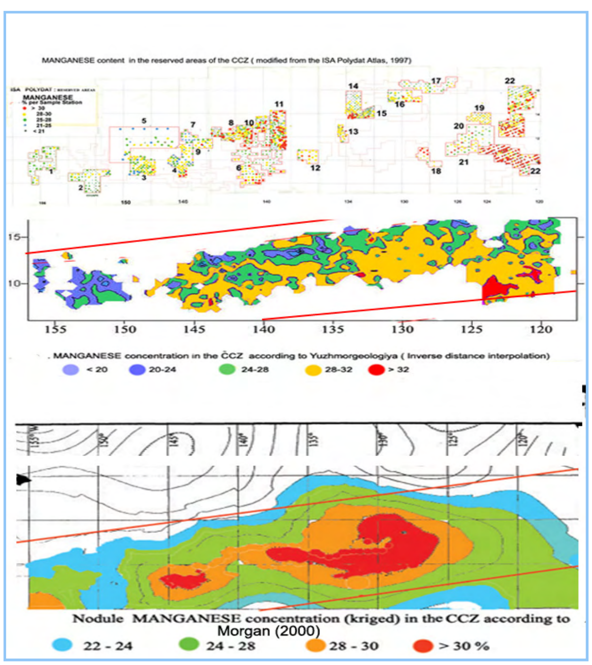


Figure 21: Comparison of Manganese concentration in the CCZ according to ISA POLYDAT (upper). Yuzmorgeologiya (middle) and C. Morgan (lower)

However, Dr. Morgan's sketch does not reflect the highest concentration of manganese in the remote east of the CCZ, distinguished by the rather reliable Yuzhmorgeologiya database and supported by the POLYDAT database for the reserved areas. We have made an attempt to compile a sketch map of manganese anomalies in the CCZ on a global scale on the basis of an analysis of the above-mentioned available information. The map is presented in *Figure 22*.

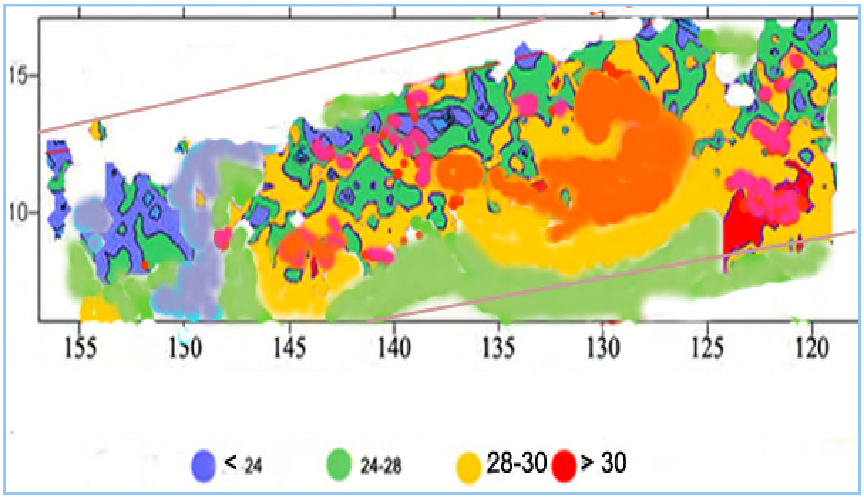


Figure 22: Abundance and Manganese

The anomalies with manganese content in excess of 30 per cent occupy vast areas in the eastern and central part of the CCZ east of longitude 135° W. To the west of longitude 135° W, these anomalies are confined to a linear belt extending in the WNW (290° -300°) direction. Another large anomaly with manganese content in excess of 30 per cent is distinguished between longitude 138 and 145° W.

There is no correlation between manganese content and water depth. Nodules with manganese values greater than 28 per cent are recorded on a global scale at depths between 3500-5500 m. A comparison of nodule abundance and manganese content is shown in *Figure 23*. It does not reveal any clear correlation between them. In the remote east and west of the CCZ high nodule abundance correlates with lower values of manganese. However, between longitude 125 and 135° W, high manganese concentrations coincide with high nodule abundance values.

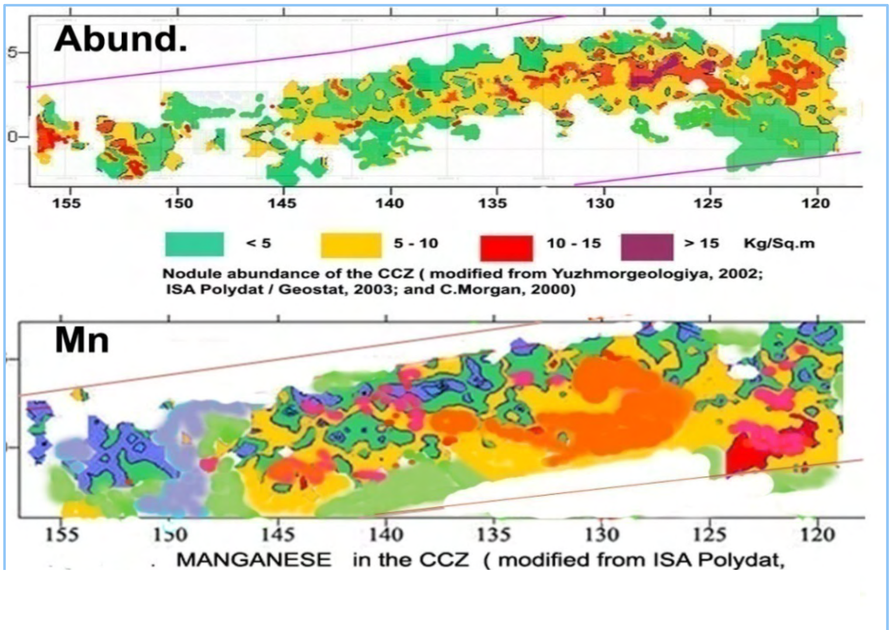


Figure 23: Abundance and Manganese

There is no clear correlation between manganese and nickel content in the CCZ on a global scale, as shown in *Figure 24*.

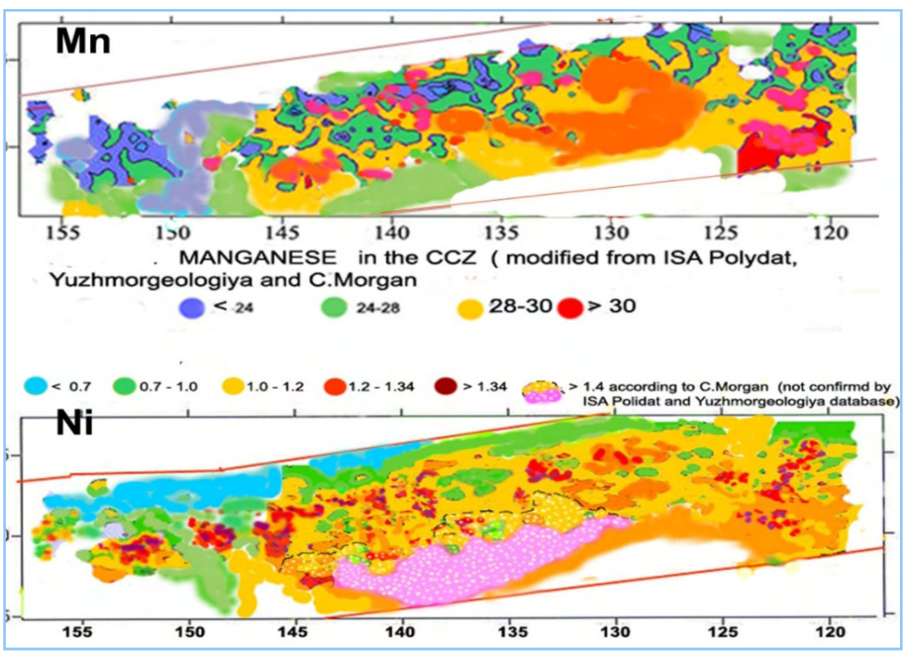


Figure 24: Manganese and Nickel

However, our comparison of the manganese and copper anomalies has revealed a distinct correlation between manganese and copper content in nodules for most areas in the CCZ as shown in *Figure 25*.

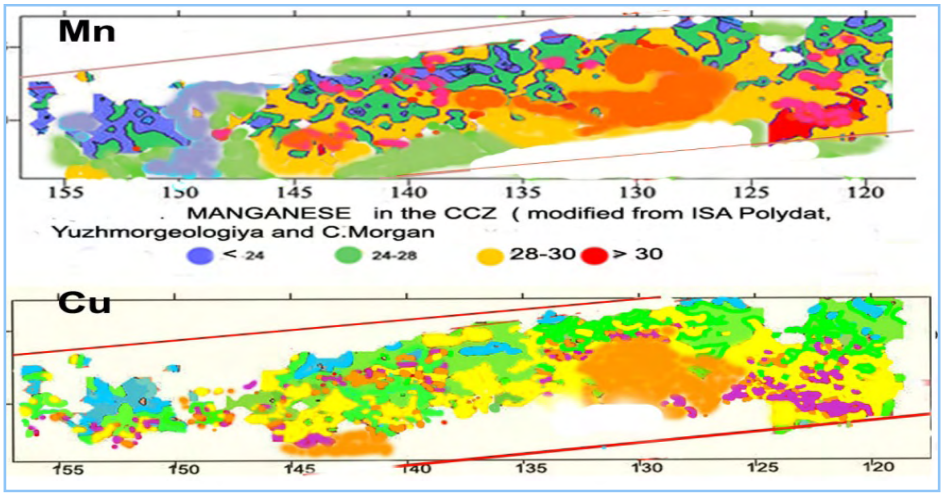


Figure 25: Manganese and Copper

As indicated by *Figure 26*, a negative trend, in general, may be established with respect to the correlation between manganese and cobalt concentration within the CCZ on a global scale. It is more distinct in the east and in the west of the CCZ. To a lesser extent, it is typical for the eastern part of the western zone between longitude 135° and 140° W. No distinct negative relationship between the manganese and cobalt concentration can be observed in the central part between longitude 127° and 132° W characterized by high manganese content (more than 30 per cent). It may be in conformity with the conclusion of the report for the reserved area in the central part of the CCZ (IFREMER/AFERNOD, Yuzhmorgeologiya and DORD, 1991) that the inverse correlation between iron and manganese is less dispersed when the manganese content is greater than 25 per cent.

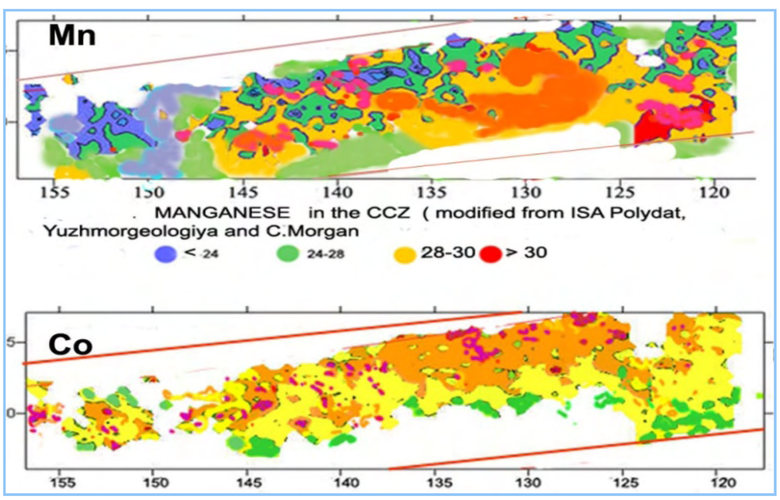


Figure 26: Manganese and copper

Nickel

The nickel content of nodules in the areas reserved for the Authority varies between 0.15 per cent and 1.87 per cent of dry weight with an average content of 1.22 per cent. The low values are recorded in block 10 (0.15 per cent), block 11 (0.35 per cent), block 9 (0.50 per cent), block 14 (0.46 per cent), block 5 (0.50 per cent), block 15 (0.53 per cent), block 1 (0.61 per cent) and block 22 (0.68 per cent), which are located in different parts of the CCZ. High values of Ni (more than 1.3 per cent) are recorded in almost in all blocks in the reserved areas. The map of the nickel content of polymetallic nodules in the blocks in reserved areas based on the ISA's POLYDAT database is shown in *Figure 27* (value per sampling stations). It shows that the spatial distribution of nickel concentrations in excess of 1.34 per cent is characterized by the presence of nickel anomalies along the entire extension of the CCZ from blocks 2, 3 and 4 in the west - through blocks 10, 11, 13, 15 and 16 in the central part, and - to blocks 21, 22 and 23 in the east.

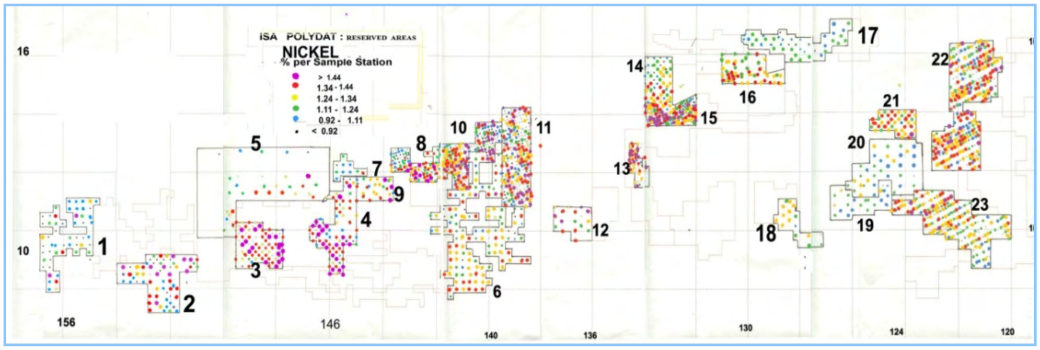


Figure 27: Nickel content in the reserved areas of the CCZ (modified from the ISA POLYDAT, 1997)

Yuzhmorgeologiya's map (*Figure 28*) indicates the location of high nickel content (> 1.2 per cent) in the remote east of the CCZ, where it correlates with a large manganese anomaly. Nickel values in excess of 1.2 per cent are typical for numerous but smaller areas in the northern part of the CCZ from longitude 128^0 W to 138^0 W. Large anomalies with the same nickel content are located in the southern part of the CCZ in the west between longitude 144^0 W and 146^0 W. Anomalies that are smaller in size are recorded in the southern half of the CCZ in the remote west (lomgitude 150^0 W to 155^0 W). Our comparison of the Yuzhmorgeologiya and ISA/POLYDAT maps shows that the two maps coincide in terms of the general location of high nickel content values along the entire extension of the CCZ. Dr. Morgan distinguished a vast nickel concentration anomaly with values of more than 1.4 per cent in the central-western part of the CCZ between longitude 130^0 W and 145^0 W. However, this anomaly is neither confirmed by the ISA/POLYDAT nor the Yuzhmorgeologiya database as shown in *Figure 28*.

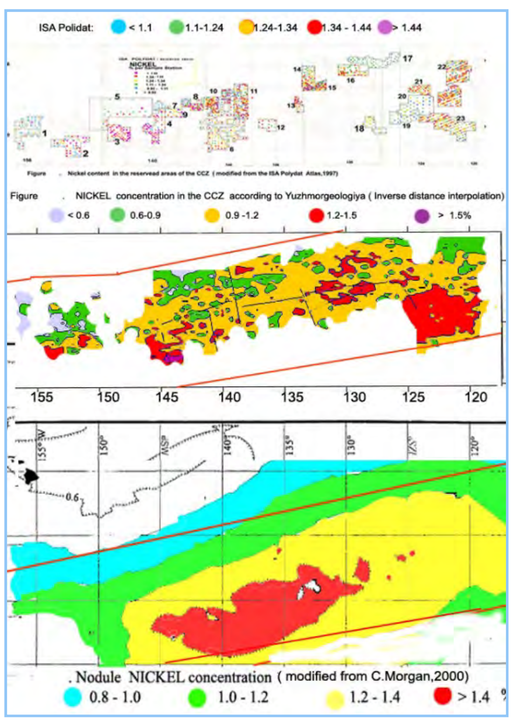


Figure 28: Comparison of Nickel concentration according to ISA POLYDAT, Yuzmorgeologiya and C. Morgan

Figure 29 represents a sketch map of nickel anomalies in the CCZ on a global scale, which we compiled by merging and appropriately modifying all available data sources.

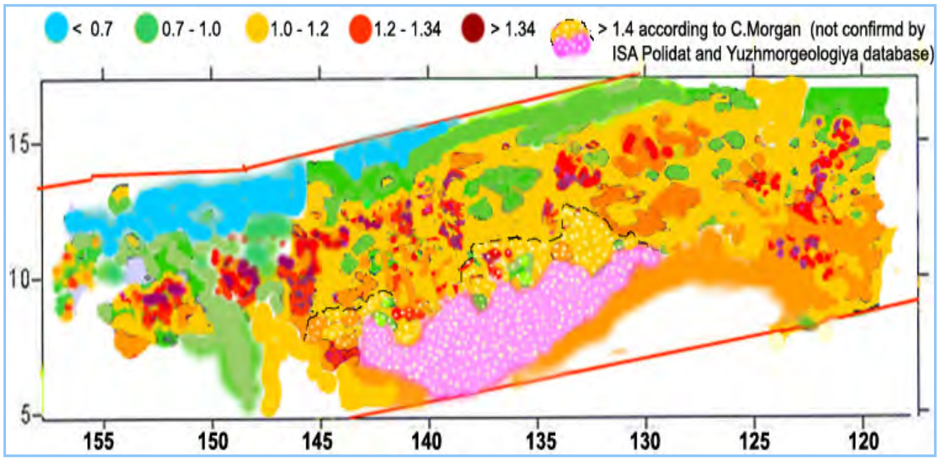


Figure 29: Anomalies of nodule – Nickel distribution in the CCZ (modified from ISA POLYDAT, Yuzmorgeologiya and C. Morgan.

As can be seen in *Figures 30 and 31*, the anomalies with nickel content higher than 1.2 per cent are scattered throughout the entire extension of the CCZ and, in general, show a similarity with the general spatial distribution of high nodule abundance. Although not necessarily coinciding with high abundance nodule areas, the nickel anomalies with metal concentrations in excess of 1.2 per cent are also confined to the linear "axial" central belt of a sub-latitudinal (70-80^0) direction. A global positive correlation between abundance and nickel anomalies generally can be detected in most of the CCZ, except some areas in the east (between longitude120^{o}W-125^o W, south of latitude 12^{o}N) and in the west between longitude 147^o W and 150^o W. No correlation is established between nickel content and water depth on a global scale in the CCZ.

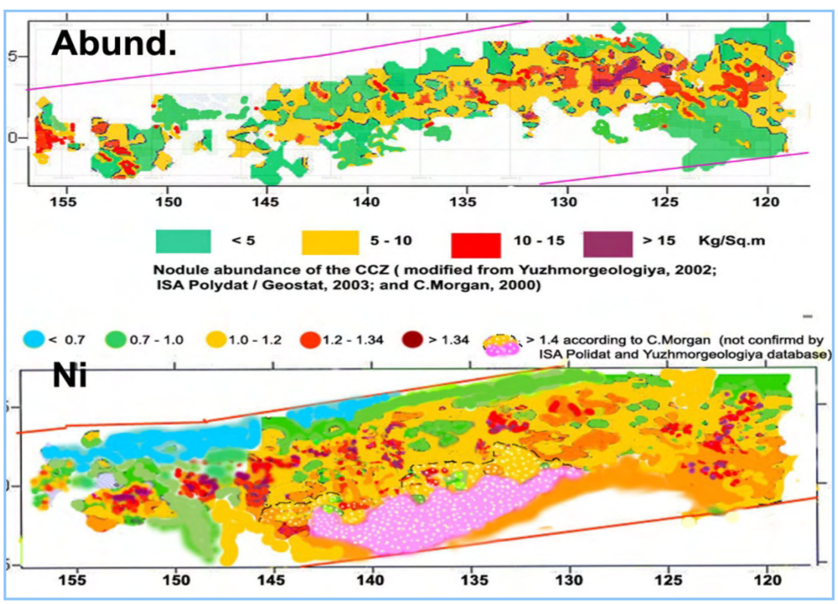


Figure 30: Abundance and nickel

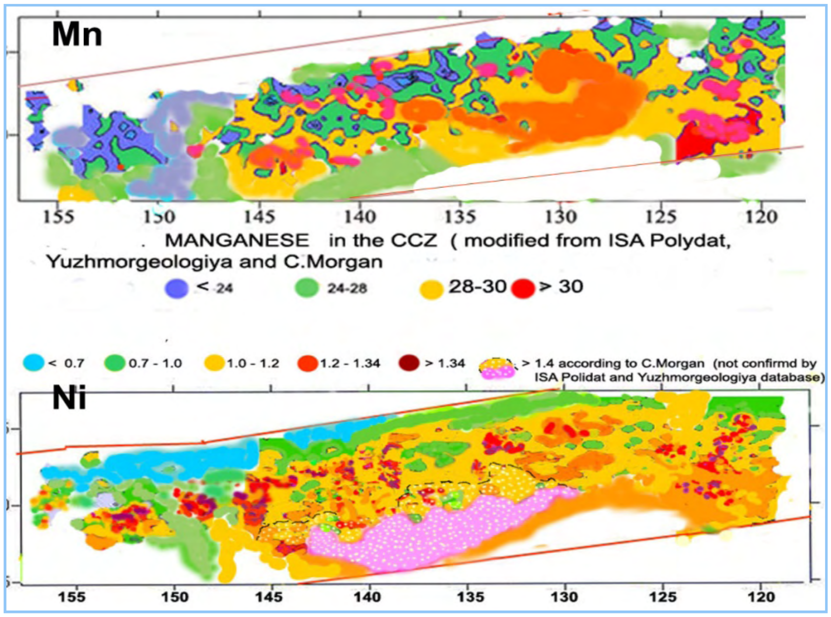


Figure 31: Manganese and nickel

There is no clear correlation between nickel and manganese content in the CCZ on a global scale either, as shown in *Figure 32*.

However, our comparison of nickel and copper anomalies revealed a distinct correlation between nickel and copper content in nodules for most areas in the CCZ east of longitude 143° W and 144°W (*Figure 33*). That positive relationship disappears in the western part of the CCZ westwards of longitude 143° W and 144° W.

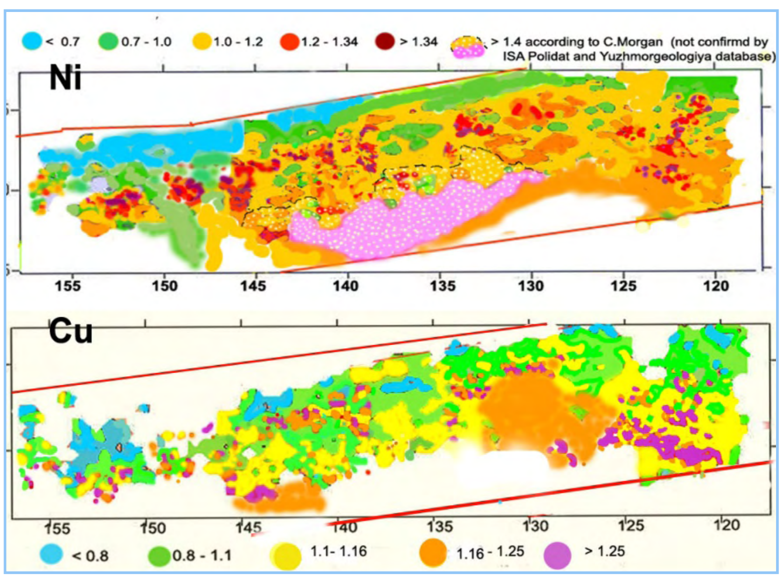


Figure 32: Nickel and Copper

As indicated by *Figure 33*, there is no correlation between nickel and cobalt concentration on a global scale for most of the CCZ. A positive relationship between nickel and cobalt anomalies may be detected only in the western-central part between longitude 137° W and147° W.

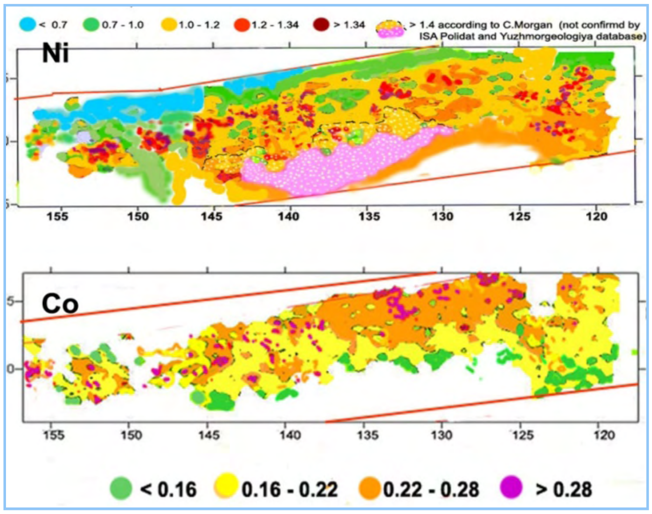


Figure 33: Nickel and Cobalt

Copper

The copper content of the nodules in the areas reserved for the Authority varies between 0.15 per cent and 1.87 per cent of dry weight with an average 1.22 per cent. The low values are recorded in block 10 (0.15 per cent), block 11 (0.35 per cent), block 9 (0.50 per cent), block 14 (0.46 per cent), block 5 (0.50 per cent), and block 15 (0.53 per cent) block 1 (0.61 per cent) and block 22 (0.68 per cent), which are located in different parts of the CCZ. The highest values of copper are recorded in the remote east (block 22) and the remote west (block 2) of the CCZ.

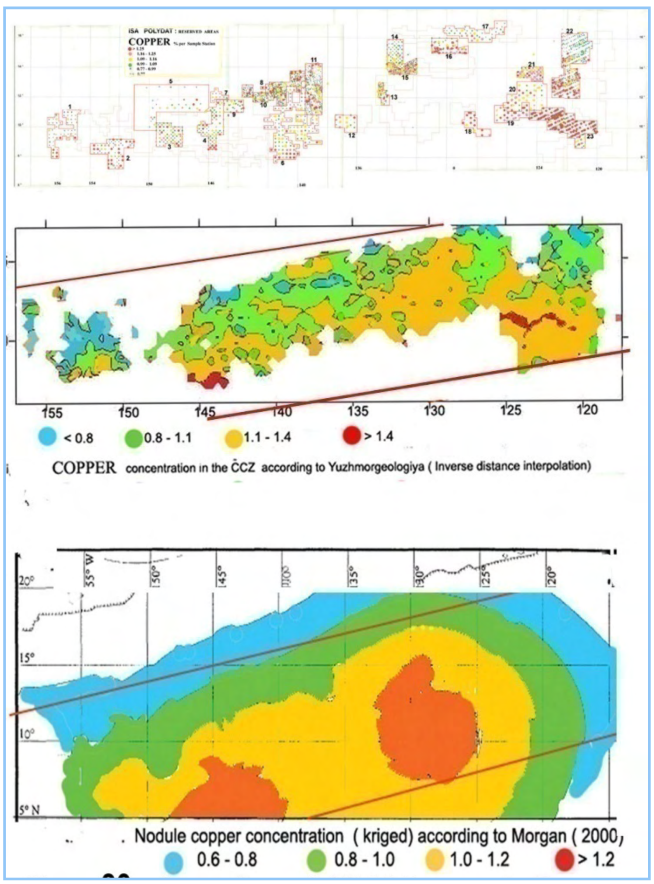
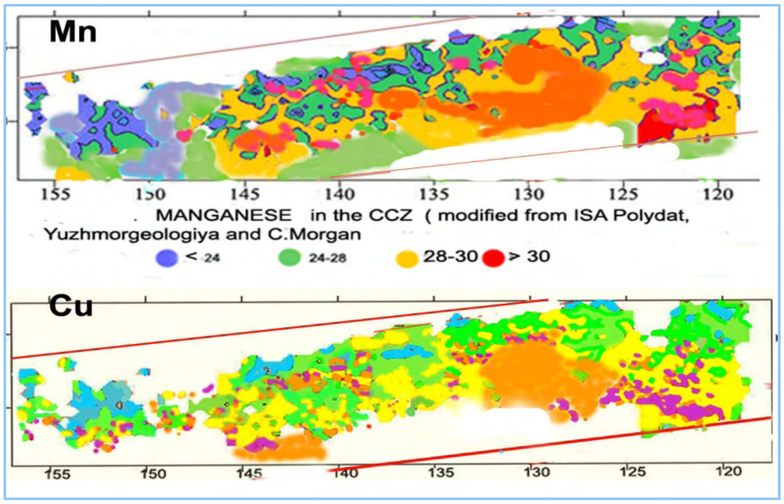


Figure 34: Comparison of Copper concentration in the CCZ according to ISA POLYDAT, Yuzmorgeologiya and C. Morgan

According to the ISA/POLYDAT map (*Figure 34*) of copper content in the reserved blocks (values per sampling stations), the eastern part of the CCZ (blocks 18, 19, 20, 21, 23 and south of block 23) is characterized by high values of copper concentration (more than 1.16 per cent). Smaller high-grade copper anomalies are reported in the central part of the CCZ (southern parts of blocks 15, 16 and 6).

Yuzhmorgeologiya's map also shows s high copper values (> 1.1 per cent) in the eastern half of the CCZ east of longitude 136^{o} W. The highest copper content (> 1.4 per cent) is confined to an anomaly between longitude 120-125^{o} W. That is well correlated with copper values according to the ISA's POLYDAT database. A similar anomaly is found in the south of the CCZ at longitude144-146^{o} W.

Charles Morgan (2000) distinguished two vast copper anomalies with values > 1.2 per cent directly north of the Clipperton fracture in the central part of the CCZ between longitude 125^{o} W and 133^{o} W. This anomaly is not detected by the ISA's POLYDAT database or the Yuzhmorgeologiya database because of lack of



data for this area. The other anomaly, according to Charles Morgan, is located in the south of the CCZ from longitude 140^{o}W to 148^{o}W, which correlates with the Yuzhmorgeologia database.

Our sketch map of copper concentration in the CCZ on a global scale compiled as a result of the analysis of the above data sources is presented in *Figure 35*.

Figure 35: Manganese and Copper

Figure 37 shows that the copper anomalies > 1.16per cent are scattered throughout the entire extension of the CCZ along the "axial" belt and that the largest anomalies are confined to the eastern part (east of longitude 132^{o} W) in the southern regions. The southern regions are separated from the Clarion fracture by a zone with lower copper concentration. The highest copper content is typical for the east of the CCZ between lomgitude120^{o} and 125^{o}W in the vicinity of the Clipperton fracture.

In general, copper concentration in the described anomalies at longitude 145^{o} W and between longitude 120^{o} and 125^{o} W show a reverse correlation with spatial distribution of high nodule abundance. For the rest of the CCZ such a negative trend is not observed and in places high copper concentration coincides with high nodule abundance.

No correlation is established between copper content and water depth on a global scale in the CCZ. Our comparison of the manganese and copper anomalies has revealed a distinct correlation between manganese and copper content in nodules for most areas in the CCZ as shown in *Figure 36*.

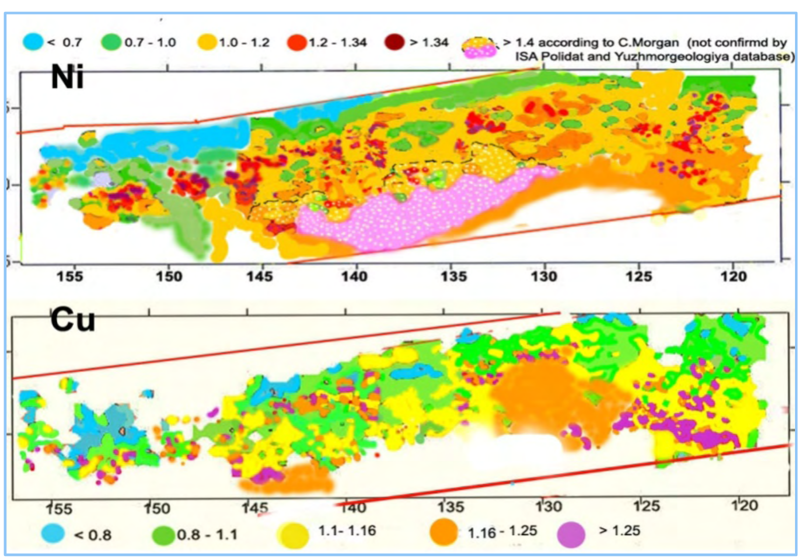


Figure 37: Nickel and Copper

Moreover, as mentioned above, there is a distinct correlation between nickel and copper content in nodules for the most areas in the CCZ east of longitude 143° W and 144° W (*Figure 37*). That positive relationship disappears in the western part of the CCZ (to the west of longitude 143° W-144° W).

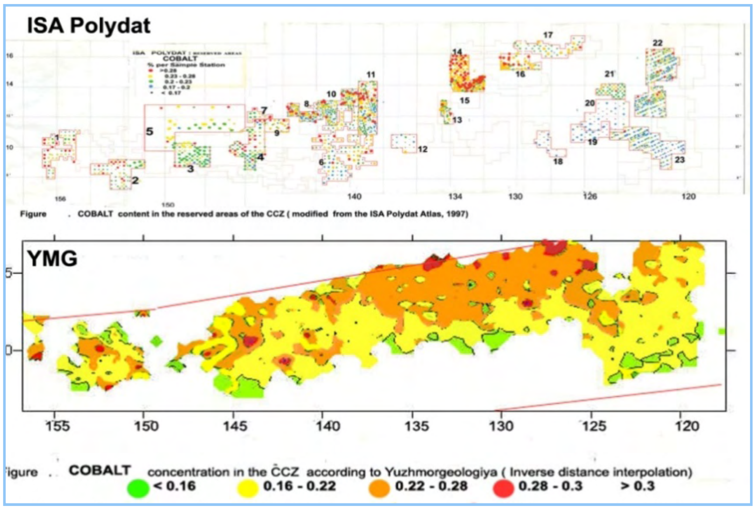


Figure 38: Comparison of Cobalt concentration in the CCZ according to ISA POLYDAT and Yuzmorgeologiya

With regard to the copper-cobalt relationship on a global scale in the CCZ, there is the inverse correlation for the most part of the zone, in general, which, in some places, is less pronounced and sometimes (longitude 138° W and 142°W) high copper values coincide with high cobalt values in nodules.

Cobalt

In the reserved areas, cobalt concentration in nodules varies between 0.02 per cent and 0.7 per cent of dry weight with an average of 0.22 per cent. The low values are recorded in block 15 (0.02 per cent). For all other reserved blocks, cobalt concentration is not less than 0.11 per cent. High values of Co (more than 0.4 per cent) are recorded in blocks 4, 10, 14 and 23.

Figure 39 shows the spatial distribution of cobalt concentration in nodules in the reserved areas according to the ISA's POLYDAT database. Cobalt anomalies > 0.28 per cent are confined to the “axial” belt of the CCZ (blocks 14-16, 11, 10 and 7) between longitude 128 and 144° W.

Yuzhmorgeologiya's map (*Figure 38*) shows that the location of the highest content cobalt nodules (more than 0.28 per cent) is north of the CCZ near the Clarion fracture between longitudes 128°W and 135°W. However, values of more than 0.22 per cent are typical for most extensions of the CCZ from longitude 125° W to 140° W in the northern part of the Zone close to the Clarion fracture. High value anomalies of smaller size are scattered throughout the “axial” zone along the entire extension of the CCZ.

In *Figure 39* one can see our attempt to produce a sketch map of cobalt anomalies in the CCZ on a global scale on the basis of available information. The anomalies with cobalt content of more than 0.22 per cent occupy vast areas in the eastern and central part of the CCZ east of longitude 140° W and are confined to the north of the CCZ. Rather limited in size, anomalies with high cobalt concentration (>0.28 per cent) are scattered along the entire CCZ.

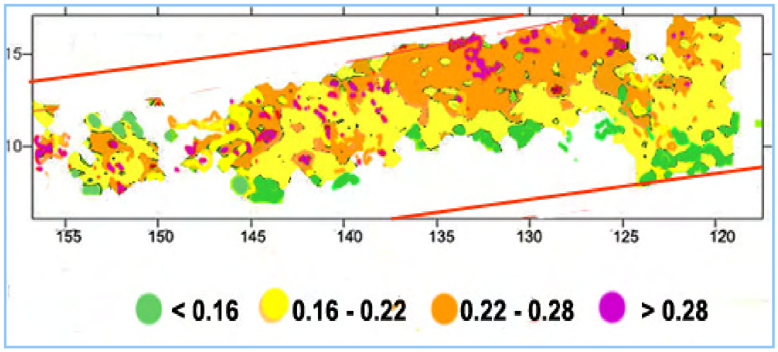


Figure 39: Anomalies of nodule Cobalt concentration in the CCZ (modified from ISA POLDAT and Yuzmorgeologiya

There is no correlation between cobalt content and depth. A comparison of nodule abundance and manganese content is shown in *Figure 40*. It does reveal a certain positive correlation, although cobalt anomalies are confined to the latitudinal linear zone which is located to the north of the "axial" high abundance belt of the CCZ. In the remote west of the CCZ, high nodule abundance also correlates with high values of cobalt.

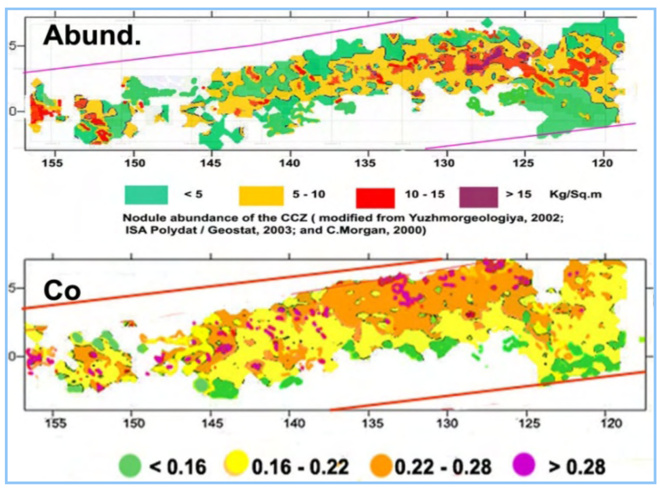


Figure 40: Abundance and Cobalt

As indicated by *Figure 41*, a negative trend, in general, can be discerned with respect to the correlation between manganese and cobalt as described above.

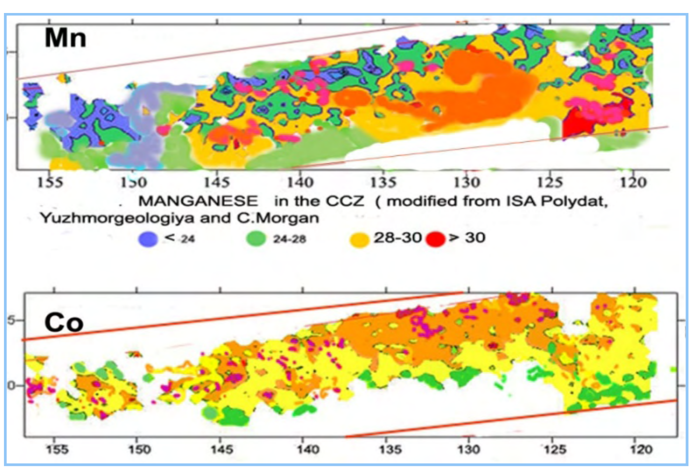


Figure 41: Manganese and Copper

As indicated by *Figure 42*, there is no correlation between nickel and cobalt concentrations on a global scale for most of the CCZ. A positive relationship between nickel and cobalt anomalies may be detected in the western-central part between longitude 137° W and 147° W.

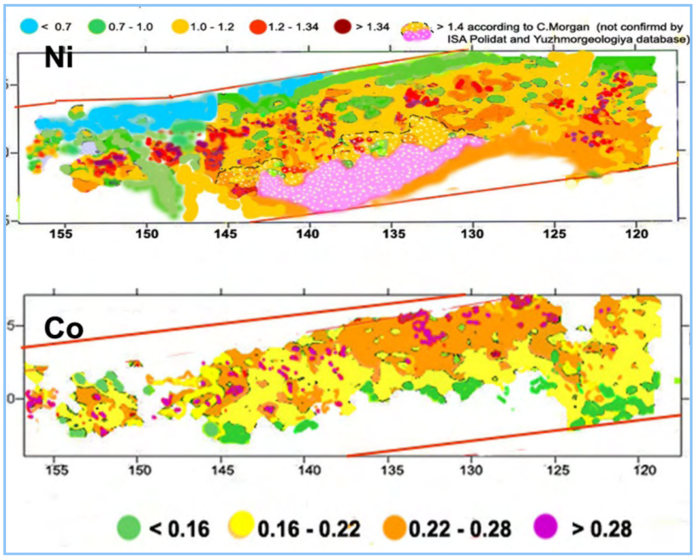


Figure 42: Nickel and Cobalt

As shown in the figure, there is, in general, the inverse correlation between copper and cobalt content for most of the Zone, which in some places is less pronounced and sometimes (between longitude 138°W and 142°W) high copper values coincide with high cobalt values in nodules.

Nodule deposits

One of the most important geological parameters of polymetallic nodules is their ability to form concentrations with high abundance and metal content, which can be considered as nodule deposits with certain cut-off grades, which may have potential for economic development in future.

For the purpose of locating such deposits in the reserved areas, the author, on a consultancy with the Authority, undertook in 1997 the study of estimating the resource potential of the reserved areas. Such basic criteria as nodule abundance and cumulative metal content of three metals - nickel, copper and cobalt – was used. A criterion based on nickel equivalent was not used, since the pioneer investors had applied a different formula to calculate that value. Besides, owing to the slight variation in manganese content values over different areas and low prices for manganese, that formula by itself will mostly represent values of content of the three metals, namely, nickel, copper and cobalt.

The nodule resources that may be favourable for possible future first and second generation mining operations were defined by us as those with nodule abundance of more than 5 kg/ m^2 and Ni+Cu+Co content of more than 2 per cent (basic assumptions used in 1980s during the drafting of the United Nations Convention on the Law of the Sea).

They were divided into four nodule grades:

Grade"A" Nodule deposits with abundance of more than 10 kg/ m^2 and Ni+Cu+Co metal content of more than 2.5 per cent.

Grade“B” Nodule deposits with abundance of more than 10 kg/ m^2 and Ni+Cu+Co metal content of between 2 and 2.5 per cent.

Grade“C” Nodule deposits with abundance of more than 5 kg/ m^2 and Ni+Cu+Co metal content of more than 2.5 per cent.

Grade“D” Nodule deposits with abundance of more than 5 kg/ m^2 and Ni+Cu+Co metal content of between 2 and 2.5 per cent.

To evaluate the spatial distribution of nodules with different grades and locate possible nodule deposits within the reserved areas, we compiled maps for each sector and the CCZ as a whole (*Figure 43*).

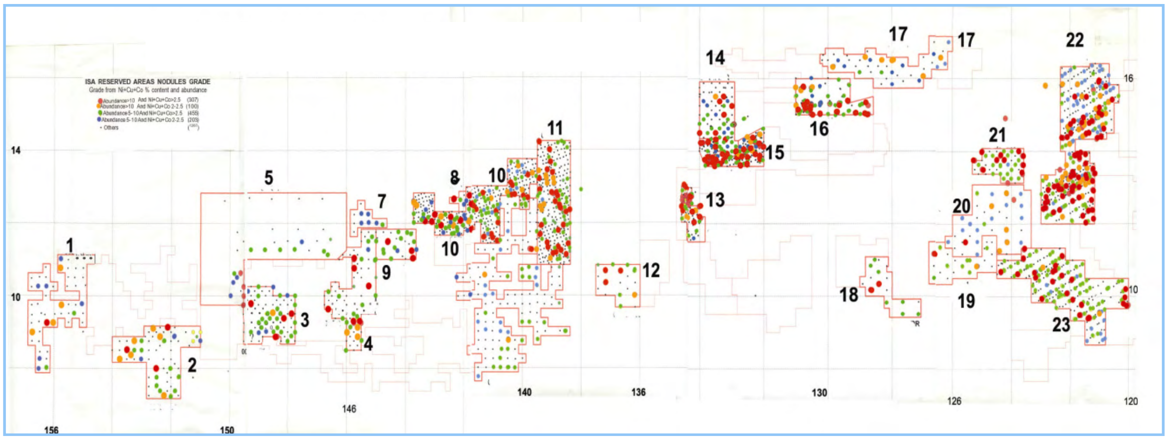


Figure 43: Nodule deposits in the reserved areas of the CCZ (modified from the ISA POLYDAT, 1997)

The following represents a conclusion, which may be drawn from the analysis of the maps and all other relative information. However, one must be careful in comparing the resource value of the various blocks without considering the density of sampling stations and methods of nodule research.

The eastern and central regions seem to be more favourable, than the western region, for the location of possible nodule deposits with higher grade. This may be due to the greater size of the areas with high nodule abundance in the centre and in the east and location of rather extended copper anomalies in the east between longitude 120° and 125°W and cobalt anomalies in the northern part of the central region.

Another important reason may be the negative correlation between nodule abundance and metal grade which appears in the CCZ to the west of longitude 145° W.

At this stage of processing of available nodules data, two areas may be identified as favourable target areas for further exploration to delineate nodule deposits in the reserved areas with grades “A” and “B”: the first area is located in the central zone and is composed of reserved blocks 13, 14, 15 and 16; the second area is located in the remote east and is represented by reserved block 22.

Our analysis has shown that there are some other areas of interest for possible future development but with lower nodule abundance (more than 5 kg/ m^2) and metal content Ni+Cu+Co= between 2 and 2.5 per cent . These are blocks 20, 21 and 23 in the east and blocks 10 and 11 in the eastern part of the western region, which may become second generation mine sites with nodules of grades “C” and “D”.

CONCLUSIONS

The following preliminary conclusions or, rather, assumptions may be made on the basis of the above considerations: with regard to the copper-cobalt relationship on a global scale in the CCZ, there is an inverse correlation for most of the zone, which, in some places, is less pronounced, and sometimes (especially between longitudes138^{o} W and 142 ^{o} W), high copper values coincide with high cobalt values in nodules.

Nodules with high abundance are confined to the central “axial’ belt extending along the entire CCZ in a sub-latitudinal direction parallel to the Clarion-Clipperton fracture.

Manganese anomalies occupy vast areas in the eastern and central part of the CCZ east of longitude 135^{0} W. Another large manganese anomaly with metal content > 30 per cent is found between longitude 138^{o} and 145^{o}W. There is no clear correlation between nodule abundance and manganese content.

There is no correlation between manganese and nickel content in the CCZ on a global scale. However, our comparison of the manganese and copper anomalies has revealed a distinct positive correlation between manganese and copper content. In general, a negative correlation may be established with respect to the correlation between manganese and cobalt concentrations within the CCZ on a global scale.

Anomalies with high nickel content are scattered throughout the entire extension of the CCZ and, in general, show a similarity with general spatial distribution of high nodule abundance.

There is a positive correlation between nickel and copper content in nodules for most areas in the CCZ east of longitude 143^{o} W. That positive relationship disappears in the western part of the CCZ to the west of 143^{o} W. There is no correlation between nickel and cobalt concentrations on a global scale for most of the CCZ.

The highest copper content is found in the east of the CCZ between longitude 120^{o} and 125^{o} W, in the vicinity of the Clarion fracture, although smaller anomalies with high copper content are scattered throughout the entire extension of the CCZ along the “axial” belt. In general, copper concentration in the described anomalies at lomgitude 145^{o} W and between longitude 120^{o} and 125^{o} W show a reverse correlation with spatial distribution of high nodule abundance. For the rest of the CCZ, such a negative trend is not observed.

There is, in general, the inverse correlation between copper and cobalt content in nodules for most of the zone which, in some places, is less pronounced.

There is no correlation between water depths and nodule abundance and metal grades in the CCZ on a global scale.

In general, most of the CCZ is not characterized by a negative correlation between nodule abundance and metal grade, which is typical for other nodule provinces of the world’s Oceans However, such an inverse correlation appears in some areas in the western part of the CCZ (to the west of 140-145^{0} W).

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SUMMARY OF THE PRESENTATION

At the outset, Dr. Yuri Kazmin emphasized the importance of data. He said that the basic requirement for establishing the geological model was the availability of relevant data. He said that the densities of sampling stations in different blocks of the CCZ were different. For instance, he remarked that sampling stations varied from at least 12 x 12 to 60 x 60 kilometres. With regard to the topography, Dr Kazmin said that the only available data on a local scale was a GEBCO map. In this regard, he said that although one could speak of a one-minute or two-minute grid, the details contained in these maps cannot be proven, because the data are based on research carried out during the 1970s and 1980s.

Dr. Kazmin said that additional data could be obtained from several activities, but they might not contribute much to the total picture of the area. He said that if one looked at the GEBCO map, there wasn't any visualization of the area, so the map could be interpreted when the data was edited; one could go to the map and see the various topographical features, which correlated to the tectonic and geological setting of the area.

According to Dr. Kazmin, in the Clarion-Clipperton Area, the whole of the morphology was different from the areas outside the Clarion Zone. With the help of figures, he showed the different morphologic regions of the Clarion-Clipperton Zone and highlighted the geological features, volcanic and other uplifts.

Dr. Kazmin said there were three other sources for data on the reserved areas in addition to those in the ISA database, POLYDAT. He recalled that these data were provided by applicants for registration as pioneer investors. He identified the second source as the pioneer investors (contractors) who might have additional data on the sites. The third source, according to Dr Kazmin, was the data obtained by the US consortia. Finally Dr Kazmin said the fourth source is the public domain.

Dr. Kazmin said that Yuzhmorgeologiya, for example, had processed all the data it had in its database, which totalled 10,000 stations (as compared to 2,080 in POLYDAT). He said that it had done a great deal of work to process all the data, and had produced the same types of maps as the Authority, including an abundance map for the entire CCZ, and other maps of the CCZ such as the manganese, nickel, copper and cobalt contents. With regard to the US consortia, he informed participants that Dr. Charles Morgan had obtained the use of their data which he could use under certain conditions, such as for scientific research. He said that Dr Morgan had utilized these data in a paper on resource assessment. He said that the paper had been published in a book edited by Professor Cronan in 2000. Dr. Kazmin said that in his presentation, he had modified Dr. Morgan's data, just to show what had been obtained from the consortia. He indicated that there were four maps, showing Dr. Morgan's analysis of the consortia data. Graphically, he compared the data from Dr. Morgan, from the Authority's database as well as Yuzhmorgeologiya's database. .

With regard to nodule abundance, he showed a map that he had produced while on a consultancy with the International Seabed Authority in 1997. He said that the map was based on data from approximately 2,600 stations. He compared these with the statistical results, which Geostat produced from the same data.

In this regard, he said that in general, the anomalies coincided, except for some areas. Comparing a map on nodule abundance by Yuzhmorgeologiya to a similar map by Dr Morgan, Dr Kazmin noted a striking resemblance. Dr Kazmnin pointed out that the Dr Morgan's identified anomalies had also been detected by Yuzhmorgeologiya. Based on the data from POLYDAT, Yuhzmorgeologiya and Dr Morgan, he showed a new map that he had produced, stating that this map could be used for the geological model, because it took into account all the availanle and published data.

Dr. Kazmin tried to compare and contrast the relationship between nodule abundance anomalies and topography, and observed that there was no relationship. He said that all high-abundance anomalies were located in different parts of the Clarion-Clipperton zone and were parts of different geological nodule structures. He said that he also tried to correlate nodule abundance with sediment types using a map of sediment types which had been compiled by Yuzhmorgeologiya for the total area. He said he tried to compare manganese and nickel contents from the three data sets; POLYDAT, Yuzhmorgeologiya and Dr. Morgan's publication. He said that although theYuzhmorgeologiya dataset did noy include some regions, its map showed an extremely large anomaly of nickel, which had not been detected by the data analysed by Dr. Morgan. He said this anomaly coincided with the data from POLYDAT. Dr. Kazmin also observed that, in some cases, the anomalies compared well between Yuhzmorgeologiya and Dr. Morgan's datasets, but not with the POLYDAT dataset.

Regarding cobalt concentration, Dr. Kazmin said that no one had produced a cobalt map, except for the data in POLYDAT and Yuzhmorgeologiya.

Dr. Kazmin tried to compare abundance with manganese content and showed that there was actually no distinct correlation. He pointed to anomalies of manganese saying that they did not coincide with anomalies of abundance. He said there was no correlation between manganese anomalies in the eastern or western parts of the CCZ with abundance.

Dr. Kazmin described the relationship between nodule abundance and metals content, as follows:

With regard to **abundance and nickel**, in some parts, there was a positive correlation, for the rest of the Clarion-Clipperton Zone, (the central and Western), there was actually no well-established correlation.

He said that the worst negative correlation was between **abundance and copper**. In general, he said that the correlation was more or less negative, but sometimes there were areas in which a positive correlation could be obtained.

Finally, Dr Kazmin said that the relationship between **abundance and cobalt** was not well established, but it was mainly more positive than negative.

Dr. Kazmin also compared the relationship between the metals.

In this regard, he said he had observed a positive correlation between **manganese and nickel**; however, there was a negative correlation between manganese and nickel in the west.

He also said that there was a positive correlation between **manganese and copper**, and that where there was no copper, there was no manganese.

Hr said that the correlation between **manganese and cobalt** was more or less positive; that there is a positive correlation between **nickel and copper** when both were low, and that the correlation between **copper and cobalt** was clearly negative.

Dr Kazmin contested the claim made by Robert de L'Etoile that nodule abundance could be a proxy for the value of the resources. As for nodule resources in the CCZ, he said he had divided them into three groups as follows: grade one for deposits with abundance greater than ten kilos per square metre, and the sum of the contents of the three metals, (nickel, cobalt, and copper) greater than 2.5 percent; grade two would comprise those deposits with abundance between 5 and10 kilos per square metre with the same metal content as the grade one deposits; and the grade three with abundance of 2 to 2.5 kilogrammes per square metre.

He said that within the CCZ, there were areas with high abundance and low grades. The reason was because of the various correlations between contained metals and nodule abundance. Secondly he said that, there was a general trend, and that between longitude140 and 145 degrees west, the general trend was for deposits to have high nodule abundance with low metal content. He concluded his presentation saying that the unique feature of the Clarion-Clipperton Zone was that, to the east of that line, that general trend was not observed. In fact, here, high nodule abundance went along with high metal content.

SUMMARY OF THE DISCUSSIONS

Recalling that the International Seabed Authority's Trustees has requested that a computer model should be established to provide reliable resource assessments, a participant commented that whatever interest existed to mine nodules in the CCZ was based on the degree of certainty of information available. With regard to spatial distribution of the model, the participant asked how the model would be coordinated so as to get a reliable estimate, since many of the resources that had been estimated were based on extrapolation.

In response, Dr. Kazmin said that resource assessments were a separate issue and should be done on the basis of the data in POLYDAT, because the desire was to do resource assessment for the reserved areas. He said that it was right to establish a geological model, to find out general trends which affected nodule formation and the concentration of metals within nodules; so the potential areas could be predicted if they were outside the reserved areas. He said that he didn't see resource assessment as a part of the geological model.

Dr. Kazmin said that there was metal content and metal concentration, and that it was metal content that was expressed as a percentage. It was not metal weight in the nodules; it was not the metal weight which was used by Geostat. He said he believed that Yuzhmorgeologiya had used a distance method for its maps and that since Dr. Morgan had used highest values, the two studies were comparable. He added that if one looked at both studies and saw the correlation between different methods and resource estimates, one would see that they coincided and that the difference was very, very small.

The same participant said that when one looked at an aerial map, one could see that the most abundant areas were also the areas that had been most sampled, remarking that this was true for the Yuzhmorgeologiya study. The participant asked Dr. Kazmin for his thoughts on the matter.

Dr. Kazmin responded that abundance was not too well known at most stations using as an example site abundance. He emphasized that using abundance as a proxy for nodule resources should be approached with caution because nodule abundance maps and Yuzhmorgeologiya's maps also showed high abundance in areas with limited data.

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CHAPTER 8 RELATIONSHIP BETWEEN NODULE GRADE AND ABUNDANCE, AND TECTONICS AND VOLCANIC ACTIVITY IN THE CLARION-CLIPPERTON ZONE

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Introduction

In 2003, the author undertook a study in connection with a proposed project to develop a geological model of the Clarion-Clipperton Zone (CCZ), to assist in the assessment of resource potential of this zone for polymetallic nodule deposits. The study consisted of two parts.

The first part was related to the analyses of basic parameters of polymetallic nodules such as abundance and metal content, with the aim of establishing general trends of nodule formation and the accumulation of metals in the CCZ on a global and regional scale. As a result of the study, new sketch maps were compiled, which reflect spatial distribution of nodules with various abundance and grade. The maps were the first to take into account all available information, although partly of an interpretive character, which is based on the analysis of about 20,000 sampling stations across the entire extension of the CCZ. An attempt was made to analyse the possible correlation between nodule abundance and metal content of four metals (manganese, nickel, copper and cobalt), as well as between concentrations of the metals themselves.

The basic results of the first part of the study are contained in the paper "The Geology of the Clarion-Clipperton Fracture Zone (CCZ) – Existing Information in Respect of Polymetallic Nodule Deposits in the CCZ," which was presented by the author at the International Seabed Authority's workshop held in Fiji in May 2003.

The present paper represents the second part of the study, which deals with the analysis of tectonics and volcanic activity in the CCZ and possible relationships between tectonic features, such as faults and fractures, with nodule abundance and grade. The maps on nodule parameters that are used for this study were presented in the above-mentioned paper. Any references to metal concentrations and metal anomalies in the text and figures shall be read in the meaning of metal content in nodules expressed in percentage per dry weight.

General remarks

The factor of age and structure of the oceanic basement is important, since its development influenced the bathymetry and depth of the ocean floor and its interrelationship with biochemical layers of the water column, the carbonate compensation depth (CCD) in particular.

Some researchers are inclined to relate nodule composition to the age of the crust substratum. The phenomenon of the CCZ with respect to spatial trends in positive or inverse correlation between metal grade and abundance in nodules may be also related to the tectonic structure of oceanic crust.

It is believed that a general structure of the CCZ crust was influenced by several stages of tectonic and volcanic activities: first by the formation of the CCZ itself between the Clarion and Clipperton transform faults; its subdivision into blocks by faults parallel or sub-parallel to the East Pacific Rise; fracturing along the sub-latitudinal regional fracture zones, parallel to the Clarion and Clipperton faults; and reactivated faulting and volcanism that lead to the formation of the present morphological structure of sub-longitudinal trend.

Many scientists advocate the internal nature of metal supply in nodules and relate the nodule grade and abundance to the major fracture systems. For instance, Gross and McLeod (1987) consider that high concentrations and high-grade nodules are confined to their proximity to the active spreading ridges, major fracture systems and active volcanism that provide sources of metals and nuclei for nodule growth.

Another theory (S. Andreev, 1994) is that fracture and fault zones may provide for infiltration of bottom-waters into sediments and volcanic substratum. Such water circulation may lead to the supply of free oxygen to the bottom and release of iron, manganese and base metals, which consequently create a favourable environment for oxidation of Fe and Mn, for nodule formation and concentration of Ni, CU, and Co.

Besides the Clarion and Clipperton transform faults themselves, the CCZ is characterized by regional faults and fractures parallel or sub-parallel to the East Pacific Rise, which subdivide the CCZ into separate blocks with various magnetic anomalies and the age of the basement.

The extended long systems of sub-latitudinal fracture zone, parallel to the Clarion and Clipperton faults are traced along the extension of the CCZ from east to west by chains of volcanoes and volcanic mountain ridges. In the remote west they belong to a fracture zone called "Unnamed." In the central part, they mark three fracture zones south and parallel to the Clarion fault. They are named (southward) Rishelie Fracture, Mathematician Fracture, and Unnamed fracture. The western extension of the unnamed fracture zone may be traced by volcanoes and volcanic mountain ridges in the reserved blocks in the remote west. In the east (reserved areas 19 and 22) volcanic mountains belong to the eastern extensions of the Unnamed and Mathematician fractures.

An important role is played by the faults system of sub-latitudinal direction which may be connected with the time of the East Pacific Rise tectonic and volcanic activity. This system is responsible for the predominant morphological landscape of the CCZ, which is connected with the horst and graben relief of sub-longitudinal trend.

Volcanic activity in the CCZ is responsible for the formation of the volcanic substratum of the basement and also resulted in the formation of various volcanic structures, which are superimposed on the basement as volcanic plateaux, old volcanic seamounts, and volcanic mountain ridges associated with compensation depressions. Large volcanic plateaux and compensation depressions 300-500m deep have been mapped in the remote western areas, which result in rather mountainous relief in some parts. In many reserved blocks, relief is complicated sub-latitudinal chains volcanoes and volcanic mountain ridges culminating 800-30000 m above sea bottom. They mark sub-latitudinal fracture zones or are associated with second order fault systems. Such volcanic chains were mapped almost in all reserved blocks from west to east of the CCZ.

The volcanic activity distinguished in various parts of the CCZ may vary in respect to its age and origin. For instance, volcanic mountains and chains of volcanoes on remote east are closely related to the volcanic activity of spreading centres in the East Pacific Rise. However, volcanic structures and mountain ridges in the remote west in the eastern flank of the Line Islands Chain may belong to another type of volcanism typical for "hot spot" processes. The available data at present is not sufficient to make certain conclusions on the age and types of existing volcanic elements of the CCZ.

Topography and tectonics

Analysis of the bathymetry and topography of the CCZ indicates that its major morphological features on a global and regional scale were formed as a result of multiple stages of tectonic movements of various orders and directions (*Figures 1 and 2*).

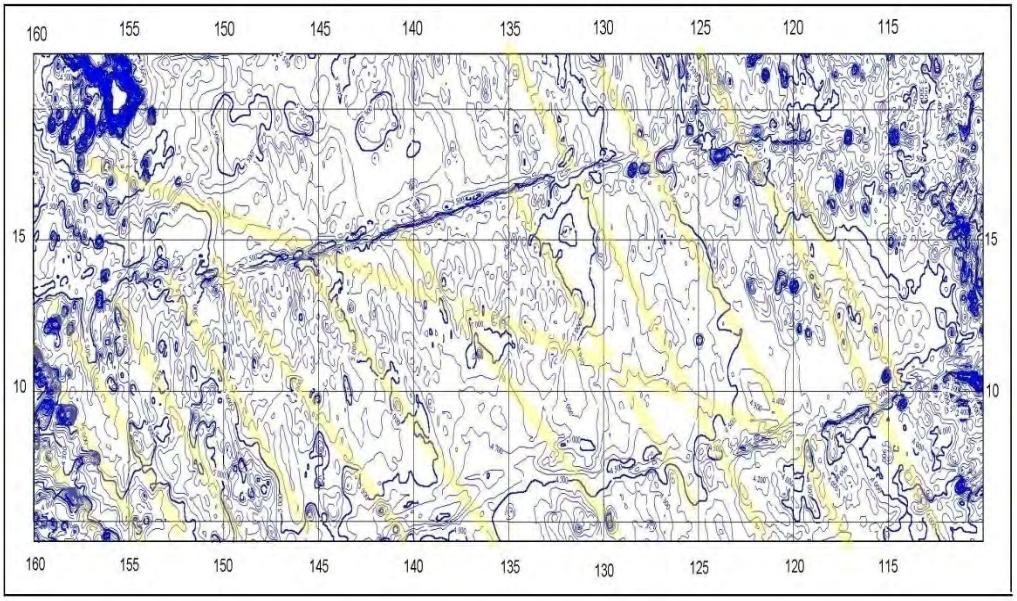


Figure 1: CCZ topography and lineaments (possible fault systems are shown in yellow)

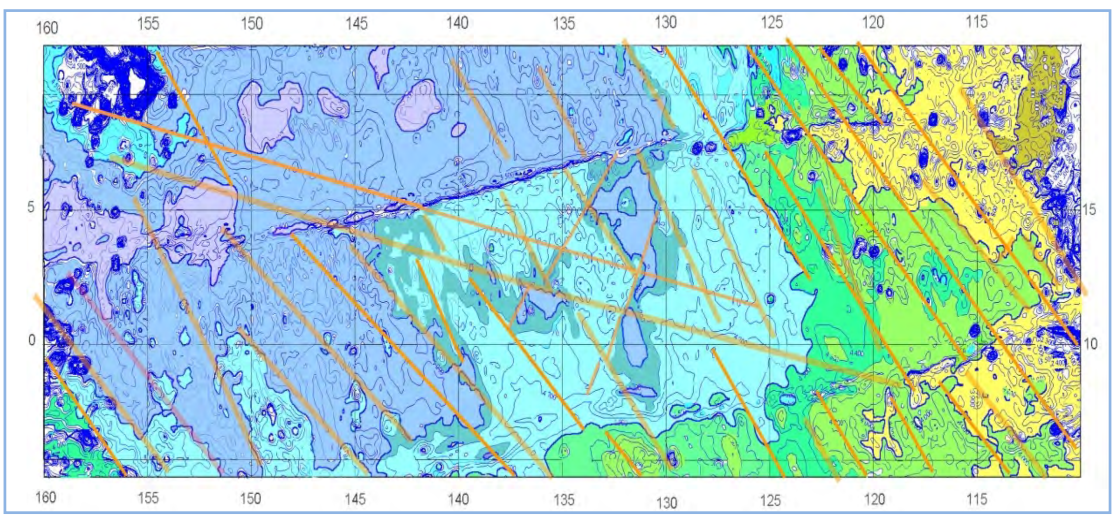


Figure 2: Topography of the CCZ and possible tectonics (Lineaments other then Clarion and Clipperton fractures are shown in orange)

It is obvious that major relief forms of a global order and subordinate regional and sub-regional relief elements are controlled by the lineaments of NW direction (300-310^{o}), representing a predominant system in the CCZ.

Another global fracture system is traced as a south-east extension of the Hawaiian Islands Ridge. It can be clearly detected by the relief forms and isobaths counters in *Figures 1 and 2*. If the relationship of the 300^{o} fault system with the Clarion and Clipperton fractures is still to be established, the age of the latest tectonic movements at this system (290^{o}) appears to be younger, since it crosses the entire CCZ from Hawaii in the E-SE direction. This is also confirmed by the location of many recent earthquake epicentres within this fault system (*Figures 3 and 4*).

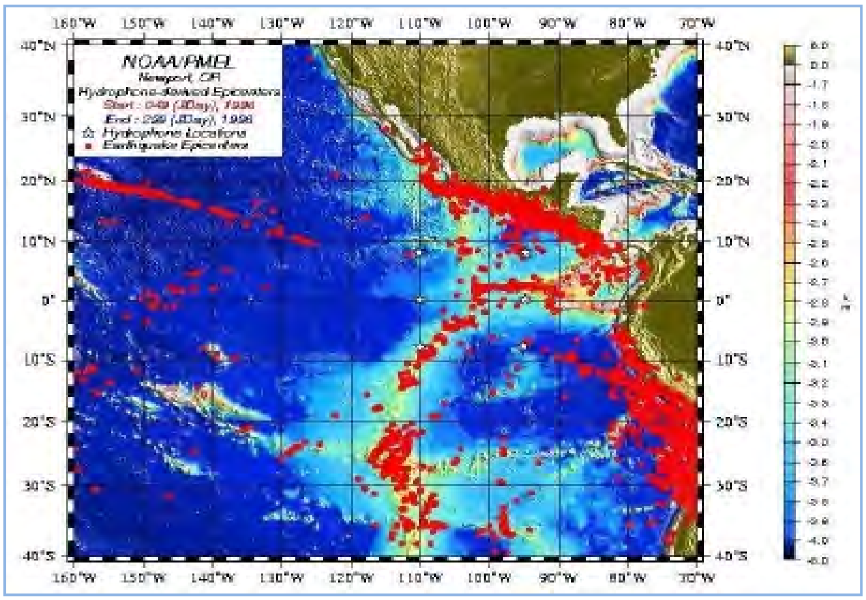


Figure 3: Earthquake epicentres in 1998 (from NOAA/PMEL)

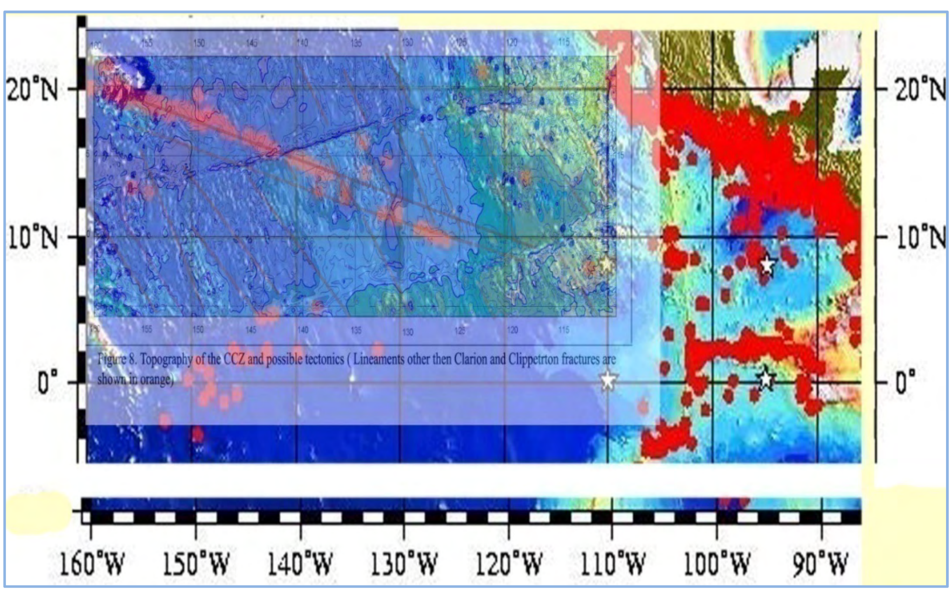


Figure 4: Lineaments in the CCZ and position of earthquake epicentres in 1998 according to NOAA/PMEL

The reserved blocks are located in all morphological areas of the CCZ, that is, in all tectonic and volcanic structures, which are reflected by seabed morphology. It is interesting to note that some reserved blocks partly enter into the zone of the Clarion fracture (block 17) in the north of the Clipperton fracture and (block 23) in the south.

The local relief also expresses tectonics. Throughout the entire CCZ are typically hilly plains with longitudinal trend of the relief forms (*Figures 5, 6, 7 and 8*).

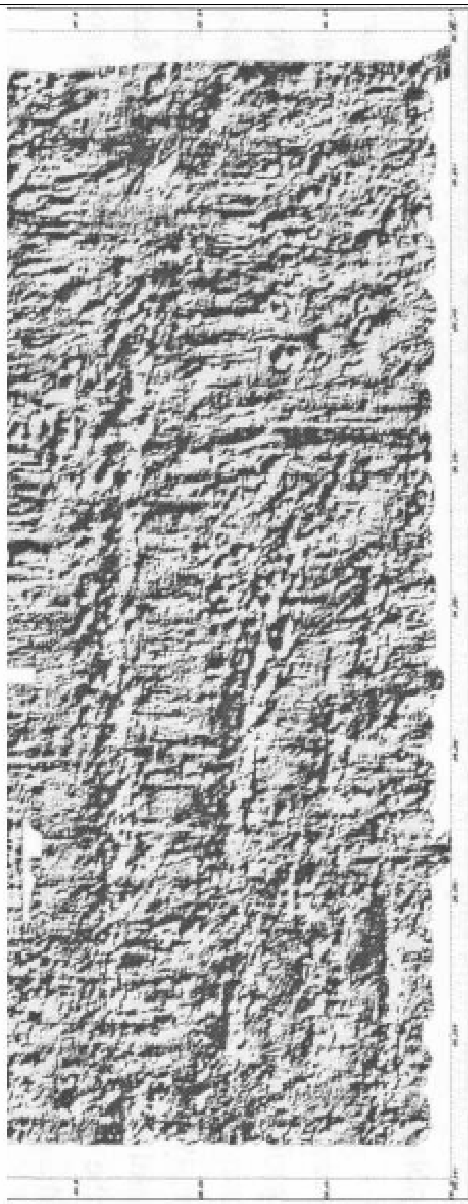


Figure 5: Local relief in the eastern flank of the Line Islands Chain (from Lu Wenzheng "Characteristics of the Distribution and Control Factors of the Polymetallic Nodules in the West Region of CCFZ (China Pioneer Area)", ISA Meeting, Kingston, January 2003

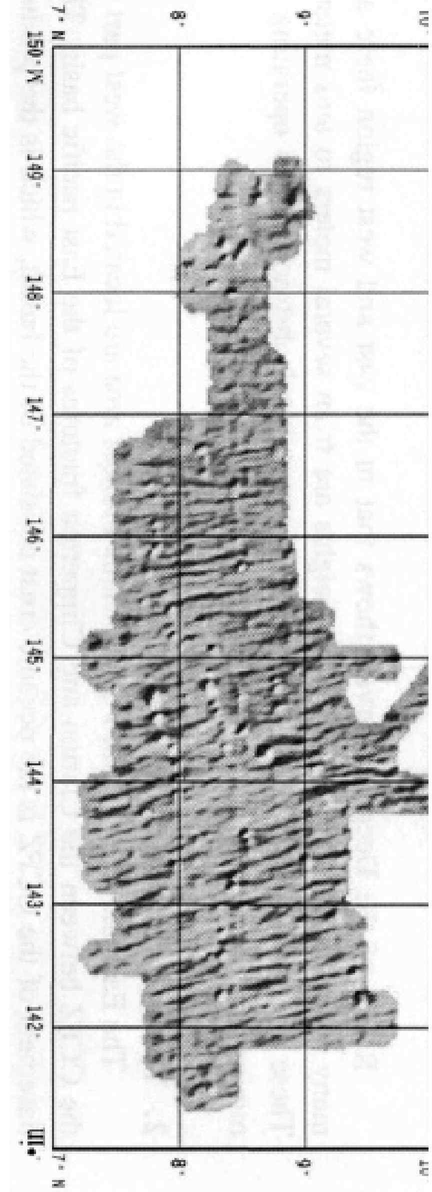


Figure 6: Local relief in the western part of the abyssal plain of the CCZ (from Lu Wenzheng "Characteristics of the Distribution and Control Factors of the Polymetallic Nodules in the West Region of CCFZ (China Pioneer Area)", ISA Meeting, Kingston, January 2003

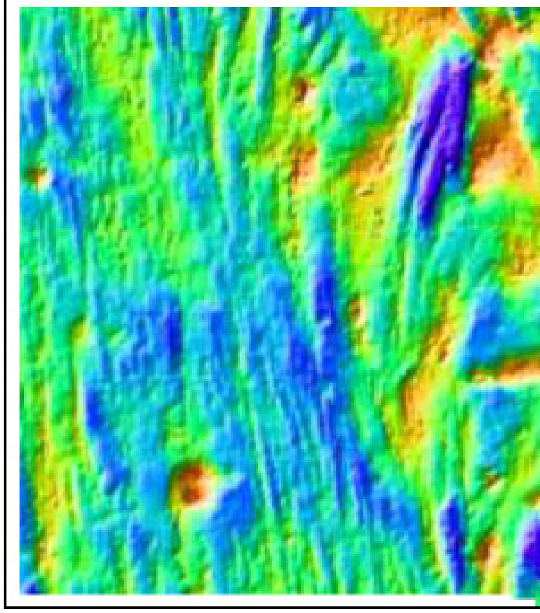


Figure 7: Local relief in the abbysal plain of the CCZ (by courtesy of Yuzmorgeologiya)

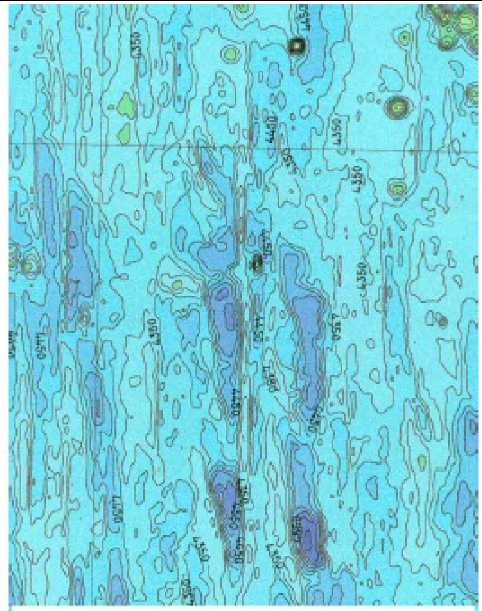


Figure 8: Local relief in the western flank of the EPR (by courtesy of IOM)

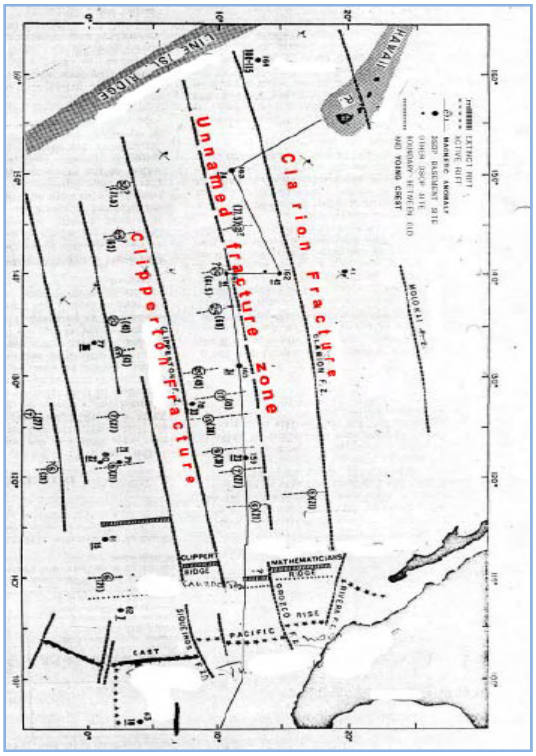
They are mainly hills, plateaux, and basins/valleys with generally gentle slopes which reflect horst and graben structure and the topography of the basaltic substratum formed by sub-longitudinal faulting and fracturing of the basement. That resulted also in rather steep slopes of valleys in some areas. The longitudinal extent of single valleys and hills varies from 5-10 to 100 km; and the width, from one to tens of kilometres. The elevations of high relief vary from 100 to 300 m.

According to Lu Wenzheng (2003), the local topography in the area located in the eastern flank of the Line Islands Chain is dominated by seamounts and seamount chains of sub-latitudinal direction (Figure 5) with elevations of 500-1,000m above the sea bottom. In the intermountain areas, the local relief is represented by chains of hills and valleys with gentle slopes with clear longitudinal direction.

Nodule abundance and tectonics

Our study on a global scale revealed a striking correlation between nodule abundance and a global fracture zone extending along the central axial part of the CCZ through the entire length of zone.

The Unnamed fracture zone (*Figure 9*) was first assumed in 1973 by Tjeerd H. van Andel and G. Ross Heath (1973), who summarized the geological results of Leg 16 of the Deep Sea Drilling Project in the Central Equatorial Pacific, including the CCZ.



The Project helped to clarify the tectonic and depositional history of the region and to establish basement ages. The authors were the first to compile a tectonic sketch of the region, including the CCZ, which showed (together with location of drill sites) magnetic anomaly patterns, position of fracture zones and extinct spreading centres (Mathematicians Ridge). According to Van Andel and G. R. Heath (1973) and references contained therein, this fracture zone was predicted by Sclater *et al*. (1971). It can be traced across the Line Islands Ridge and is required by ages and position of drill sites on both sides. Herron (1972) has assumed a fracture zone in approximately the same position.

Figure 9: Tectonic sketch of the Eastern Central Equatorial Pacific (from Tjeerd H. van Andel and G. Ross Heath "Geological results of Leg 16…" initial Reports of DSDP, vol 16, 1973)

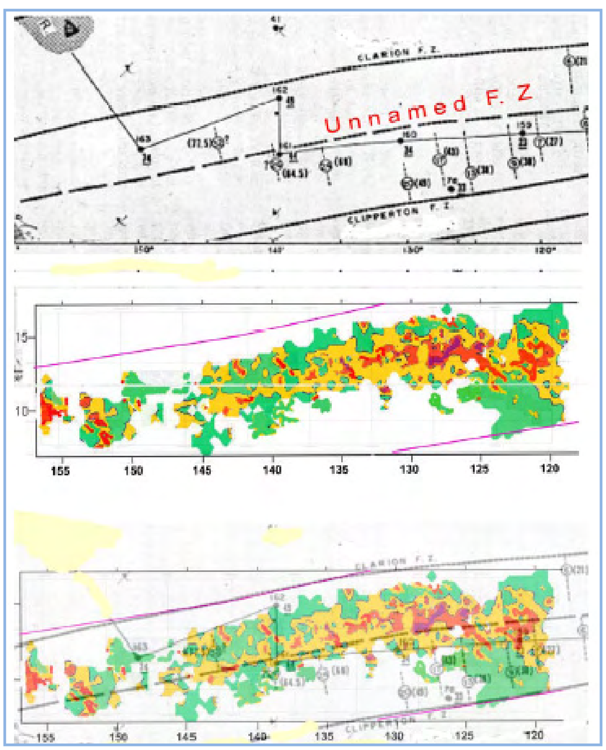


Figure 10 represents our comparison of the position of high nodule abundance anomalies with the position of the "Unnamed" fracture zone according to Van Andel and G.R. Heath (1973) which indicates their general correlation except some local deviation between longitude 125°W and 135°W.

Figure 10: Position of the "Unnamed fracture zone" (from Tjeerd H. van Andel and G. Ross Heath, 1973) and Nodule Abundance in the CCZ

The results of nodule research in the CCZ by the Russian enterprise "Sevmorgeologiya" (S. Andreev, 1994) confirm that the Unnamed Fracture has a positive relationship with high nodule abundance and cobalt concentrations. The position of the “Unnamed” fracture zone according to S. Andreev (1994) is shown in *Figures 10 and 11*.

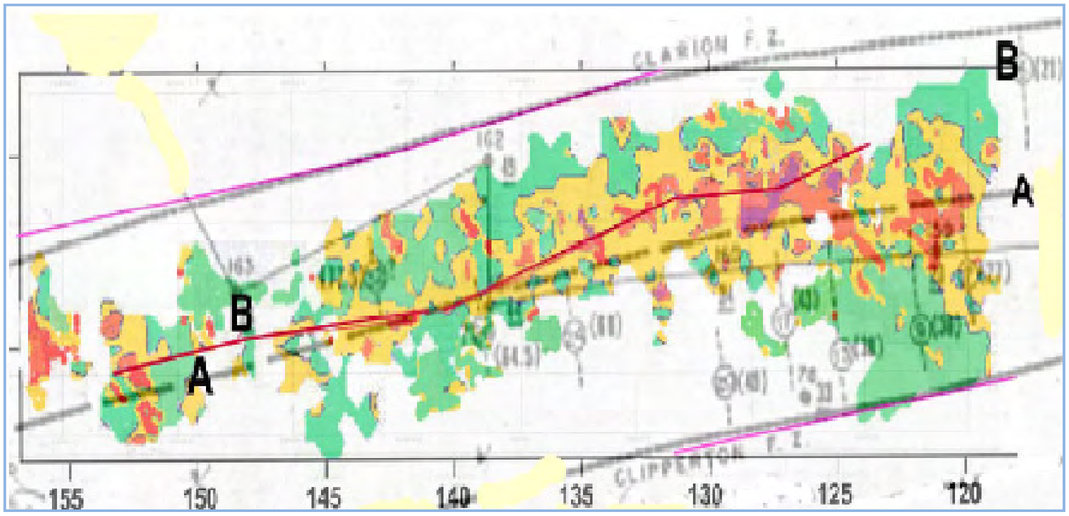


Figure 11: *Position of the “Unnamed fracture zone” (A from Tjeerd H. van Andel and G. Ross Heath, B from S. Andreev) and Nodule Abundance in the CCZ.*

Although there are some unimportant deviations, it resembles the position of the fracture which was assumed by Van Andel and Heath in 1973, and it clearly indicates a correlation of nodule abundance with the fracture zone in the area between longitude 125°W and 135°W, which was clear from the 1973 map.

The measurements of nodule abundance and metal content of manganese, iron, nickel, copper, and cobalt along four profiles across the “Unnamed” fracture zone (*Figure 12*) had shown that manganese and iron have no visible connection with the fracture. Nickel and copper do not show a clear correlation.

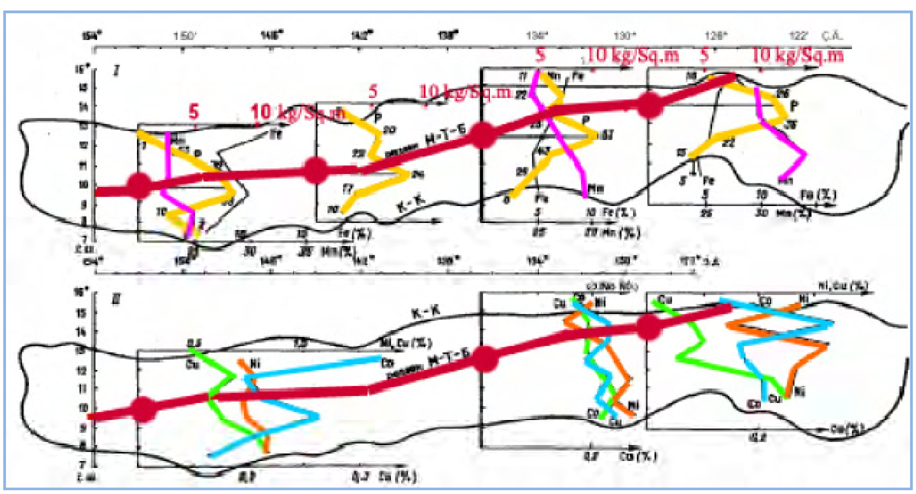


Figure 12: Unnamed Fracture Zone and Nodule Abundance and Grade (modified from S. Andreev, 1994)

The cobalt content in the fracture zone is regularly increased. The nodule abundance can be clearly connected with the fracture. On the profiles in the proximity of the fracture it reaches the maximum value. The research done considered the fracture not only as a probable conductor of the delivery of metals, but also as a supplier of oxygen. It surplus might have lead to active formation of the large volumes of nodules.

In *Figure 13*, we attempted to delineate possible fractures and faults by spatial disposition and configuration of nodule fields with various abundances. It clearly indicates that the latter have certain interrelationship with lineament systems of various order and direction. The predominant trend of lineaments is in a NW and a NW-W direction.

Further analysis led to an assumption that the "Unnamed" fracture zone might have been dislocated and complicated by the NW fault system. Having taken that into account, we reconstructed a hypothetical picture of the Unnamed fracture (*Figures 14 and 15*), which shows a distinct correlation with the axial belt of high nodule abundance in the CCZ.

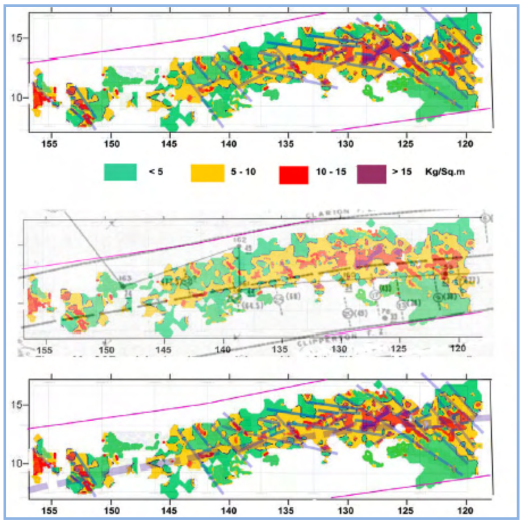


Figure 13: CCZ nodule abundance and tectonics (position of the Unnamed fracture and possible faults

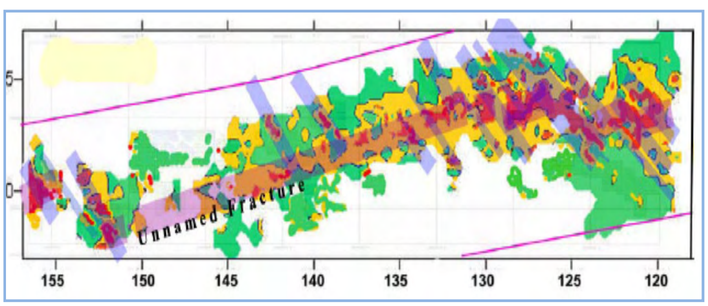


Figure 14: Possible relationship of nodule abundance in the CCZ with global fractures/faults systems

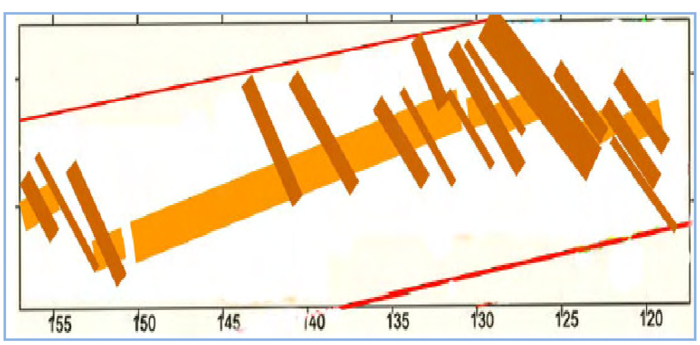
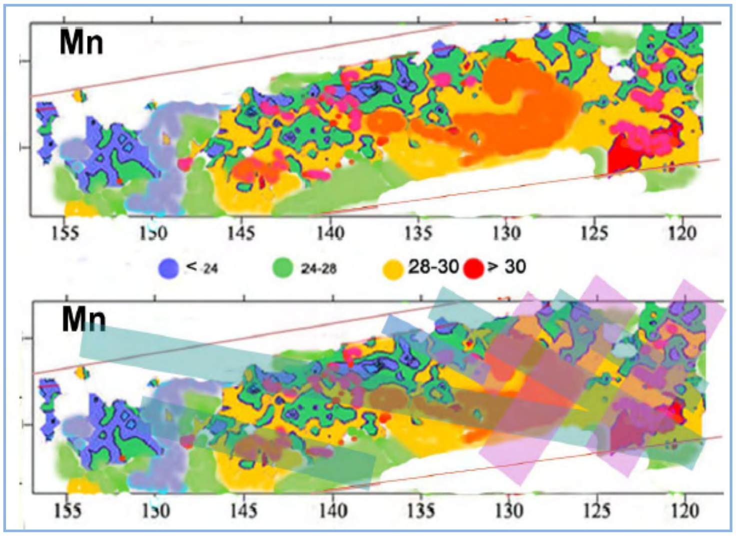


Figure 15: Lineaments related to nodule abundance

Metal content and tectonics

Manganese

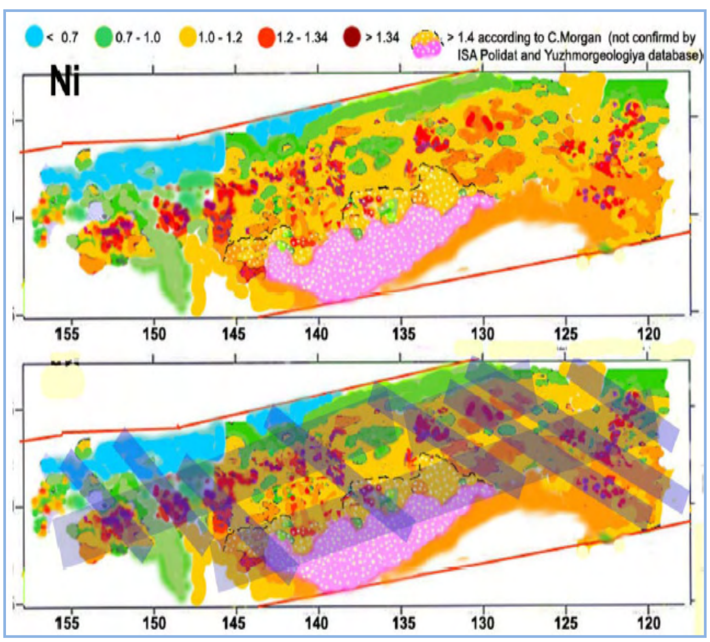
Figure 16 contains an attempt to delineate possible fractures and faults by configuration of nodule fields and spatial distribution of manganese anomalies along lineaments.



There is a clear relationship of manganese concentrations in the central part with possible fault system of a NW-W direction (290-300^{o}). In the Eastern part of the CCZ, where the fields with manganese content occupy more than 30 per cent vast areas, the manganese anomalies follow also the direction of NW and NE lineament systems, the highest concentrations being localised at the crossing points of such systems. The comparison of lineaments related to nodule abundance and manganese content show no correlation.

Figure 16: Manganese concentration and Lineaments in the CCZ

Nickel



From *Figure 17*, it may be assumed that nickel anomalies are influenced generally by lineaments of an E-NE direction along the extension of the CCZ, and are also controlled by subordinate order fault systems of a NW direction.

Figure 17: Nickel concentration and Lineaments in the CCZ

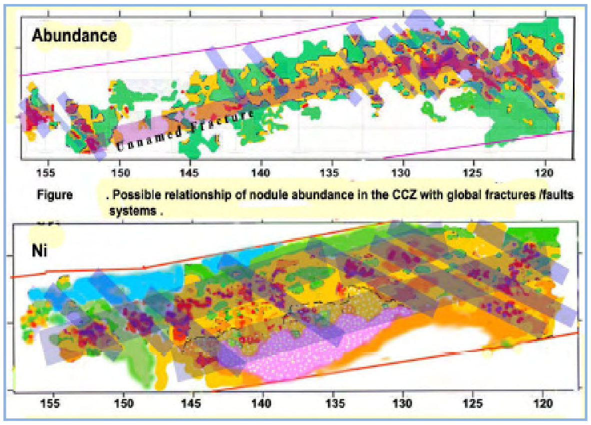
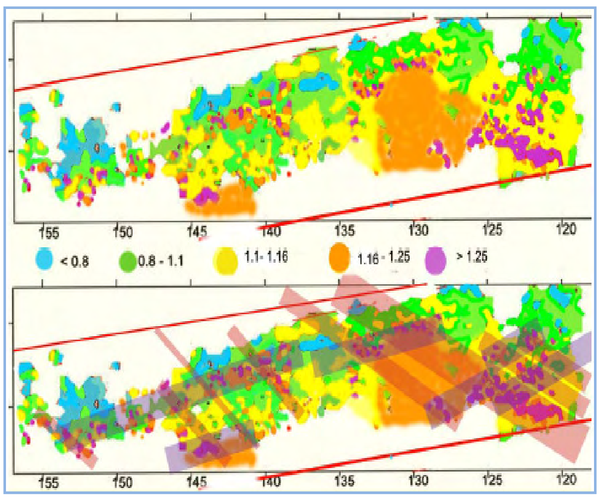


Figure 18 indicates that there is a certain correlation of lineaments related to nodule abundance and nickel content as a general trend. However, nickel anomalies tend to be confined to the linear zones which are located to the north and south of the axial “Unnamed” fracture zone.

Figure 18: Nodule abundance, Nickel concentration and Lineaments in the CCZ

Copper



As can be seen in *Figure 19*, in the eastern part, the largest anomalies of high content of copper are located in the western flank of the East Pacific Rise, in the close vicinity of the Clipperton fracture. Here they are generally controlled by the NW (330-310^{o}) lineaments system, which is complicated by faults of the NE direction.

To the west of 130^{o}W, the anomalies with copper content more than 1.16 per cent are scattered throughout the entire extension of the CCZ along the "axial" belt, following a general pattern of the “Unnamed” fracture zone.

Figure 19: Copper concentration and Lineaments in the CCZ

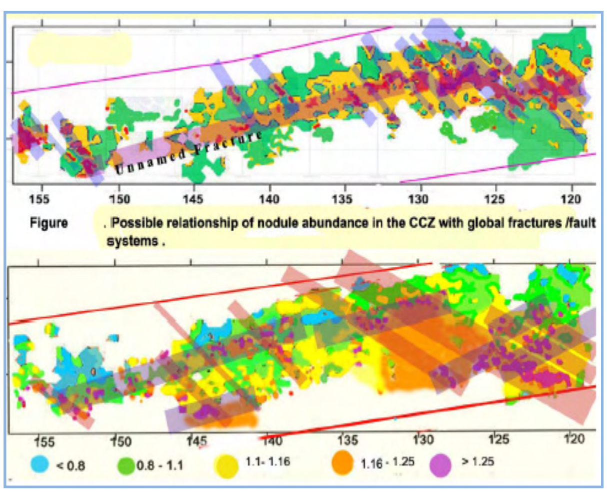


Figure 20 confirms that the general trend of lineaments for the eastern part is different for nodule abundance and copper grade. To the west of longitude 130^{o}W, one can find a correlation of possible fault systems related to abundance and copper.

Figure 20: Copper concentration and Lineaments in the CCZ

Cobalt

An analysis of the cobalt grade distribution (*Figure 21*) has shown that the highest grades are confined to the areas in the northern part of central zone close to the "Unnamed" fracture zone. As has been mentioned above, the nodule abundance and metal content of manganese, iron, nickel, copper, and cobalt along four profiles across the "Unnamed" fracture zone, had shown that the increase of cobalt content has a visible connection with the fracture.

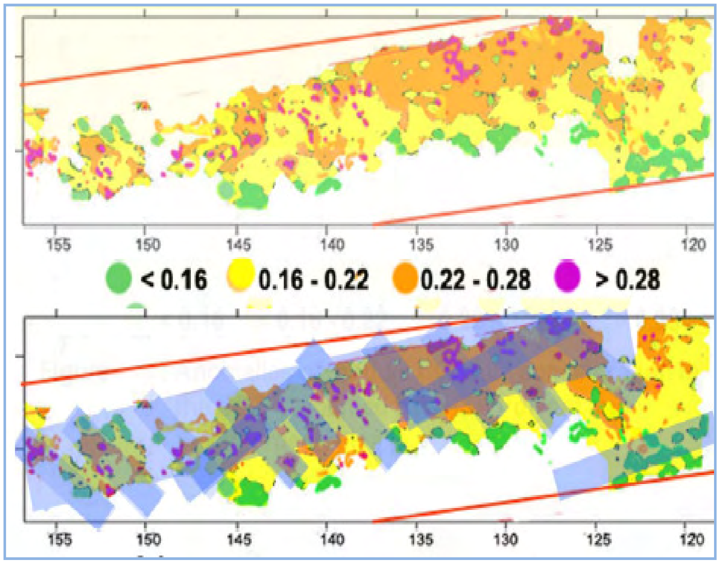


Figure 21: Nodule cobalt concentration and Lineaments in the CCZ

At the same time, the configuration of cobalt anomalies also shows their relation to the lineaments of a NW direction, which may be subordinate systems crossing the "Unnamed" fracture zone.

Our comparison of lineaments related to nodule abundance and cobalt content (*Figure 22*) reveals a general relationship of major possible tectonic features controlling or influencing these nodule parameters.

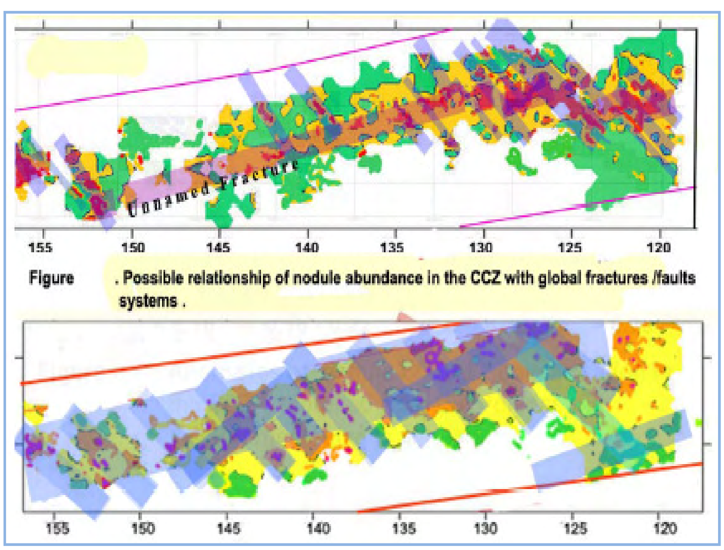


Figure 22: Nodule abundance and cobalt concentration and lineaments in the CCZ

Figures 1 to 22 represent our attempt at a comparative analysis of possible relationships between various lineaments related to manganese, nickel, copper and cobalt concentrations. It shows that lineaments related to manganese have no correlation with those related to the three other metals.

Nickel and copper lineaments have no correlation with the areas with high metal content, although in the western parts, small anomalies follow a similar pattern.

Nickel and cobalt lineaments indicate a certain correlation with respect to their general direction and even coincide in the northernmost part of the CCZ.

There is no correlation with respect to the lineaments related to copper and cobalt.

Conclusions

The following conclusions, or rather assumptions, can be made from the study:

- There is a certain relationship between nodule abundance and nodule metal grades and possible fault and fracture systems on a global scale, as indicated by spatial distribution and configuration of the anomalies of high abundance and metal content for all four metals: manganese, nickel, copper and cobalt.
- Nodules have a visible relationship to the “Unnamed” fracture zone along the entire extension of the CCZ.
- Manganese concentration is related to a global fault system, which is traced as a southeast extension of the Hawaiian volcanic chain. It is clearly marked by the location of earthquake epicentres, registered in 1999. This system is of a planetary scale and crosses the East Pacific Rise. It could be a major control factor responsible for manganese supply.
- Copper content may have a relationship with the Clipperton fracture in the east near the spreading centres of the East Pacific Rise, where young volcanic activity may be related to the concentration and supply of copper.

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SUMMARY OF THE PRESENTATION

Dr. Kazmin said that he would present the results of acoustic surveys, side-scan sonar surveys, and bathymetric swath mapping to highlight his presentation on the relationship of nodule grade and abundance with tectonics and volcanic activity in the Clarion-Clipperton fracture Zone (CCZ). First, with regard to the question of the density of information, he said that survey lines had been run in acoustic spacing of a few kilometres or less, and the reconnaissance surveys had been checked with air guns at 3.5 kilowatt acoustics.

He said that bathymetry was tremendously important in sedimentation processes. He indicated the northernmost area of the CCZ, between the two major fracture zones and pointed to a typical ridge welling system, which he said was sometimes dotted with little cones on top of the ridges. He said that that the cones are at elevations ranging between a few hundred and five hundred metres.

Dr. Kazmin showed an illustration of the typical seafloor appearance in an area of the CCZ, a dark opaque basement, on top of which an acoustically transparent zone could be seen. It had varying thickness. In the center of the area was a hill, which rose from 500 metres above the neighbouring plains. Dr. Kazmin then pointed to a detailed profile of the area, in which the transparent layer could be seen; underneath, there were opaque reflections, which he said had to be clarified and that had been done on the basis of intercalibrations with known seismics which were linked to deep-sea drilling or, ODP sites. He indicated in the illustration, the transparent layer on top of the formation.

Dr. Kazmin informed participants that during this leg of the deep-sea drilling project scientists had drilled through this formation, and therefore, the seismics were easily calibrated. Dr. Kazmin said that this information had also been used to intercalibrate Yuzhmorgeologiya's own records. In the illustration, he indicated the transparent layer on top of the formation, a stratified layer underneath it, a transparent layer beneath the stratified layer, and then an acoustic base. At deep-sea drilling site 163, he said that Yuzhmorgeologiya had been able to calibrate the transparent layer; which consisted of brown clays and radiolarian ooze**.** According to Dr. Kazmin, in the northernmost area, the transparent layer is about 16 metres thick. He said it consisted of, *inter alia*, zeolite brown clays and radiolarian ooze in the lower part of the formation.

Dr. Kazmin said that on top of the basalts found in the area, pockets with single sediment layers might be found. He said that this was the result of a 3.5 kilowatt survey run in the area, around 12^{o} north of the Equator. Dr. Kazmin told participants that in the southern areas, the picture changed dramatically. Through slides, he pointed out a stratified layer that contained individual layers. On top of the stratified layer, one could see a transparent layer. Dr. Kazmin explained that after the samples had been taken, air gun seismics had been used and detailed surveys were run.

Dr. Kazmin said that all the seismic work had been calibrated including other transparent layers from early Miocene to Pliocene, radiolarian and zeolitic clays and oozes. The charts that he showed illustrated the different hiatuses created between the early Miocene, and the Pliocene. He indicated a lower transparent layer underneath, which consisted of radiolarian nannofossil ooze and chalk. What could be seen, he said, was a high degree of alteration of segments from soft into hard; one got diagenetic nodules.

Dr. Kazmin said that what was left was a siliceous nannofossil layer based on the lower stratified layer. Those layers ranged from middle Eocene to early Miocene. He indicated another important hiatus, which formed the first generation of nodules, which later became fragmented, and formed the basis for a new, younger generation of nodules, which had formed and started growing at the hiatus between early Miocene and Pliocene. This was the story for the area lying in the south. He drew the participants' attention to the transparent layer which he said was limited to two small areas. He showed that the stratified layer, lying underneath the transparent layer cropped out at various points. He also pointed out a basalt outcropping, or basement outcropping, with a little sediment layer on top of it.

Dr. Kazmin showed that on the western flanks of the basalt hill, the transparent layer thickened and was similar to the situation in the north. He said that in the north, the accumulation of sediment was much thicker than the average terrain.

Through an illustration, Dr. Kazmin showed that in the southern area, a dramatic thickening of the transparent layer occurred. He remarked that the varying thickness of the transparent layer would have to be taken into account in model development.

Dr. Kazmin spoke about the stratigraphy and hiatuses in the area. With regard to stratigraphy, he said it wasn't as thick as the transparent layer, and that it consisted of radiolarian zeolitic clays and oozes, interspersed with carbonate. With regard to hiatuses, he said that in the north they were from the late Miocene period while in other areas they ranged from early to middle Miocene.

Dr. Kazmin spoke about tectonics and structure**.** He said that he had put the issue in his presentation based on knowledge of the structure of the crust, the magnetic anomalies and their ages. He recalled that in another presentation a remark was made that the topography expressed the regional tectonics. Dr. Kazmin said he agreed with the remark because the topography expressed the tectonics not only on a regional and global scale, but also on a local scale.

In this regard, Dr. Kazmin invited participants to take a closer look at the global and regional topography in the CCZ through slides, and said that the topography was expressed clearly by the configuration of topographic features, the configuration isobaths, and horsts and fractures. Dr. Kazmin also said that lineaments could be traced by analysing the topographic features of the bathymetry in the Clarion-Clipperton Zone on a global scale. He recommended the compilation of a very good topographic map of the Clarion-Clipperton Zone as a basis for the geological model.

With regard to nodules and tectonics and faults, Dr. Kazmin informed the workshop that he had undertaken research and studied all the available literature on fractures and faults for the Clarion-Clipperton Zone. He showed participants the last sketch of the Clarion-Clipperton area that had been published by van Andel and Heath in 1973 and said that at that time, no one cared about nodules in the area, except probably international consortia and pioneer investors. It therefore did not deal with the nodule problem, but rather with the map which was produced as a route for the 16th leg of the Deep Sea Drilling Project.

Dr. Kazmin then displayed a map showing the Clarion and Clipperton fracture zone, and said that it showed a station that had been studied in 1973. It was between the two fractures, and later it was discovered that it was another fracture zone. He said that this fracture was parallel to the Clarion and Clipperton fractures. Since it wasn't named at the time, it became known as the "Unnamed" fracture zone. Dr Kazmin said that before the discovery of the "Unnamed" fracture zone, its existence had been predicted by scientists dealing with seafloor spreading in the Eastern Pacific area. He said that the "Unnamed" fracture zone had later been studied by Russian geologists who had measured nodule abundance and metal content along it. Dr. Kazmin also said that there was a striking correlation between all the positions of that fracture with the nodule abundance anomaly.

Referring again to the research carried out by the Russian geologists, Dr. Kazmin said that they had measured abundance and metal content along four profiles in the Clarion-Clipperton Zone and found that except for cobalt, there was no correlation between metal values and the "Unnamed" Fracture Zone. He said that he had combine the information on lineaments with the "Unnamed fracture" zone and concluded that a new fracture zone was growing along the axis of the Clarion-Clipperton zone, located in a northwest direction coinciding with nodule abundance anomalies.

Through other slides showing lineaments, tectonics and metal contents, Dr Kazmin made statements about the relationships between anomalies of nickel, copper and cobalt with leneaments and tectonics.

Dr. Kazmin said that although he could not prove it, his theory is that the abundance of nodules in parts of the CCZ had been caused by the change in tectonics caused to “Unnamed” fracture zone in the centre of the Clarion-Clipperton Zone. He observed that the explanation was obvious because it had already been established that fracture zones were the source of the supply of additional oxygen, from the circulation of cold, bottom water. He said that bottom water, rising through the fractures causes temperatures to increase, decreases the dissolution of oxygen, which is then made available for nodule growth in relation to manganese and iron oxides

With respect to manganese, Dr. Kazmin said that it was also natural that the source might be endogenous, because it was known that the main proxy for the rise in hydrothermal activity was manganese anomalies in water. He said that whether the search objective is hydrothermal activity or massive sulphides deposits, the first step was to measure anomalies of manganese in seawater. Dr. Kazmin said that the main source of manganese in the Clarion-Clipperton Zone was its tectonic structure trending through Hawaii to South America.

In conclusion, Dr. Kazmin said that there were two schools of thought with regard to the source of the nodules and the results for growth, accumulation of nodules in the particular area under discussion. He was of the opinion that tectonic and other features that he had addressed in his presentation along with factors such as the location of the Calcium Carbonate Compensation Depth (CCD) and biological productivity led to the formation of nodules, their abundance and the metal enrichment of nodules.

SUMMARY OF THE DISCUSSIONS

A participant asked Dr. Kazmin how much hydrothermal activity played in the metal content of nodules. Specifically, the participant referred to two of Dr. Kazmin’s slides where greater nodule abundance is observed above the “Unnamed” fracture zone and in the other, there appeared to be a greater distribution of manganese below the fractures.

With regard to the role of hydrothermal activity to metal content, Dr. Kazmin said that he could not explain it, but that he believed that the presence of hydrothermal activity during the formation of metals was proven by two factors: the existence of volcanic ridges and volcanic activity, and volcanic activity as a part of hydrothermal activity. In some places, it was mostly connected; and he said these lineaments are the channels through which hydrothermal activity would enrich the area with nodules.

In conclusion, Dr Kazmin said that on the basis of the available data he had tried to draw the attention of workshop participants to the role of volcanics and tectonics to nodule formation and enrichment. He said for the model, a fundamental issue would be the scale to be used. In this regard, he suggested a scale of one to one million, adding that at such a scale, the widths and sizes of the lineaments would be more precise.

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CHAPTER 9 GEOLOGICAL PROCESSES IN THE FORMATION OF CENTRAL PACIFIC MANGANESE NODULE DEPOSITS

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Introduction

Marine ferromanganese oxide deposits comprise hydrothermal, hydrogenous (hydrogenetic) and diagenetic deposits, respectively. Manganese nodules form a subset with continuous mixing from diagenetic end members - which contain the mineral 10Å manganite (todorokite) and are enriched in manganese (Mn), nickel (Ni) and copper (Cu) - to hydrogenetic end members which contain the mineral δMn O_2 (vernadite) and are enriched in iron (Fe) and cobalt (Co). The diagenetic deposits receive their metals at least in part from the recycling of elements previously hosted in organic phases on their decay and dissolution, whereas the hydrogenetic deposits receive their metals from normal seawater or unenriched interstitial waters. Ore grade manganese nodules fall near the diagenetic end member and contain Ni plus Cu in excess of 2 per cent, which is generally accepted as the lower cut off for "ore grade" manganese nodules.

The diagenetic enrichment of metals in "ore grade" nodules does not derive from deeply buried sediments, but from the recycling of metals within the uppermost sediment sections. Muller et al, (1988) concluded that "surficial diagenesis, either by decomposition or dissolution of biogenic trace metal carrier phases or by reductive dissolution of oxides within microenvironments, may well provide the trace metal amounts required for the formation of deep-sea manganese nodules, and that "trace metals released from their carrier phases at sediment depths greater than a few centimetres would hardly be able to migrate upward through the oxygenated interstitial water environment". Subsequent studies referred to in this paper have borne out these conclusions.

Distribution in the Central Pacific Ocean

Ore grade nodules in the Central Pacific are generally confined to two zones trending roughly east-west in the tropical regions, which are well separated in the eastern Pacific but which tend to converge between longitude 170^{o} and 180^{o}W (*Figure. 1*).

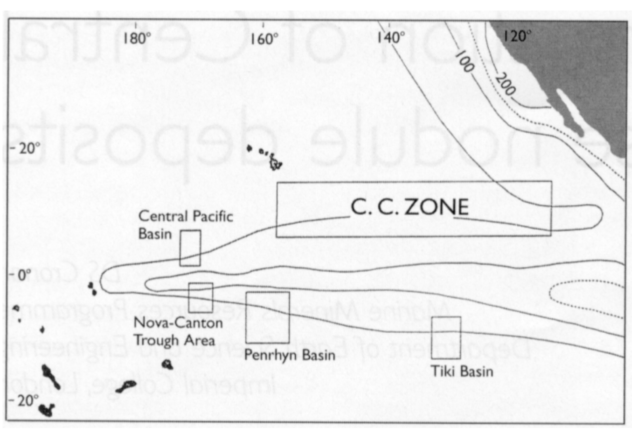

Figure 1: Ore grade manganese nodule bearing areas in the Central Pacific

They follow the isolines of intermediate biological productivity, strongly suggestive of a biological control on their distribution. Within these zones, the nodules preferentially occupy basin areas near the carbonate compensation depth (CCD). Thus they are found in the Penrhyn Basin, Tokelau Basin, Central Pacific Basin, Clarion-Clipperton Zone and Tiki Basin. Nodules in all these areas have features in common and are here suggested to have attained their distinctive composition by similar processes. It is proposed to deal with the Penrhyn Basin deposits first and then attempt to extrapolate the conclusions drawn to the other areas. Comparisons by Cronan and Hodkinson (1994) of bulk nodule data from the Penrhyn Basin with other Pacific nodule data (Halbach & Puteanus, 1988) shows that they fall within the lower and middle parts of the Mn/Fe range for Pacific nodules as a whole. However, nodules from the northern part of the Basin where calcareous/siliceous clay predominates have the highest Mn/Fe ratios and highest Ni and Cu concentrations (*Figure 2*), although they decrease slightly as the equator is approached, reflecting diagenetic supply of metals to them.

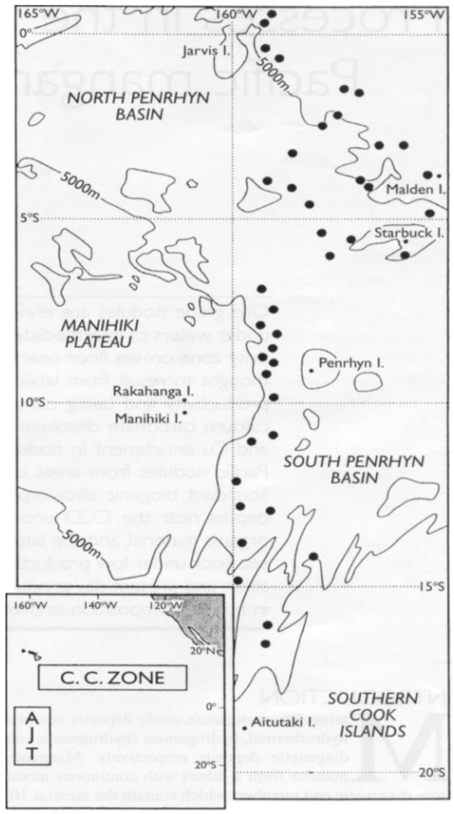

Figure 2: Nodule sampling stations groups in the Penhyn Basin

Superimposed on this trend are variations in nodule composition with their distance above or below the CCD (*Figure 3*).

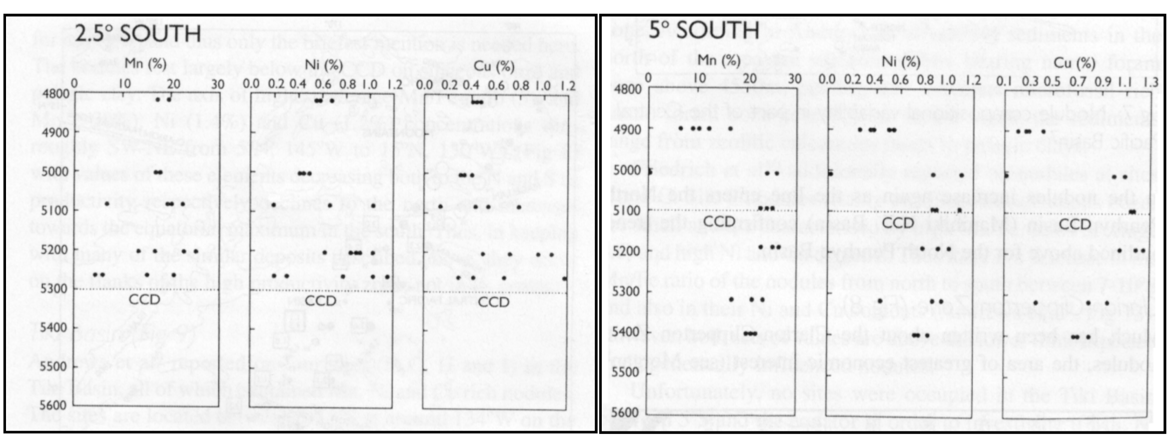

Figure 3: Variations in nodule composition with distances above and below the CCD in the North Penrhyn Basin

In the Mn, Ni and Cu-rich nodule area, maximum values of these metals in nodules occur within about 200m of the CCD. Thus, although overall maxima in Mn, Ni and Cu occur in the latitudinal range where diagenetically formed 10Å manganite predominates (between latitude 2 and 6^{o}S) there is a very wide scatter of metal values within this latitudinal range which diminishes both to the north and south (*Figure 4*) where, respectively, siliceous ooze and pelagic clay sedimentation prevail.

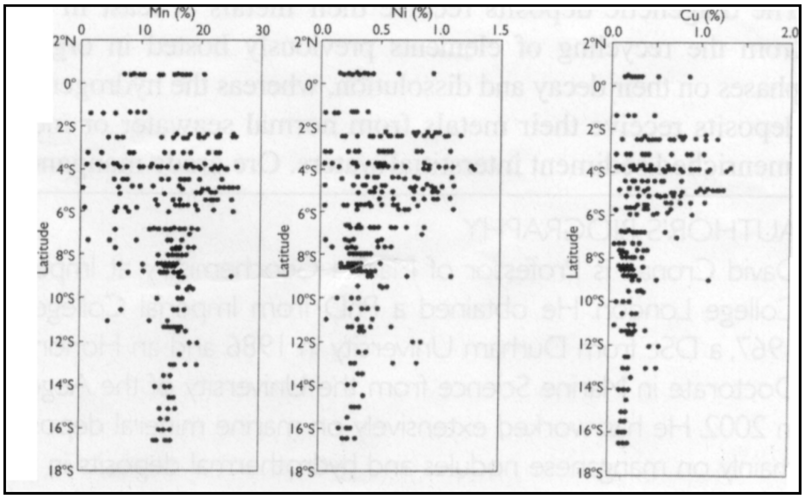

Figure 4: Latitudinal compositional variability of nodules in the Penrhyn Basin

This may be explained by the varying composition of nodules with distance from the CCD under the high productivity area (Cronan & Hodkinson, 1994; Cronan, 1997). The latitudinal variation in Mn, Ni and Cu in Penrhyn Basin nodules may thus be due to there being a hydrogenous Mn, Ni and Cu poor source of these metals throughout the Basin, superimposed on which is a major diagenetic source of them between about 2^{o} and 6^{o}S at depths near the CCD, but less so in the very north of the Basin (between latitude 0 and 2^{o}S) where siliceous sedimentation prevails under highest productivity waters. Miller & Cronan (1994) have shown that the composition of surface sediments in the Penrhyn Basin bears a relationship to that of their associated nodules. Examination of the metal content of surface sediments with latitude on a carbonate-free basis revealed that Mn, Fe, Zn, Co and Pb increase from the equator southwards. Nickel and Cu increase from the equator to about latitude 6^{o}S and 8^{o}S and then decrease again, confirming some additional supply of these latter two elements to the sediments under the southern part of the zone of high biological productivity. The organic carbon content of the sediments varies from 0.03-1.67 per cent of the bulk sediment. The data show considerable enrichments of organic carbon in some of the sediments from the north of the Basin, the ultimate source of which is likely to be from biological production in the surface waters. A relationship between organic carbon and primary productivity is supported by its variations both with water depth and with latitude (*Figure 5*). Values are highest in sediments from north of latitude 6^{o}S on the southern margin of the high productivity zone and near the CCD.

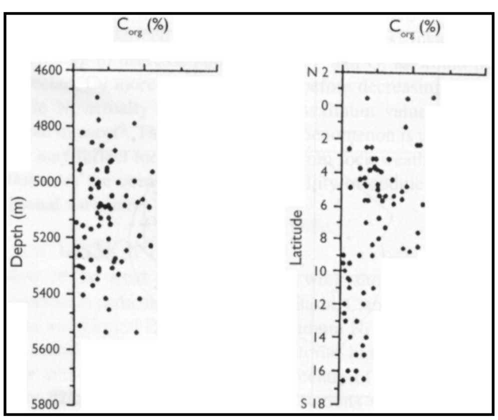

Figure 5 : Variation in organic carbon in sediments with water depth and latitude in the Penthyn Basin.

The Phoenix Island exclusive economic zone and Nova Canton Trough nodule area in and adjacent to the North Tokelau Basin are centred approximately on latitude 2^{o}S and longitude 168ºW in water depths of 5200-5600m. It lies on the southern margin of the high biological productivity zone where it is narrowing westwards. Manganese, Ni and Cu rich nodules are situated within the northeastern part of the Phoenix Islands exclusive economic zone where it abuts the Nova Canton Trough (Cronan & Hodkinson, 1991). Underlying sediments consist largely of siliceous clay in the northern part of the area under the highest productivity waters and brownish pelagic clay in the southern region *(Figure 6).*

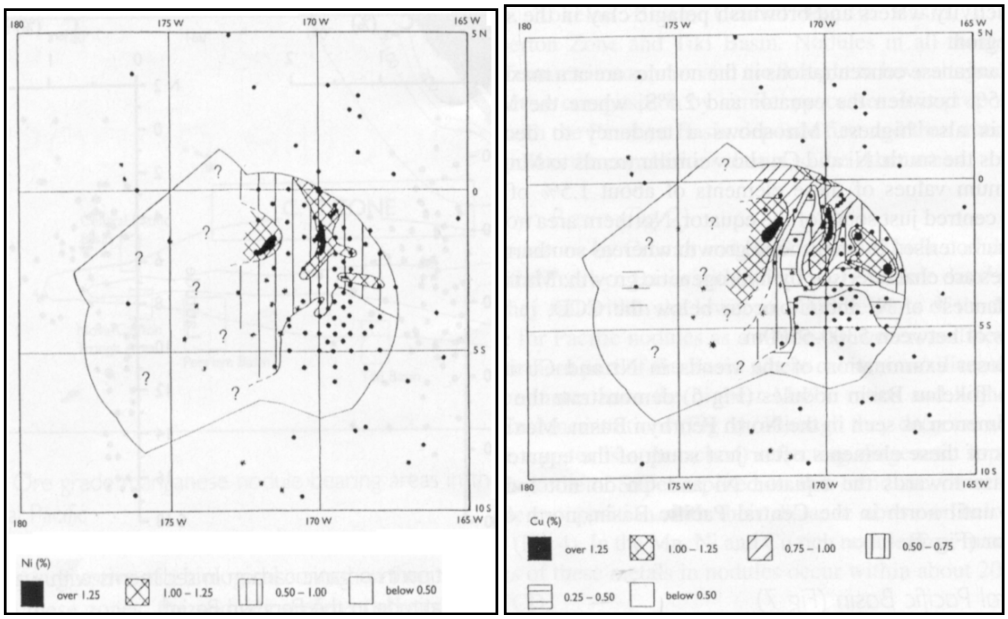

Figure 6: Compositional variability of nodules in the North Tokelau Basin

Manganese concentrations in the nodules are at a maximum of >25 per cent between the equator and latitude 2.5^{o}S, where the Mn/Fe ratio is also highest. Manganese shows a tendency to decrease towards the south. Nickel and copper show similar trends to Mn, with maximum values of these elements of about 1.5 per cent of each being centred just south of the equator. Northern area nodules are characterized by diagenetic growth, whereas southern area nodules are characterized by hydrogenetic growth. Maximum abundances of Ni and Cu occur below the CCD in water depths of between 5300 and 5500m (MMAJ, 1988).

Closer examination of the trends in Ni and Cu in the North Tokelau Basin nodules (*Figure 6*) demonstrates the same phenomenon as seen in the North Penrhyn Basin. Maximum values of these elements occur just south of the equator and decrease towards the equator. Nickel and Cu do not increase again until north in the Central Pacific Basin north of the equator (*Figure 7*).

Usui (1984) described manganese nodules from a transect between Wake Island and Tahiti, part of which passed through the Central Pacific Basin. In the central part of the area, between the Magellan Trough (10^{o}N, 176^{o}W) and the Nova Canton Trough (1^{o}S, 168^{o}W), rough surfaced diagenetic nodules were found associated with siliceous ooze and clay sedimentation below the CCD. These nodules had an average Mn/Fe ratio of about 4 (max 9.9) and contained the highest average concentrations of Mn (24.3 per cent), Ni (1.23 per cent) and Cu (1.18 per cent) found on the transect. Smooth type nodules with lower Ni and Cu contents were found near the Magellan Trough.

Within the Central Pacific Basin, Ni and Cu increase southeastwards from the Magellan Trough to a maximum of 3.6 Ni+Cu+Zn at about 3^{o}N (Zn averages around 0.1 per cent) and then decrease again towards the equator where productivity is highest (*Figure 7*). Clearly, these observations show similarities with those from the North Penrhyn and North Tokelau Basins to the south of the equator in that Ni and Cu increase from low productivity areas towards the high productivity area, but then decrease again as maximum productivity is approached at the equator.

Comparison of the trends in nodule composition between the Magellan Trough and Manihiki Plateau along lines A and B (*Figure 7*) reveal some differences. Along line A the Ni and Cu increase in a fairly regular manner from about latitude 10^{o}N to about latitude 3^{o}N and then decrease again towards and south of the equator (the latter almost certainly influenced by the Manihiki Plateau). By contrast, on line B the southwards increase from latitude 10^{o}N is not so marked and there is more local variability in Ni and Cu content in the nodules than on line A. This may be the result of distal turbidites from the Line Islands Ridge locally increasing sedimentation rates along line B which would decrease their content of diagenetically supplied metals like Ni and Cu. South of the equator on line B, Ni and Cu values in the nodules increase again as the line enters the North Penrhyn Basin (Manihiki N.E. Basin) confirming the trend outlined above for the North Penrhyn Basin.

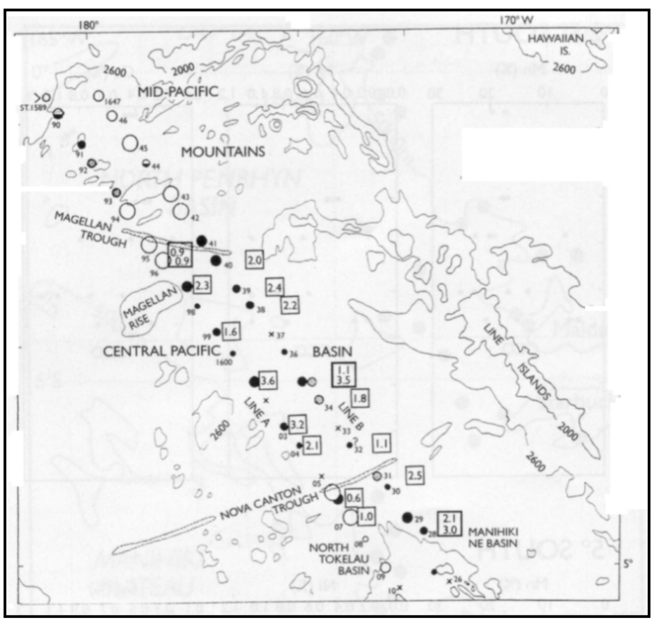

Figure 7: Nodules compositional variability in part of the Central Park Basin

Much has been written about the Clarion-Clipperton Zone nodules, the area of greatest economic interest (see Morgan 2000 for a review), and thus only the briefest mention is needed here. The nodules rest largely below the CCD on siliceous ooze and pelagic clay. The axis of highest average Mn/Fe ratio (5), and Mn (>30 per cent), Ni (1.4 per cent) and Cu (1.2 per cent) concentrations runs roughly SW-NE from latitude 5^{o}N and longitude 145^{o}W to latitude 15^{o}N and longitude 130^{o}W (Morgan, 2000) (*Figure 8*), with values of these elements decreasing both to the north and south as productivity respectively declines to the north and increases towards the equatorial maximum in the south. Thus, in keeping with many of the similar deposits described above, they occur on the flanks of the high productivity zone, not in its centre.

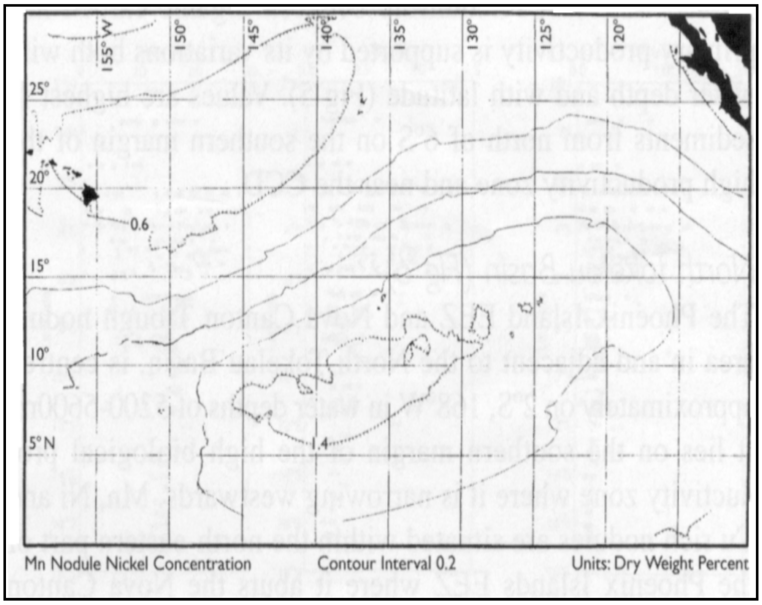

Figure 8: Compositional variability of nodules in the Clarion Clipperton Zone

Andrews *et al*. (1984) reported on four sites (F, G, H and I) in the Tiki Basin, all of which contained Mn, Ni and Cu rich nodules. The sites are located between latitudes 5 and 15^{o}S at around longitude 134^{o}W on the southern flank and south of the high biological productivity zone. According to Andrews et al. (1984), sediments in the north of the area are siliceous debris bearing nanno foram ooze above 4550m, passing into siliceous microfossil rich nanno foram ooze below the CCD. In the south, the sediments range from zeolitic calcareous muds to pelagic clays.

Friedrich et al. (1983) additionally reported on nodules at sites F and G. Site F nodules resting on siliceous/calcareous oozes are small and are characterized by high Mn/Fe ratios (average 4.8) and high Ni and Cu contents. Thus, there is a decrease in the Mn/Fe ratio of the nodules from north to south between latitudes 7^{o} and 10^{o}S and also in their Ni and Cu contents (Andrews et al., 1984). However, both sets of values are above the lower limit expected in diagenetically influenced nodules.

Unfortunately, no sites were occupied in the Tiki Basin between latidue 5^{o}S and the equator in order to investigate whether Mn, Ni and Cu decrease as the equator is approached as they do in the Penrhyn Basin. At site E, right on the equator near the centre of the productivity maximum, no nodules at all were found.

Sites H and I (*Figure 9*) nodules show some anomalous features in regard to their Ni and Cu contents, compared with what might be expected in view of the nodules' metal behaviour described above in the other basins. Instead of continuing to decrease south of sites F and G, as would be expected, Cu more or less levels off before decreasing again, while Ni actually increases to its maximum value for the whole transect. (Andrews et al. 1984). The reason for this phenomenon is unknown and may affect local sources of Ni from rock weathering. It illustrates the occasional unpredictability of nodule compositional variation.

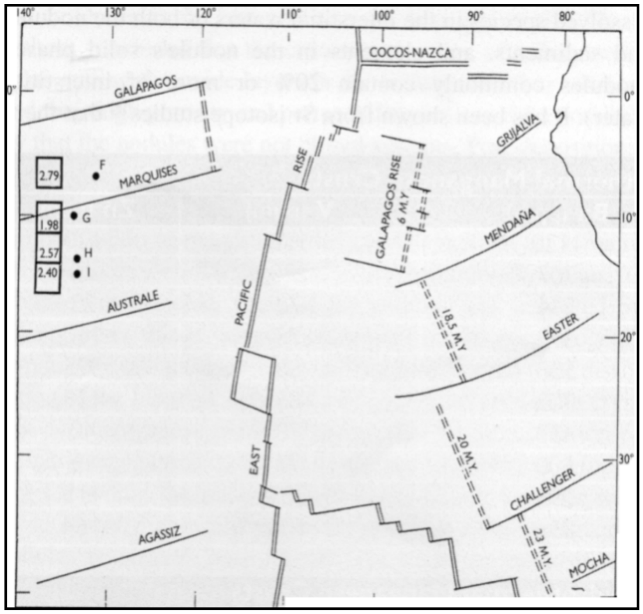

Figure 9: Nodule compositional variability in part of the Tiki Basin

Discussion

Most of the areas described in this work show features in common. In particular, in the Penrhyn Basin, Clarion-Clipperton Zone and Central Pacific Basin, maximum Ni and Cu values are found on the flanks of the equatorial high productivity zone and decrease both towards the centre of that zone and away from it. In the Tiki Basin, no stations were occupied between the equator and latitude 5^{o}S, so it is not possible to say whether the same trend occurs there. In the North Tokelau Basin, the highest Ni+Cu values of over 2.5 per cent are separated from the highest values in the Central Pacific Basin to the north by lower values along the equator, and so the trend seen in all but the Tiki Basin occurs there too.

Cronan and Hodkinson (1994) and Cronan (1997) developed a model to explain the compositional variability of nodules in the Penrhyn Basin, which can be summarized as follows. Under the flanks of the high productivity area, reduced sedimentation rates due to calcium carbonate dissolution near the CCD enhance the content of organic carbon-bearing phases (faecal material, marine snow, etc.) in the sediments there, the decay of which promotes 10Å manganite and Mn, Ni and Cu enrichment in the nodules.

Away from the CCD, organic carbon concentrating processes are less effective. South of about 6^{o}S, as productivity declines, there is probably insufficient organic carbon supplied to the seafloor to promote the formation of diagenetic nodules at any depth. North of about latitude 2^{o}S, siliceous ooze replaces pelagic clay as the main sediment builder at and below the CCD, and its high rate of accumulation dilutes the concentrations of organic material at all depths to levels below that at which diagenetic Mn, Ni and Cu rich nodules can form.

To a greater or lesser extent, this model can account for much of the variability in nodule composition found in the other South Pacific basins described here, although local factors may modify it as in the Tiki Basin. As the South Pacific basins deepen to the west, where the productivity isolines converge, more and more of the sea floor is below the CCD and the areas of diagenetic nodules tend also to occur below the CCD, for example, in the North Tokelau Basin. The settling rates of large organic particles are quite fast in the deep ocean. For example, Berger and Wefer (1992) report that, at 4000m, the flux of organic matter can be similar to that at 2000m. Probably only limited decay of this material takes place between it settling through the CCD and reaching the sea floor, although these authors imply that more could take place during its re-suspension in the benthic boundary and nepheloid layers. Nevertheless, enough organic matter forms sediment to extend the depth of diagenetic nodule formation to well below the CCD under high productivity areas of great depth and limited sediment accumulation. This may partly explain the asymmetric distribution of elements in nodules in relation to the CCD.

In the North Pacific, the trends in nodule composition in relation to the equatorial zone are reversed. Thus, in both the Central Pacific Basin and the Clarion-Clipperton Zone, the highest nodule grades occur in diagenetic nodules on the northern flanks of the high productivity area and decline both to the north and south. The general model erected to explain the Penrhyn Basin nodule variability thus probably applies, at least in part, to these areas also.

The role of siliceous sedimentation in influencing nodule composition has been discussed by Friedrich et al. (1983), who proposed that the dissolution of metal-bearing siliceous organisms can lead to the liberation of Mn, Ni and Cu into interstitial waters and their uptake into forming nodules. However, the observations in the preceding sections point to a seeming paradox in this regard. For example, siliceous sedimentation in the Penrhyn Basin between 0-2^{o}S appears to reduce Mn, Ni and Cu uptake in the nodules there, compared with the concentrations of these metals found in the nodules between latitudes 2^{o} and 6^{o}S, whereas in the Clarion-Clipperton Zone, some of the highest concentrations of these metals in Pacific nodules occur in those resting on siliceous sediments. The resolution of this paradox may lie in the rate of accumulation of the siliceous sediments, rather than in their composition. Friedrich et al. (1983), note that siliceous sediment accumulation rates in the CCZ have been low since Miocene times. This could have led to metal mearing carbonaceous organic material being concentrated in them near and below the CCD, as outlined for the subequatorial Penrhyn Basin (latitudes 2^{o} and 6^{o}S) by Cronan and Hodkinson (1994), and the nodules resting on them accordingly being enriched in diagenetically supplied metals. By contrast, in the equatorial Penrhyn Basin (between latitudes 0-2^{o}S), siliceous sedimentation rates may be too high for this to take place to the same extent. Bostrom et al (1973) reported very high concentrations of opaline silica in sediments from the equatorial North Penrhyn Basin and adjacent areas, higher than in the Clarion-Clipperton Zone, but had no data on sediment accumulation rates there. Another apparent paradox in accounting for nodule compositional variability is that bulk nodule compositions appear to reflect modern productivity conditions, and yet the nodules have been forming over quite long periods of time, in some cases, since the Miocene. During these long periods, environmental conditions must have varied and certainly could have been different from those prevailing today. For example, Berger and Herguera (1992) present evidence for a major productivity decrease in the western equatorial Pacific between the glacial and postglacial time. Productivity there was about 1.8 times higher in glacial than in postglacial times. Are these differences reflected in the composition of the underlying nodules? In order to answer this question, detailed layer-by-layer studies on the nodules would be needed.

An alternative possibility to account for the bulk composition of nodules reflecting present-day productivity conditions is that post-depositional changes in nodule composition over time can result in their "equilibriating" with changing depositional conditions. The open porous nature of the nodule structure would lend itself to exchange reactions between dissolved species in the nodule and sediment interstitial waters and elements in the nodule's solid phases (nodules commonly contain 20 per cent or more of interstitial water). It has been shown by Vonderhaar *et al*. (1995) from Strontium (Sr) isotope studies that there is exchange of Sr with seawater in some ferromanganese oxides and that this takes place throughout the history of the deposit regardless of its porosity. If Sr can behave in this way, so possibly can other elements.

Evidence for metal exchange between the solid phase of ferromanganese oxides and sediment interstitial waters is also forthcoming from studies carried out on ferromanganese oxide crusts from the S.W. Pacific (Cronan *et al*, 2002). During leg 135 of the ODP, some fossil buried hydrothermal ferromanganese oxide crusts were recovered in the Lau Basin. The stratigraphic location of the crusts in the sediment section would suggest that they range between 0.2 and 3.5 million years old. In comparison with modern hydrothermal crusts from the region, they are enriched in several elements, including Ni and Cu (*Table 1*). These compositional differences were thought to be due to the element enrichments in the buried crusts having occurred post deposition (Cronan *et al*, 2002). Consequent on their porous nature, the most likely mechanism for post-depositional compositional change in them is the uptake of minor elements from the interstitial waters of the sediments in which they occur. A lack of any clear compositional trend in the buried crusts with age (from 0.2-3.5 my) would indicate that duration of burial has had little effect on their composition. Further, that the youngest of the crusts is only 0.2 my old suggests that the process of diagenetic minor element uptake from interstitial waters must have occurred near the sediment surface relatively soon after deposition

Table 1:
Comparison of Lau Basin surface and buried hydrothermal manganese crusts

Lau Bain/Tonga Ridge- Hydrothermal Manganese crusts					
Site	NI(ppm)	Cu(ppm)	Ba(ppm)	V(ppm)	Zn(ppm)
VFR 85KD		78	1120	153	120
TR D17	19	52	707	280	26
TR D18	8	27	564	78	23
TR U23	140	38	396	78	160
TR U24	270	116	558	88	395
TR U40	77	36	302	85	128
VFR D1	18	31	482	78	40
VFR 80KD	58	17	800	72	16
VFR 97KD	43	218	299	209	115
VFR 187KD	117	413	856	106	184
Average Ocean Drilling Program sites 835 & 838 – hydrothermal manganese crust					
	313	531	71.15	507	234

Studies of sediment interstitial waters in areas of Ni and Cu rich nodules in the Clarion-Clipperton Zone have shown that Cu, Ni and Zn are frequently enriched in oxic pore waters of near surface sediments to levels well above those of bottom sea water (Callender and Bowser, 1980), interpreted as being a result of the decay of recently deposited organic material (Klinkhammer, 1980). These metals could diffuse into the nodules as well as precipitate on their outer layers, thus leading to their uniform enrichment in the nodules as a whole rather than just at their surfaces.

Additional support for post-depositional alteration of nodules is forthcoming from studies on nodules in the Central Indian Ocean Basin "ore province" by Banerjee et al. (1999). These authors concluded that the common presence of radial cracks cross cutting the oxide layers in the nodules that they studied, and their high porosity and permeability, indicated the possibility that the nodules were not closed systems. Post-depositional inward diffusion of radio nuclides into nodules was held to confirm this belief. External supply or porewater mediated internal remobilization of metals were believed to account for some of the structures seen. These processes are not mutually exclusive. Changes in the older parts of the nodules were indicated, among other things, by partial replacement of siliceous biogenic remains by manganese oxides, followed by almost total dissolution of the biogenic debris and by growth of phillipsite crystals and manganese oxides in the molds. Recrystallization of primary manganese oxide led to the redistribution of Mn, Ni and Cu within the nodules. Such observations, together with those reported above, point to the possibility that manganese nodules in general, once formed, can undergo compositional changes over time to equilibrate with changing depositional conditions. If so, the correlation between the composition of Central Pacific nodules and present day depositional conditions would be explained.

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SUMMARY OF THE PRESENTATION

Professor Cronan began his presentation of the subject on the variation of the calcium carbonate compensation depth with latitude, saying that as part of research conducted across the Aitutaki-Jarvis transect such a hypothesis had been suggested. He announced that this suspicion had recently been confirmed for the rest of the southwest Pacific Ocean by his research student, who had done a similar exercise for other transects in the Southwestern Pacific Ocean. He therefore concluded that this was not just an Aitutaki-Jarvis transect trend, but a general Southwestern Pacific trend of the calcium carbonate compensation depth's (CCD) variation with latitude.

On this basis, Professor Cronan said that an examination of nodule parameters in relation to the CCD could be undertaken. The first parameter he suggested to be looked at was mineralogy in relation to the CCD. He however said he did not wish to get into nodule mineralogy because it was a subject fraught with complexities and contradictions. Professor Cronan described the two types of minerals found in nodules: 10-angstrom manganite and delta-$MnO_{2.}$ He said that if one looked at the ratio of 10-Å manganite to δ-MnO_2, that is, the relative proportions of those two minerals in deposits, one could see that relative to the CCD, the highest concentrations of 10- Å manganite to δ-MnO_2, were within 100 to 200 metres of the CCD. As one went away from the CCD, that ratio dropped.

According to Professor Cronan, 10- Å manganite nodules were enriched in nickel, copper, and zinc, and δ-MnO_2 nodules were enriched in cobalt. Utilizing data from the research on the Aitutaki-Jarvis transect, where the scatter points were large, Professor Cronan said one could see that the trend from the mineralogy variations with CCD are visible in nodule composition. He said that the five stations in that area, notwithstanding the scatter, indicated that the maximum values of manganese, nickel, copper and zinc increased towards the CCD. With regard to iron, cobalt, and lead, he said that they decreased towards the CCD; operating in exactly the opposite manner to manganese, nickel, copper and zinc.

He emphasized that this trend existed down to the CCD at latitude 2.5^o south. Professor Cronan said that no sediment samples had been taken below the CCD, but at latitude 5^o south, samples had been taken at six station groups, both above and below the CCD. He said that at the six stations there was an increase in manganese, nickel, copper and zinc, as one went down to the CCD then a decrease in iron, cobalt and lead; and then the trend reversed itself below the CCD. So, clearly, there was a compositional variation in the nodules, which was related to the CCD. He further described the trend as asymmetric above and below the CCD.

Professor Cronan said that, in order to understand these trends, it is necessary to examine the sediments. He said that by studying the sediments, one could learn an awful lot about the nodules, explain what was happening in them, and predict what might happen with the nodules in the Clarion-Clipperton Zone. He said he would look at organic carbon as a principal sediment parameter, which influenced nodules.

Professor Cronan explained that the maximum concentrations of organic carbon in the sediments peaked on the lower flanks of the equatorial high productivity zone at between four and six degrees south. He believed that the reason was that, in the centre of the high productivity zone, there was a lot of biogenic silica production, which essentially diluted the organic carbon content of the sediment. Organic biogenic silica dropped off fairly dramatically, starting at about two degrees south. He said that its diluting effect manifested in a progressive decrease as one went into the southern part of the high productivity zone. Thus, there was maximum organic carbon content in the sediments between four and six degrees.

He further explained that, if one looked at the relationship between organic carbon in the sediments associated with the nodules at depth, it could be seen that the maximum concentrations peaked at around the calcium carbonate compensation depth, which is exactly what one would expect, because calcium carbonate was also a diluent of organic carbon in the sediments, and below the calcium carbonate compensation depth, that diluent was removed.

Professor Cronan said that the large organic particles in which most of the organic carbon was trapped fell fairly rapidly, and would perhaps reach the seabed below the CCD, which could explain the asymmetric distribution that he had referred to earlier; but the sinking of organic nodules could skew the distribution of organic carbon in the sediments at deeper depths, and could also skew the concentrations of those elements influenced by the carbon.

Utilising a diagram of the Central Pacific Ocean Basin (*Figure 1* in his paper), Professor Cronan explained that all along the Aitutaki-Jarvis transect, from north to south, nodules had formed as a result of hydrogenous processes, that is, processes deriving metals from relatively unenriched seawater or interstitial waters. He said that superimposed on the flanks of the equatorial high productivity zone was a diagenetic supply of metals to the nodules, resulting from the settling of organic particles, the decay of organic carbon, and the release of the metals that were entrained within it, into the interstitial waters of the sediments, and hence, into the nodules.

Thus, he said, the highly scattered values that looked a bit mystifying at first, were a result of a mixing of hydrogenous nodules and diagenetic nodules, whereas, to the south, there was only hydrogenous nodules, but no diagenetic nodules because productivity was too large to supply organic carbon to the sediments in any abundance.

Professor Cronan said that, although productivity was highest in the equatorial zone, the slight decrease in the concentrations of manganese, nickel, copper, and zinc in that zone was probably the result of biogenic silica, which was produced in abundance in those waters, and acts as a diluent of the organic carbon in a similar way to calcium carbonate above the CCD. He said that with biogenetic silica there was no silica compensation depth, and so biogenetic silica was preserved in the sediments at all depths, and it was probably there that its high production was giving rise to the slight reduction in values.

What was being observed in the Aitutaki-Jarvis transect then, was essentially, an increase in nickel and copper values to a maximum from the southern flanks of the high productivity zone, and then a decrease as one went towards the equator, where productivity was highest.

Professor Cronan said that he wanted to see to what extent these conclusions could be extrapolated to the other Central Pacific Ocean basins. Pointing to the Penrhyn Basin, he said he wanted to find out if the same processes could be seen in the other basins, including the Clarion-Clipperton Zone.

Starting from the Northumbria basin, which is the area around the Nova Canton trough including the exclusive economic zone of the Phoenix Islands in Kiribati, Professor Cronan said that within that area, the topography was quite complex. He referred to a SOPAC report, which he had authored, back in the early nineties, which had been based on all available nodule data in the Phoenix Islands area. Using an illustration, he pointed out the stations where compositional and abundance data had been acquired during a SOPAC cruise in 1988.

According to Professor Cronan, the maximum metal values were not obtained on the equator, but rather south of the equator, decreasing with distance from the high productivity zone. He further stated that metal values continued decreasing until north of the equator and increase in the Central Pacific OceanBasin.

Professor Cronan said that the same trend had been found in the Penrhyn Basin: high metal values on the flanks of the high productivity zone, and lower values going away in both directions.

Looking at copper in the Finnish Islands, Professor Cronan said that the same trend could be seen again, that is, that maximum copper values of over 1.25 per cent occurred, not on the equator, in the axis of the high productivity zone, but just south of it, between latitude one and two degrees south. Towards the Southwestern Pacific Basin and further north approaching the equatorial region, Professor Cronan said metal values decrease. There were therefore two areas of similar features.

Professor Cronan then turned his attention to the Central Pacific Ocean Basin on the northern margin of the equatorial high productivity zone as compared with the other two areas that are on the southern margin. He said that the basin had been the subject of a cruise by the Geological Survey of a Japan in the early 1980s. He said that the cruise had focused on the so-called Wake-Tahiti Transect, from Wake Island to Tahiti. During the cruise, Mr Cronan said that data had been obtained from two sets of stations, and nodules had been collected at these stations. Professor Cronan said that the results of the work had been published by Akira Usui in 1984 in the publication Marine Geology.

Professor Cronan said that the Central Pacific Ocean Basin was between the Magellan Trough and the Nova Canton Trough. He said that nodules in the basin are found below the CCD, are associated with siliceous oozes, and have many of the other characteristics of nodules in the Clarion-Clipperton Zone. He reminded participants that it was these types of nodules that contained the maximum concentrations of nickel and copper.

Professor Cronan remarked that what had not been realized at the time the work was done was the small scale, local variation within the Central Pacific Basin. Professor Cronan said that he had taken those stations from the transect in the Central Pacific Basin and computed the combined nickel and copper values in them. He said that the computed metal values increase from near the Magellan Trough to a maximum at about three degrees (3^{o}) north, and then decreased again towards the equator. He said that the same trend as in the South Pacific Basins was evident, but in reverse, because north of the equator, there was an increase in metal values, as one went towards the flanks of the high productivity zone. He said that the maximum values were obtained at about two or three degrees (2-3º) from it, and then a decrease occurred towards the equatorial region.

Next, Professor Cronan summarized what was known about the Clarion-Clipperton Zone (CCZ), based on Dr Morgan's paper in the book that he, Professor Cronan, had edited a couple of years before, namely, *The Handbook on Mineral Deposits*. In this regard he said that in the area between the Clarion Fracture Zone and the Clipperton Fracture Zone, the deposits rested largely on siliceous oozes below the calcium carbonate composition depth. He said that the concentrations of nickel and copper were at a maximum between five and ten degrees north, slanting in the direction of the isolines of biological productivity. Noting that the biological productivity influence was clearly active, he said that the maximum metal values were not where productivity was highest, but rather, on the flanks of the high productivity zone.

Again, he said that in the CCZ, one saw what was observed in the other Central Pacific Ocean basins, which reinforced his view that the Central Pacific Ocean basins had a lot to tell about what was going on in the CCZ; and what is known about them could be used to develop a CCZ model.

With regard to the Tiki Basin in the South Pacific Ocean, Professor Cronan said that he had left this for last because it was the area about which the least was known. He said that in 1978, as part of the so-called CB program - basically a Hawaii, Imperial College and French study, a transect had been investigated from the CCZ due south, at 134^{o} west, in order to see to what extent the processes that were thought to control the CCZ nodule variability could be extrapolated south of the equator.

According to Professor Cronan, the results were paradoxical, namely, that as one went south of the high productivity zone to about ten and fifteen degrees south, one obtained metal values higher than on the southern flanks of the high productivity zone, and in fact, almost as high as the highest values.

Professor Cronan remarked that what this illustrated was that the best laid plans of mice and men could go wrong. One could think one knew what was affecting variability, and then suddenly one got a spurious result which was completely out of order. He therefore suggested that the some latitude should be provided in the occasional glitch. Professor Cronan thought that if the model worked 90 per cent of the time, things would be going quite well.

Professor Cronan pointed out that basically, in all of these areas, similarities were being seen in nodule composition variation, from maximum values of nickel and copper on the flanks of the high productivity zone, declining values as one went towards the central zone, and declining values as one went north, away from the high productivity zone.

He believed that the model set up to explain this in the Penrhyn Basin area could be extrapolated to the other areas, and that model could be summarized as follows: the nodules, which were enriched in manganese, nickel and copper, in the Pacific, occurred in waters of intermediate productivity, at the margins of the equatorial high productivity zone, or on the seafloor near the calcium carbonate compensation depth.

According to Professor Cronan, in the Clarion-Clipperton Zone, most of the evidence seemed to suggest that the plate movement had taken the area from one productivity zone to another. He said that in the Western Pacific, scientific work suggested that, in fact, the nodules moved in a predominantly western direction, and had remained in the same productivity zone. However, Professor Cronan said that this was not the explanation that he preferred. He preferred another explanation, which was that the nodules on the seabed had equilibrated with changing interstitial water conditions over time, due to their open porous nature. Explaining the situation another way, Mr Cronan said a nodule was formed under a set of conditions that change along with the interstitial waters surrounding the nodules. Additional metals in those interstitial waters, which would result from higher productivity, or the plate taking the nodules into a higher productivity zone, got into the nodule structure (it was an open porous structure, with 30 per cent or more water) and, essentially, changed the nodule composition, over time. He said that this explanation would take care of all the problems of extrapolating nodule movements back to 20 million years, and worrying about what happened during the late tertiary, because if one could show that nodule composition was a result of what was happening now, and not what happened in the past, one did not have to worry about what happened in the late tertiary.

Professor Cronan said that one might say this was entirely speculative, but there was some evidence for it, and that evidence came from another area and another study. Professor Cronan told participants that a study of crusts, dredged from the Lau basin ridge at the Ocean Drilling Program (ODP) sites 1 to 5, showed striking differences when compared to modern crusts in the same area. He said that many possibilities had been explored to explain this, and the only conclusion that had been arrived at, which explained the data, was that the buried crusts had undergone post-depositional diagenetic enhancement of those metals.

By extrapolation, he said that if that could happen to crusts, it could happen to nodules, and that was really the most compelling evidence that he had for his hypothesis.

SUMMARY OF THE DISCUSSIONS

There were no discussions following Professor Cronan's presentation.

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CHAPTER 10 SCIENTIFIC CHALLENGES RELATED TO THE DEVELOPMENT OF A GEOLOGICAL MODEL FOR MANGANESE NODULE OCCURRENCES IN THE CLARION-CLIPPERTON ZONE (EQUATORIAL NORTH PACIFIC OCEAN)

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Introduction

This paper provides scientific background for guiding the International Seabed Authority (ISA) in the establishment of a geological model of polymetallic ferromanganese nodule deposits (manganese nodule deposits) in the Clarion-Clipperton Zone of the Equatorial North Pacific Ocean. Based on the extensive studies of the Federal Institute for Geosciences and Natural Resources (BGR) and other relevant studies in the so-called “nodule belt” of the Clarion-Clipperton Zone (CCZ), the paper will help to provide an understanding of the geological processes leading to the formation of manganese nodule deposits, and will provide an approach to modelling these in this region.

The economic value of nodule deposits mainly depends on nodule quantity (abundance) and quality (grade). Abundance, size, structure, and composition of nodules are strongly related to the nature and history of the underlying sediments and seafloor topography. Therefore, detailed information about origin and evolution of sedimentary sequences and their interrelationship with the evolution of seafloor relief is needed to develop a nodule deposit model.

As most nodules are many million years old but rest at the seafloor on young sediments, an explanation must be given for this puzzling observation. The long variable growth history is most visibly reflected by the more or less concentrically layered internal structure of nodules. To understand the long history of nodule growth since the Tertiary we have to consider the underlying sedimentary, paleoceanographic, biologic, volcanic, plate tectonic, atmospheric and even orbital processes.

About 20 Ma ago, near the Early-Middle Miocene boundary, a dramatic change in ocean circulation started due to the up lift of Central America closing the Tethyan Seaway (Keller and Barron, 1983) and the opening of the Drake Passage (Kennett *et al*., 1975). Since that time, more oxygen-rich Antarctic Bottom Water (AABW) could flow into the Pacific Basin causing increased deep-seabed erosion but, because of the formation of an oxygenated bottom water layer, also favourable conditions for nodule growth (the turn from the “petroleum ocean” to the “manganese nodule ocean”).

The authors’ experience in polymetallic nodule research dates back to a 1970 cruise with Deep Sea Venture.’s research vessel, the R/V *Prospector* but is based mainly on several cruises in the Equatorial Pacific Ocean between 1972 and 1982 with the German research vessels *Valdivia* and *Sonne*, and subsequent studies. These were part of a programme sponsored by the *Bundesministerium fuer Forschung und Technologie (BMFT)*, Bonn (Germany). The main results were derived from cruise areas VA-13-2, VA-18 and SO-25-1 to 3 (*Figure 1*). In addition, information on manganese nodule formation was collected outside the CCZ in 1992 and 1996 in the Peru Basin during cruises SO-79 and SO-106 by the research vessel *R/V Sonne*.

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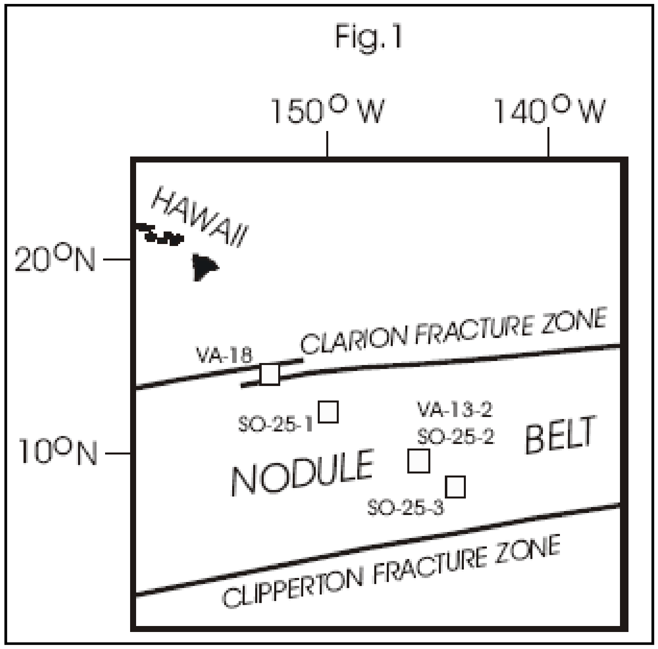

Figure 1: Location of survey areas of R.V. Valdivia cruises VA-18 and VA-13-2, and R.V. Sonne cruise SO-25 (reference areas to this article

The scientific results from the *Valdivia* and *Sonne* cruises in the CCZ are based on 566 bottom samples and 277 cores (total core length: 986m; max. length: 14m). Those for the Peru Basin come from the investigation of 172 bottom samples, 56 cores (total core length: 598m; max. length: 17m). In addition, the interpretation of several thousand kilometres of geophysical profiles added to the knowledge of both regions. The conclusions drawn from those investigations have been synthesized in von Stackelberg & Beiersdorf (Compilers) (1987), von Stackelberg & Beiersdorf (1991) and von Stackelberg (2000). Only such citations have found entry in the reference list of this article which are not listed in the references of these synthesis papers or need to be highlighted.

Principles of nodule growth and development of local nodule facies

Any modelling of nodule deposits has to consider a great variety of processes which underlay nodule formation. They are dealt with in the following paragraphs.

Character of nodule facies

We can distinguish two different major types of nodule facies due to different growth conditions: hydrogenetically grown nodules, which are rich in iron (Fe) and cobalt (Co) and relatively depleted in manganese (Mn), copper (Cu) and nickel (Ni), and diagenetically grown nodules which are rich in Mn, Cu and Ni and relatively depleted in Fe and Co.

Hydrogenetic growth takes place at the water-sediment interface where metal and other ions are supplied directly from seawater. The surface structure of hydrogenetically grown nodules is smooth. They are called s-type nodules (for major growth types see (*Figure 2*).

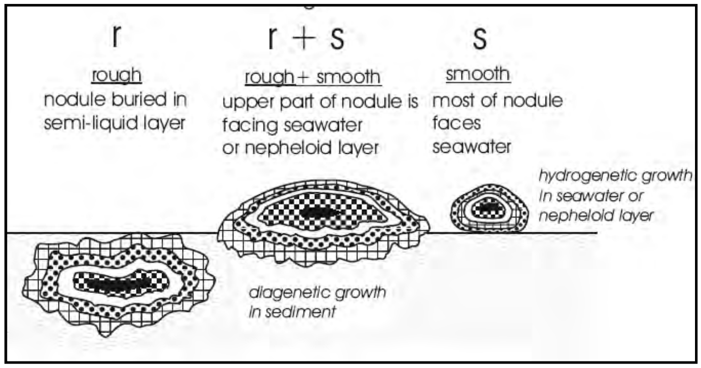

Figure 2: Major surface types of polymetallic nodules according to the classification schemes of Meylan, (1974), Moritani, et al. (1977), and Usui (1982).

Diagenetic growth takes place within the sediment but close to the sediment-sea water interface. The metals in nodules are provided by sediment pore water. The surface structure of diagenetically grown nodules is rough and this type of nodule is named an r-type nodule. Many nodules, especially large ones, show diagenetic growth at the sediment-facing surface and hydrogenetic growth features at the seawater-facing surface. They are called r + s-type nodules.

Owing to the different chemical environments in the sediments close to the seawater-sediment interface and in the seawater itself, we find different types of Mn-minerals having been precipitated. In the seawater preferentially δ -MnO_2 is formed, while in sediments preferentially todorokite formation takes place. δ -MnO_2 is Fe- and Co-rich; todorokite is Mn-rich, and accommodates Cu and Ni.

The concentrically layered inner growth structure of nodules indicates varying growth conditions. Repeated rotation and shifting of nodules by benthic activity the position of hydrogenetic and diagenetic growth-zones within the nodules changes from layer to layer. Most nodules are mixtures of both growth types, reflecting varying conditions for the precipitation of Mn-minerals. However, in many nodules one growth type predominates.

Nodule deposits with predominating diagenetically grown nodules have a higher percentage of Cu and Ni and are hence considered to have a higher economic value than deposits with mainly hydrogenetic nodule growth.

Sedimentary processes controlling nodule growth

The nodule facies within each surveyed area show local variations and may change within a range of 100 m. Extensive sediment coring and acoustic surveys revealed also a great variation of sediment facies from area to area and within each area (*Figures 3 & 4*).

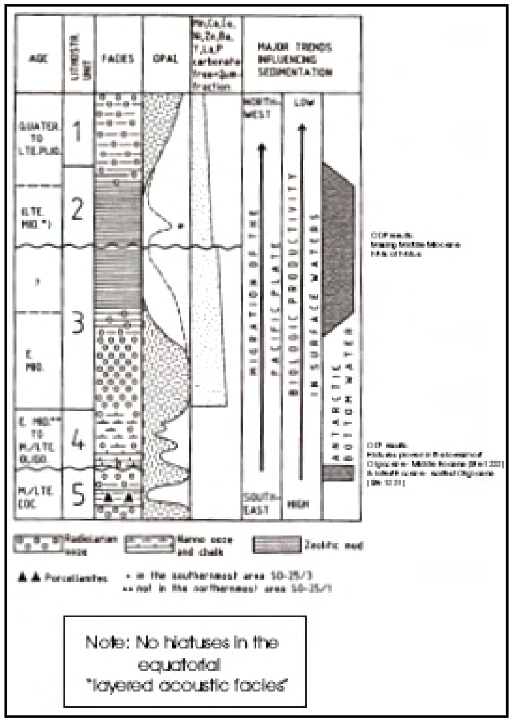

Figure 3: Schematic core diagram for areas VA-13-2, S)-25-1, S)-25-2 and SO-25-3 (from Von Stackelberg et al., 1987)

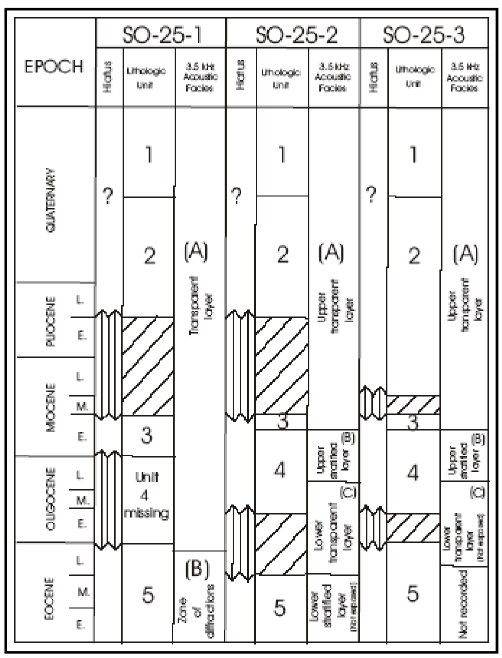

Figure 4: Correlation between lithological units (see Figure.3) and 3.5 kHz acoustic facies for the SO-25 areas. Thicknesses and age spans are not to scale. Maximum thicknesses of acoustic layers: A = 66 m; B = 69 m; C = 84 m: Acoustic facies types as in Figure.9.

These coring results are consistent with the latest drilling results by the Ocean Drilling Program (ODP) Leg 199 (Lyle, M.W., Wilson, P.A.., Janecek, T.R., *et al*., 2002). The sedimentary history is greatly influenced by paleoclimatic processes and, therefore, linked to orbital variations. However, the variability of nodule facies distribution in the investigated areas, in most cases, is due to local variations in sediment accumulation rates, which in turn are strongly influenced by bottom-current induced erosion and redeposition which in turn are often linked to seafloor topography.

Intensified currents of the Antarctic Bottom Water between Early Miocene and Late Pliocene, triggered by global tectonic processes, were responsible for hiatuses in the sedimentary column. The influence of bottom currents is stronger in the northern than in the southern survey areas, implying a general southward flow. Bottom currents may winnow sediment from elevations and carry the reworked material within turbid layers to adjacent basins. Sediments deposited in such a way are called drift sediments. They are found asymmetrically accumulated by the Coriolis Effect at one side of submarine hills in marginal basins. This observation was already made in the Eastern Atlantic at the Great Meteor Seamount (von Stackelberg *et al*., 1976). In the SO-25 areas, we found drift sediment basins on the western sides of hills which again imply a bottom current from the north.

Buried nodules from the SO-25 areas did not show any evidence of dissolution (as was observed in the Peru Basin, see below) which is explained by the generally oxic nature of the sediments.

Start of nodule growth

Nodule growth only starts where a nucleus of foreign material is available. Very often, nodules contain more than one nucleus. Nuclei may be fragments of indurate sediment (including ash-layers), fragments of submarine volcanic rocks, pumice, single mineral grains, skeletal remains or test of micro-organisms, as well as fragments of older nodule generations. A total of 54 per cent of all nuclei from the SO-25 areas consist of indurate sediment, 26 per cent of nodule fragments, 8 per cent of basalt and 4.7 per cent of remains of micro organisms (*Figure. 5*).

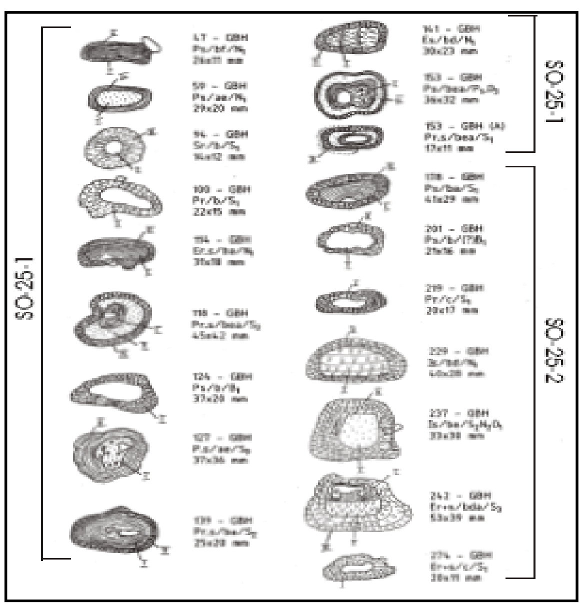

Figure 5: Sketches of sections of manganese nodules. 47-GBH etc. is the freefall grab sample from which the nodules were selected for analysis (47 = station no., GBH = acronym for freefall grab). The points from which small-scale samples were taken

are indicated by I, II, and III. The other symbols are taken from the classification scheme of Meylan, 1974, Moritani et al 1977, and Usui 1982. Example: Ps/bf/N1 Ps (morphological type) = polylobate nodule with a smooth surface; bf (growth sequence type) = laminated to columnar growth outside and pillar growth inside; N1 (nucleus type and number) = nodule fragment, one nucleus. 26x11 mm = maximum and minimum diameter.

In SO-25 areas the supply of nuclei was discontinuous, and was restricted to distinct events. Most nodules of the CCZ started to grow at sedimentation hiatuses mainly between Early Miocene (about 20 Ma) and Late Pliocene (about 2 Ma) caused by intensified AABW currents (*Figure 3*). During the hiatuses erosion and winnowing concentrated coarse particles and formed diagenetically indurate sediment layers from which fragments occasionally were detached by bioturbation. The prevalence of such nuclei-forming fragments indicates the preferred start of nodule growth at hiatuses. This seeding of nuclei during a distinct period is the reason why many nodule deposits consist of nodules with a similar size, because these nodules have more or less the same age and grew over the same period of time as well as under the same growth conditions.

Nodule fragments are produced by auto-fragmentation which is caused by shrinkage after dehydratation and ageing of the Mn-minerals. Basalt nuclei were supplied by outcropping volcanic rocks during increased activity of bottom currents. Therefore, their occurrence is restricted to the neighbourhood of hills.

The onset of post-hiatus sedimentation varied from place to place (*Figures 6 & 7*). Especially on flanks of hills it may have started late, only a few Ka ago. Therefore, nodules are small, because of the late start of growth.

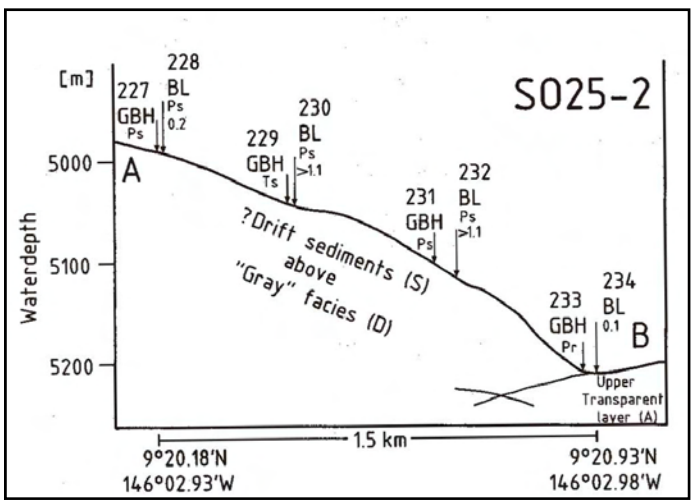

Figure 6: Type section of 3.5 kHz acoustic facies in area SO-25-2 and geological sampling. GBH = freefall grab station; BL = freefall corer station. Number below BL stations indicates combined thicknesses (in meters) of post-hiatus sedimentary units 1 and 2. Manganese nodule types: r = rough, s = smooth, r+s = rough on bottom, smooth on top, r.s = transitional between rough and smooth.

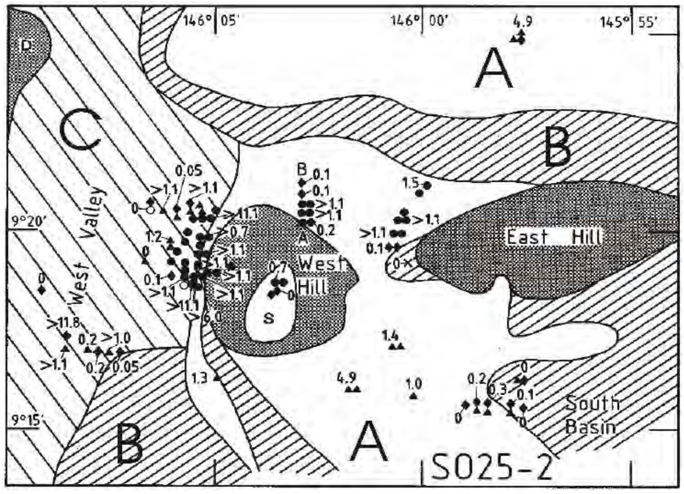

Figure 7: 3.5 kHz acoustic facies map of area SO-25-2 with manganese nodule types and combined thicknesses (in meters) of post-hiatus Units 1 and 2. Symbols for surface types of nodules: diamonds = rough, dots = smooth, triangles = rough on bottom, smooth on top, open circles = transitional between rough and smooth. Acoustic facies: blank = A, hatched bottom left to top right = B, hatched vice versa = C, dark = D, blank within dark = S.

In area VA-18 several layers of indurate ashes were found which originated from volcanic eruptions on Hawaii 1 to 2 million years ago (*Figure 8*).

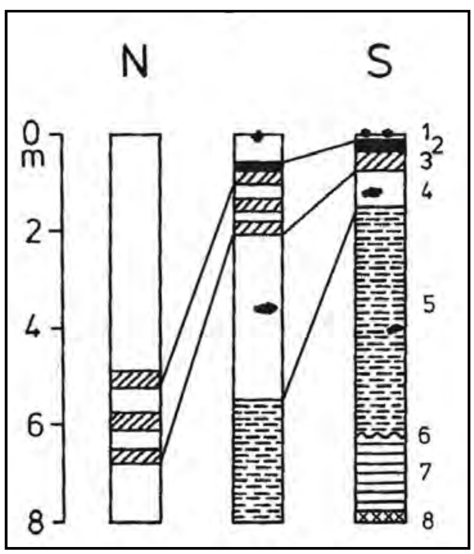

Figure 8: Schematic diagram of cores from area VA-18 (modified from von Stackelberg 1982). Numbers on the right: 1 = manganese nodules, 2 = manganese crust, 3 = volcanic ash layers, 4 = dark-brown clay, 5 = dark reddish-brown clay, 6 = hiatus, 7 = laminated clay, 8 = laminated chart.

Burrowing organisms detached fragments of the youngest ash layer and supplied nuclei for subsequent nodule growth. The nodules with such nuclei, now lying at the seafloor, are small (about 1 cm in diameter) because of the relatively short time available for their growth. Nodules of an older generation remained buried by the ash layers because the rapid accumulation of the ashes with their life-impeding composition prevented benthos activity and further lifting of the nodules.

The earliest nodule growth around nuclei in most cases is hydrogenetic due to the extremely low sediment accumulation rates or even non-accumulation during the hiatus periods.

Benthic lifting of nodules

Nodules predominantly found at or near the present-day sediment surface, started to grow at sediment surfaces which now may be up to 14m below the present seafloor. The question why nodules did not become buried, despite of deposition of post-hiatus sediments, had produced a number of theories. The most reasonable assumption for keeping the nodules unburied was benthic activity.

Sessile benthic organisms settle on manganese nodules as they need a hard substratum to attach. Therefore, nodules are the target for “grazing" organisms searching for food. Other organisms, in their search for food, specialized in sediment feeding, may burrow the sediments extensively. In this case the concentration of organic matter in the sediment column determines the degree of burrowing. The process of “grazing” and burrowing will move the nodules laterally, turn them over and push them upwards (von Stackelberg, 1984). This pushing upward, or lifting, occurs sporadically and stepwise. Due to the low sedimentation rate (a few mm/Ka), moving about every 500 years will be sufficient to keep a nodule always at the seafloor, that is on top of the sediment.

Bottom currents may winnow sediment, uncover nodules, and keep them free of sediment. However, it is unlikely that they are able to keep nodules on top of the sediment over such extended time-spans as benthos activity can do.

Due to statistical selection, few nodules, mainly from the prevailing size classes, escape the lifting, and become buried. Such buried nodules are the “early deceased” members of the nodule generation which rests now on the seafloor.

Distribution of local nodule facies

As was mentioned before, sediment accumulation rates strongly influence the growth of nodules. During zero-sedimentation or times of significantly reduced sedimentation rates hydrogenetic growth prevails. Typically, on top of submarine elevations, where winnowing hampers or prevents sedimentation, we find Mn-crusts with the purest hydrogenetic growth (*Figure 9*).

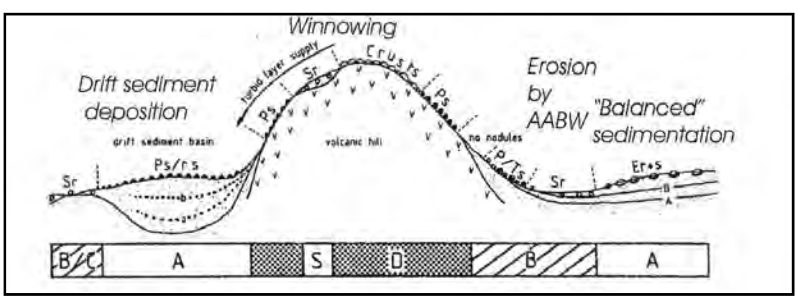

Figure 9: Manganese nodule facies in relation to acoustic facies and seafloor morphology (for correlation of acoustic facies and lithologic units see Figure.4). Nodule facies types: Ps/r.s = polylobate, smooth/rough to smooth; Ts = tabular, smooth; Sr = spherical, rough; Er+s = ellipsoid, rough on bottom, smooth on top. Acoustic facies: A = upper transparent layer; B = zone of diffractions (area SO-25-1) or upper stratified layer; C = lower transparent layer; D = acoustic basement; S = remnant of sediment cover. Horizons within sedimentary sequences: A and B = Neogene hiatuses; a and b = Neogene turbidites in drift sediments (from von Stackelberg et al. 1987).

Hydrogenetically grown s-type nodules with a smooth surface structure are mainly found on the slopes of abyssal hills but surprisingly also in sediment accumulations near hills (e.g. marginal basin fills), consisting of reworked material from the neighbouring elevations, or so-called drift sediments. Here, we observed the highest sedimentation rates among all SO-25 coring sites. They were in the order of several cm/Ka, while the average sedimentation rate is only a few mm/Ka.

This surprising occurrence of s-type nodules is explained by the generally good preservation of primary organic matter in the sediments due to rapid burial by reworked (drifted) material which prevents its oxidation and reduces the manganese flux (*Figure 10*, sedimentation type 2).

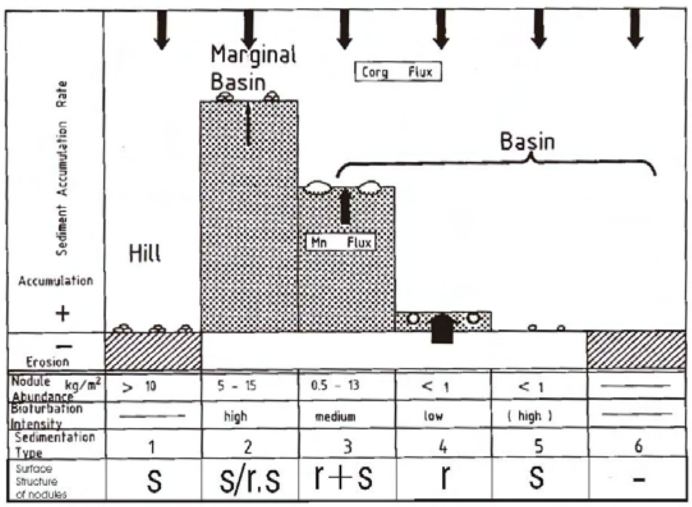

Figure 10: Schematic diagram showing the relationships between accumulation rate, Corg flux, Mn flux, intensity of bioturbation sedimentation type (see text) and abundance.

This stimulated bioturbation and benthic lifting keeps nodules at the sediment surface. The lack of dissolved metals in the pore fluids of the mainly reworked material results in a primarily hydrogenetic growth of the nodules. These and other s-type nodules are commonly small. They show a median maximum diameter of 2.5 cm (*Figure 11*).

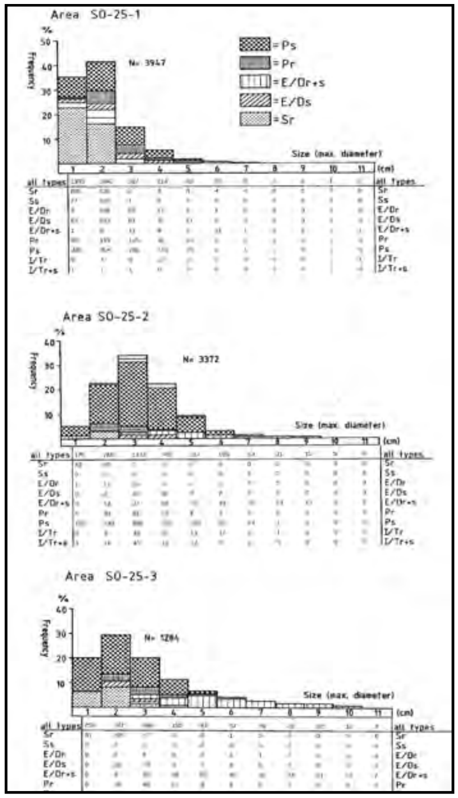

Figure 11: Size distributions of manganese nodule types in SO-25 areas. Symbols are taken from the classification scheme after Meylan, 1974, Moritani et al 1977, and Usui 1982. N = number of nodules. Blank sections of columns represent remaining nodule types. Note: These diagrams are biased in terms of statistics, because sampling on the drift sediment (marginal) basins near abyssal hills is overrepresented.

Their high abundance (up to 15 kg/m^2) is explained by the great number of nuclei such as volcanic detritus supplied from the neighbouring hills and by fragments of older nodules.

r + s type nodules resulting from predominantly diagenetic growth are mainly found in basins with medium sediment accumulation rates (*Figure 10*, sedimentation type 3). Due to the influence of the oxygen-rich bottom water, most of the organic material decayed rapidly after deposition, changing the chemical microenvironment of the surrounding sediment. As a consequence Mn is increasingly released and the upward Mn-flux in the sediment, responsible for diagenetic nodule growth mainly at the lower portion of the nodules, is enhanced.

The high abundance of r + s-type nodules (up to 13 kg/m^2) in basins with medium sediment accumulation rates is due to their size not to their number. The maximum diameter of r + s-type nodules observed by us was 11 cm; the median diameter was 5 cm. The large size of these nodules is explained by their relatively high growth rate which is a consequence of the high Mn-flux. Deposits of such r + s- type nodules, also called "Hamburger"-type nodules, have the highest economic value due to their great abundance and their high grade, especially if Cu and Ni are considered.

Surprisingly, diagenetically grown r-type nodules are found in areas of low accumulation rates at slopes of hills and in basins, especially in area SO-25-1, the northermost of the SO-25 areas. This can be explained by the increased influence of bottom water oxidizing the organic matter in sediments near the sediment-seawater interface. This in turn enhances the upward manganese flux. Due to the lack of organic matter, bioturbation and, consequently, lifting of nodules by benthos is reduced. As a result nodules lie within the uppermost sediment and are not exposed to the seawater. In most cases these r-type nodules are small with diameters between 1 and 2 cm. Due to the small size and the common burial, nodule abundance is low (*Figure 10*, sedimentation type 4).

Principles of nodule growth in relation to the development of regional nodule facies

As explained in the preceding chapters the formation and growth of nodules is controlled by the availability of nuclei during times of very low or zero-sedimentation rates, subsequent sedimentation, availability of metal and other ions in pore- and bottom water, as well as benthic lifting. This implies that the sedimentary regime determines abundance and type of nodules.

Zonation of recent sediments

The CCZ is characterized by a sub-latitudinal zonation of recent sediments (see Horn *et al.,* 1970; Johnson, 1972; *Figure. 16*) which in turn is a consequence of zoned particle fluxes to the seafloor (*Figure 12*).

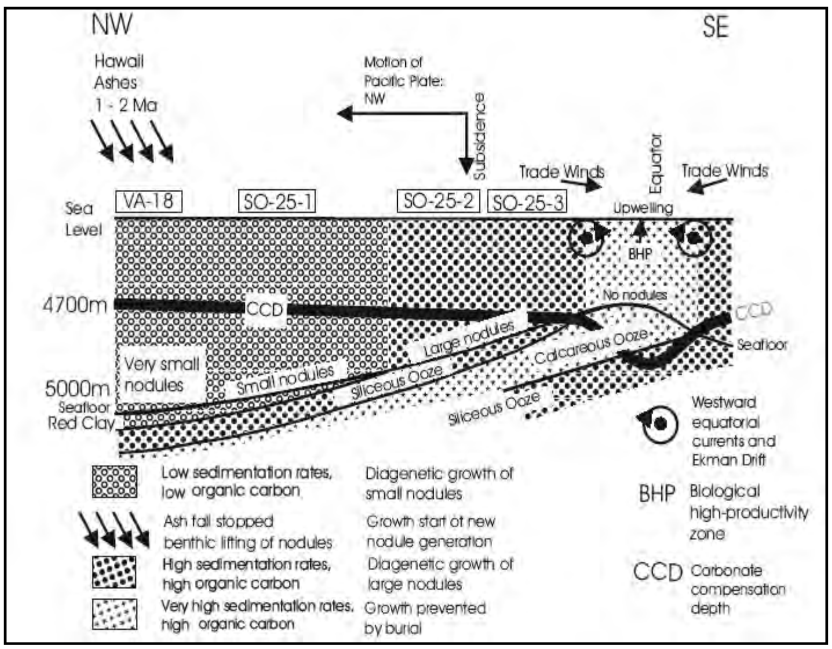

Figure 12: Facies of manganese nodules in relation to factors governing the depositional regime in the Clarion-Clipperton Zone, and relative position of reference areas for this article investigated by the Federal Institute for Geosciences and Natural Resources (Germany). Not to scale. Note: The graphic pattern between Sea Level and Seafloor represents the "lithologic" composition of the particle flux leading to the sediment type underlying the respective seafloor.

The nutrient-rich photic zone of the equatorial upwelling waters has a high primary productivity which is responsible for a high carbonate-dominated export flux resulting in calcareous ooze deposition. (Note: the distinction of sediment types follows the classification scheme of the Deep Sea Drilling Project and the Ocean Drilling Program). Sediment accumulation rates are among the highest in mid-oceanic realms (>2g/cm^2/1,000yrs). The adjacent zone to the north is characterized by a silica-dominated flux forming siliceous ooze deposits. Accumulation rates here are still high (1-2g/cm^2/1,000yrs), because of a still relatively high nutrient level in the photic zone. The silica dominated band lies between approximately 3°N and 15°N. North of this band a wide zone of nutrient-depleted waters follows in which particle flux is dominated by inorganic components resulting in red clay deposition at low accumulation rates (<1g/cm^2/1,000yrs).

The particle flux in each zone is altered by dissolution and bacterial decomposition. Therefore, the sediment accumulation rate is considerably lower than the particle export rate of the photic zone. The dissolution of carbonate is controlled by the carbonate compensation depth (CCD). In the upwelling zone with its carbonate-dominated flux, the CCD is at approximately 4,900m, which is generally below the seafloor; thus carbonate is well preserved and the equatorial sediment "bulge" is accumulated. The deepening of the CCD towards the equator is a consequence of the high concentration of Ca^{2+} and HCO_3^- in the water column resulting from the abundant calcitic biogenic remains. The decreased calcareous particle export in the adjacent zones to the north causes the shallowing of the CCD to <4,700 m.

In the zones north of the calcareous ooze zone most of the seafloor lies below the CCD (which is below 4,000 – 4,700 m), and no carbonate is deposited. Exceptions are the summit areas of some abyssal hills shallower than the CCD.

Water depths in the CCZ are controlled by the abyssal hill relief, as well as by the subsidence of the oceanic crust along the path of the Pacific Plate motion. The abyssal hill relief is an expression of the roughness of the oceanic crust created by near-ridge magmato-tectonic processes, and smoothened by subsequent sedimentation. The subsidence is a result of crustal cooling. In the CCZ it follows the subsidence curve for fast-spreading ridges (see, e.g, Le Pichon *et al*., 1976). The subsidence results in a general northwestward increase in water depth of the CCZ. The depth increase may be enhanced by compaction of the sediment blanket during burial diagenesis.

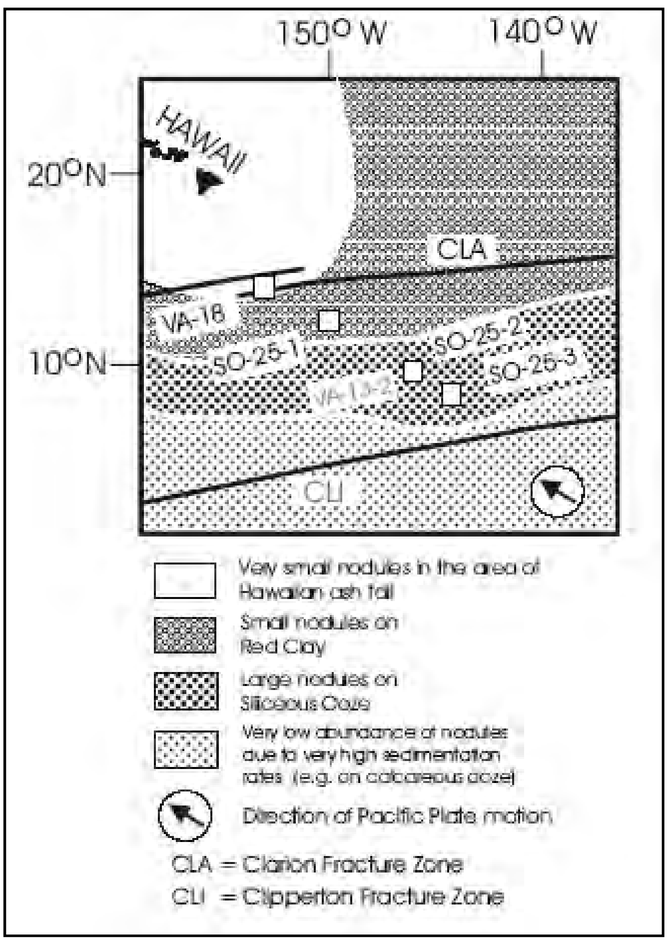

Figure 13: Regional distribution of major manganese nodule facies in the Clarion-CLipperton region, and reference areas for this article

Present-day zonation of nodule facies

Nodules are very rare in the zone of calcareous ooze and the southern part of the siliceous ooze deposition, while in the other zones they are common (*Figure 13*).

In the calcareous ooze and southern siliceous ooze zones accumulation rates are obviously too high to allow a continuous precipitation of manganese around any nuclei, although enough supply with metal and other ions is possible according to the high concentrations of organic matter and other remains of microorganisms in the sediment as well as in bottom water or nepheloid layer respectively.

In the other sedimentary zones nodule growth is not impeded or prevented by high sediment accumulation rates, except for rare sporadic high-accumulation rate events like volcanic ash rains (see above). However, growth is influenced by the laterally changing environment along the drift path of the moving crustal plate. Increasing water depths due to subsidence and vertical compaction of the sediment cover as well as a shallowing CCD increase the ratio of non-calcareous vs. calcareous deposition towards the northwest while accumulation rates decrease simultaneously. Parallel to this trend as well as parallel to the north-westward decreasing biological productivity in the photic zone, the availability of remains of micro-organisms, in particular of organic matter, decreases. Accordingly nodule growth gradually turns from dominantly diagenetic in the south to more hydrogenetic in the north. This general pattern of growth conditions has persisted over a long geological time span.

Nodule growth history and regional nodule facies

The areas in which the Federal Institute for Geosciences and Natural Resources focused its research on manganese nodules form a chain along a single line parallel to the motion of the Pacific Plate (*Figure 14*). This guaranteed that the north-westward moving seafloor of the investigated areas crossed the boundaries of the depositional regimes (although these varied slightly in latitude with time) at the same general position, but sequentially at different times.

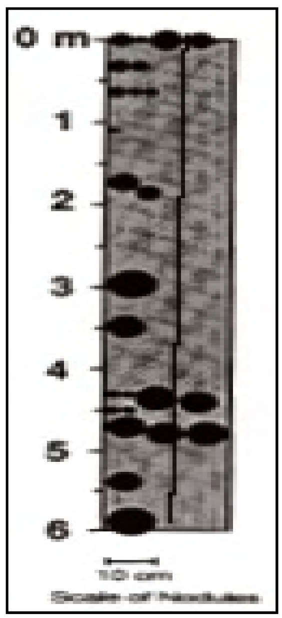

Figure 14 Buried manganese nodules in Quaternary sediments of long box core 64 KA in the Peru Basin. Water depth is 4260 m. Scale of nodule size is 2.5 times that of the core length (after von Stackelberg, 1997).

Nodules, during their growth history, could have started growing when the seafloor left the calcareous ooze sedimentation zone that is when it reached the siliceous ooze zone with already reduced sediment accumulation rates. The growth in the siliceous ooze zone would have been dominantly diagenetic, combined with high nodule abundance as well as high accumulation rates for Mn, Cu and Ni.

When the seafloor approached the zone of red clay sedimentation, hydrogenetic growth would have become more common, with low nodule abundance, and low accumulation rates for Mn, Cu, and Ni, but relatively high ones for Fe.

In area SO-25-1 the age of the oceanic crust is 78±5 Ma (Beiersdorf, 1987 In*:* von Stackelberg & Beiersdorf, 1987). Fifty Ma ago the stratigraphic equivalent of the area was at about 1°30'N and 126°W and probably just left the zone of "nodule preventing"carbonate deposition with the high-sedimentation rates. Nodule growth and biogenic lifting became possible since that time. For the next 30 to35 Ma the nodules moved through the zone which is now most favourable for nodule formation and growth. But this occurred before the major hiatuses during which most of the nodule deposits were initiated. Therefore no significant nodule cover could develop. According to the present-day situation this nodule generating zone was left between latidue 9°30' and 10° N. During the last 15 to 20 Ma, this includes the major nodule growth-initiating hiatus times, the area moved already within the "oceanic desert, characterized by a high degree of carbonate dissolution because of a shallow CCD and increased water depth. In the area sediment supply, particularly input of organic matter was scarce, causing little attraction for "grazing" and burrowing life forms, hence biogenic lifting was reduced. In addition strong Anatrtic Bottom Water currents, causing erosion of sediments and redeposition of this material were responsible for the generally small size and low abundance of mainly diagenetically grown nodules in area SO-25-1.

In stratigraphic equivalents of areas SO-25-2 and -3 the period of predominantly calcareous deposition ended 19 and 22 Ma ago. Since then favourable conditions for the formation of diagenetically grown nodules with high percentages of Mn, Cu and Ni, as well as for high nodule abundances prevailed. Both areas are still within the zone dominated by siliceous ooze.

The input of volcanic ashes may have led to a regional nodule sub-facies. Herbst *et al.*,1980, and von Stackelberg, 1982 described 1 to 2 Ma old tuff layers in area VA-18, located on a fault block of the Clarion Fracture Zone (*Figure 8*). The tuff material was blown in from the Hawaii Islands. These ashes were deposited at a very high sedimentation rate. They were infertile and unfavourable to life; thus, further benthic lifting of already existing nodules was inhibited. A new generation of nodules started growing after the ash deposition. These nodules have the character of nodules which have been formed within the red clay zone, but they are much smaller than the usual "red clay" nodules. Since no systematic mapping of the 1 to 2 Ma old ashes has been performed yet, the size and shape of this sub-facies zone can only roughly be determined.

Relationship between sedimentary, nodule, and acoustic facies in the CCZ

As the sedimentary regime has determined abundance and type of nodules it was logical to test whether the acoustic character of the sediment can hint at the type of nodule cover resting on the sediment, with the development of a rapid method for mapping nodule deposits in mind.

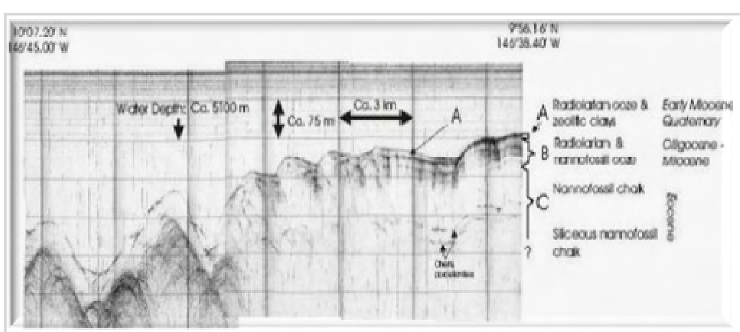

Figure 15: Registration example from 3.5 kHz sub-bottom profiling obtained immediately northwest of area SO-25-2 on transit from area SO-25-1. A = upper transparent layer; B = upper stratified layer; C = lower transparent layer. Calibration of the acoustostratigraphy according to bottom photographs and samples obtained during VALDIVIA and SONNE cruises, as well as coring results by the Deep Sea Drilling Project. From an economic point of view only acoustic layer A can be expected to carry sufficiently abundant high-grade manganese nodules.

Acoustic facies

The VA-18 and SO-25 areas were mapped acoustically with 3.5 kHz echosounders. The acoustic stratigraphies were calibrated with seafloor photographs, bottom samples and cores collected during *Valdivia* and *Sonne* cruises as well as with dated lithostratigraphies of drill-holes of the Deep Sea Drilling Project, DSDP. Acoustic facies maps were drawn subsequently (von Stackelberg & Beiersdorf, 1991; for examples see *Figures 4 & 7*).

In area SO-25-1 an acoustically transparent layer forms the uppermost acoustic sequence (upper transparent layer, acoustic facies A) representing 34 to 75m of Eocene to Quaternary zeolitic brown clay and clayey radiolarian ooze with intercalated chert beds in the lower part of the section. Below the upper transparent layer a zone of diffractions (acoustic facies B) follows. It represents approximately 62m of Eocene radiolarian ooze and closely spaced chert beds. Acoustic facies A and B are restricted to low-lying parts of the area. Outcropping basalts of the Cretaceous oceanic crust, the age of which has been derived from the magnetic seafloor anomaly pattern for the CCZ, are associated with a prominent hill and are acoustically "gray"(acoustic facies D).

Another transparent layer (acoustic facies S) rests on D caused by remnants of a sediment cover of unknown, but possibly Cretaceous age in its lowermost section.

In areas SO-25-2 and SO-25-3, the acoustic stratigraphy again shows an upper transparent layer (acoustic facies A) which represents 34 to 46m of Early Miocene to Quaternary radiolarian and zeolitic clays and oozes. In places calcareous ooze is intercalated. Below follows a stratified layer (upper stratified layer, acoustic facies B) caused by up to 69 m of Oligocene to Early Miocene alternating nannofossil and radiolarian oozes to chalk with chert beds at their base. Again the basalt of the oceanic crust is acoustically "gray" (facies D) with an acoustically transparent layer (S) resting on it. According to the magnetic anomaly pattern the age of the crust is Paleogene. S is caused by remnants of a sediment cover, which in places consists of Oligocene chalk. Below B follows facies C representing 84m of Eocene to Oligocene radiolarian nannofossil chalk with chert at its base. The acoustic facies is transparent in its upper section (lower transparent layer, exposed in SO-25-2 only) but stratified in the lower section (lower stratified layer, not exposed anywhere in the SO-25 areas). A good example of an acoustogram obtained by 3.5 kHz sub-bottom profiling immediately northwest of area SO-25-2 is shown in *Figure 15*.

It shows the acoustic characteristics of the stratigraphic sequences as well as the erosive effects caused by the Antarctic Bottom Water.

Correlation between acoustic and nodule facies

Zones of erosion and non-deposition are characterized by erosional windows and outcrops visualized in the acoustic records by acoustic facies B, C, D, and S, underlying the seafloor reflector. The nodule facies in these zones is represented by hydrogenetically grown s-type nodules (*Figure 9*).

Zones of high and medium sediment accumulation rates correlate with acoustic facies A and are restricted to basin settings. The highest accumulation rates are associated with the drift sediment bodies (see drift sediment basin or marginal basin, sedimentation type 2; *Figures 9 & 10*). The nodules here are s- and r. s-type nodules (classification scheme by Meylan, 1974, Moritani *et al*., 1977, and Usui, 1982). They are distinctly different from the r+s-type nodules on top of sediments accumulated at medium accumulation rates (see "balanced" sedimentation; sedimentation type 3; *Figures 9 & 10*). It is difficult to distinguish the "transparent" drift sediments acoustically from the "transparent" autochthonous sediments. In area SO-25-1, two turbiditic layers are intercalated in the drift sediments.

They can be correlated with two internal reflectors "a" and "b" within the transparent layer, which may be used as marker reflectors for the distinction from other acoustically transparent areas within SO-25-1 and its vicinity.

In areas SO-25-2 and SO-25-3 such a distinction cannot be made, the only internal reflector R2 within the upper transparent layer (A) is caused by an intercalation of carbonate (Embley & Johnson, 1980; Beiersdorf, 1987 in von Stackelberg & Beiersdorf, 1987). The Neogene hiatuses found in these areas by coring have no acoustic equivalent. Therefore a careful approach has to be taken when the acoustic facies A is used for the prediction of nodule facies. Coring has to be used to determine first whether the sediments are autochtonous or reworked before an attribution to the nodule facies s-/r. s-type or r+s-type is undertaken. The position of the acoustically transparent sediment deposit with regard to neighbouring elevations may help to interpret the acoustically transparent character of such deposits, and accordingly predict their nodule cover.

Principles of nodule growth in the Peru Basin

Although the nodule fields of the Peru Basin are outside the nodule belt of the CCZ, similarities and differences to observations mentioned earlier are discussed in this chapter.

The survey areas lie south of the equatorial maximum of biological productivity. Therefore, particle flux and supply of organic matter to the seafloor and consequently, sediment accumulation rates increase from south to north (Von Stackelberg, 2000).

During the eastward drift of the Nazca Plate the survey areas moved more or less parallel to the isolines of bio-productivity rates, and not transverse to them as in the CCZ. Therefore, in contrast to the CCZ, the particle flux did not change very much during plate motion.

A comparatively high supply of organic matter explains a distinct redox boundary at about 10cm depth in the sediments, separating very soft oxic uppermost sediments from underlying stiffer sub-oxic sediments. Within the sub-oxic sediment Mn is remobilized and concentrated again in the oxic uppermost sediment. Due to this upward Mn flux, which is unusually high, diagenetic nodule growth is especially high (up to 250 mm/Ma) immediately above the redox boundary. The high growth rate is the reason for the large size of Peru Basin nodules (maximum diameter up to 21 cm!).

Due to the strong geochemical gradient within the semi-liquid layer of uppermost sediments the lower portion of large nodules grows up to 50 times faster than the portion exposed to the sea water. Therefore, nodules with large axes greater than 7cm show mainly diagenetic growth because the slow hydrogenetic growth is significantly more than the fast diagenetic growth.

Compared to the CCZ, the nodules in the Peru Basin show a generally lower concentration of Cu + Ni. This is probably caused by a lower ratio of siliceous vs. calcareous skeletal remains and tests due to the position of the seafloor near the CCD, enhancing preservation of calcite in sediments. Furthermore, Ni + Cu concentrations decrease with increasing nodule size.

Moving of nodules with large sizes by benthos was hampered, and therefore, a great number of mostly large nodules became buried (*Figure 14*). This type of burial is different from that of the CCZ, where burial of nodules was determined by statistical selection (relatively few nodules, especially those from the prevailing size class, failed to be kept at the seafloor by benthic lifting; see above). However, nodule burial due to statistical selection is also found in the Peru Basin in shallower water depth where hydrogenetic nodules predominate.

Due to the suboxic environment below the oxic layer, buried nodules are more or less dissolved, a fact which is not observed in CCZ. In the Peru Basin, the CCD lies at about 4,250m which coincides more or less with the regional water depth, a condition which has existed in SO-25 areas only when they were closer to the equator. Therefore, the unique chance to study in detail the influence of the CCD on nodule growth was taken in the Peru Basin. Immediately below the CCD a distinct maximum of nodule abundance (up to 50 Kg/m^2) is observed, which is due to increased nodule growth rates. As in the CCZ, a number of hiatuses were observed. The main hiatuses in the Peru Basin are found at the Pleistocene-Pliocene and the Pliocene-Miocene boundaries. Most of the nodules started to grow at the upper hiatus. This is supported by the occurrence of exclusively Quaternary diatom remains within Peru Basin nodules.

Approach to modelling

The SO-25 areas and area VA-18 are small compared to the size of the “nodule belt” in the CCZ. Therefore, the model developed for the formation of nodule deposits by von Stackelberg & Beiersdorf (1991) may apply only to a relatively restricted area of the “nodule belt” between longitudes 140^o and 155^{o}W. A test for the applicability of the model has to be made for the remaining nodule belt as well.

Applicability of the model of von Stackelberg & Beiersdorf (1991) in terms of regional nodule facies in the Clarion Clipperton Zone

The claims of the former pioneer investors and contractors to the International Seabed Authority are located between latitude 7° and 17°N, and latitude 115^o and 157^{o}W. Between latitude 122^o and 157^{o}W they lie within an approximately 500 km wide undulating but generally east-north-easterly trending band. East of this band the claims are within an irregular but roughly triangular area between latitude 8^o and 17^{o}N and latitude 115^o and 122^{o}W (*Figure 16*).

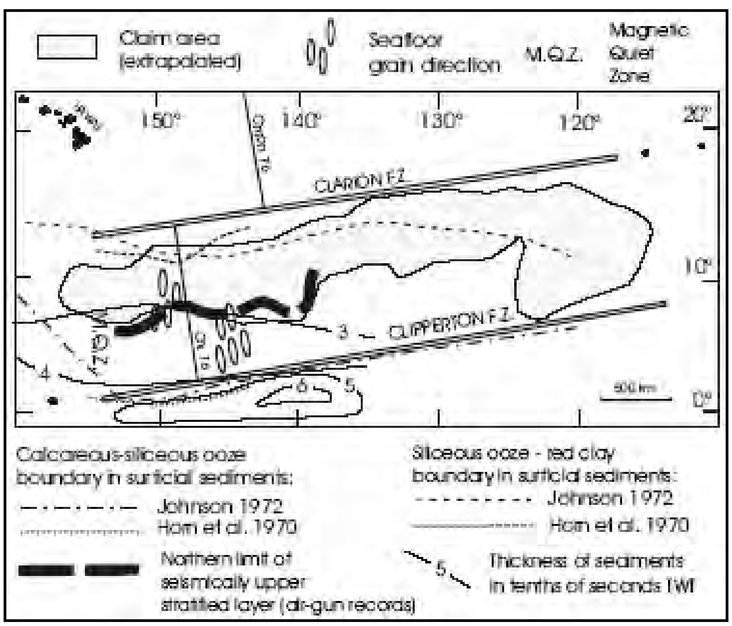

Figure 16: The total CCZ claim area in relation to some of the geological features relevant for geological modeling. E.g.: The change in seafloor-grain direction from north-south in the Cretaceous magnetic quiet zone to north-northwest east of Chron 76 is associated with a change in water-depth distribution as a function of seafloor spreading rates, which in turn will have influenced the flow of Antarctic Bottom Water, hence will have changed the erosion and redeposition regime.

If one assumes that the total area of claims reflects the finding of enough high-grade nodule fields to justify claiming, then the area must coincide with the regional nodule facies of the siliceous ooze zone, that is, the zone of many fields with a high abundance of Mn-, and Cu+Ni+Co-rich nodules. Indeed, the area lies greatly within the northern part of that zone which is dominated by siliceous or non-calcareous deposition.

The wavy form of the 500 km wide band is related to lateral variations in depositional regimes. The zone of calcareous ooze deposition with its very limited potential of nodule formation makes distinct northward excursions between longitude 147^{o} and 157^{o}W, as well as between 122^{o} and 140^{o}W. The western excursion can be explained by the shallowing of the seafloor towards the Line Island Ridge, and above the CCD. The eastern excursion can be explained by an equatorial carbonate-dominated sediment bulge (Embley & Johnson, 1980, Mitchell, 1998) which is associated with a shallowing of water depths. The thick sediment accumulation and bulging is most likely a result of the change in seafloor spreading direction due to a jump of the East Pacific Rise spreading axis from an ancient north-north-west-trending ridge system to the present north-north-east-trending system between 20 and 10 Ma.

It is interesting to note that in reflection seismic records from the western part of the CCZ, the southern boundary of the claim area coincides fairly well with the disappearance of the “seismic facies B” (Hinz & Schlueter, 1973; Duerbaum & Schlueter, 1974; Lyle, 2002, and unpublished German industry data), which is characterized by densely spaced reflections, representing calcareous oozes which have been deposited from the Eocene to Quaternary preventing nodule growth widely (*Figure 16*).

The eastern irregularly shaped area of claims also lies entirely within the siliceous ooze zone. Its southern boundary is again associated with the calcareous ooze-siliceous ooze transition, caused by the deepening of the seafloor and shallowing of the CCD.

The eastern limit of the total claim area is related to a roughening of the seafloor relief (Mathematicians Seamounts) enhanced by the general thinning of the sediment cover towards the ridge axis. In addition increased input of volcanic detritus from the seamounts and other oceanic basement outcrops makes the area east of the claim area economically unfavourable.

The western limit of the claim area is associated with the rise of the Line Island Ridge, and its hemipelagic sediment shedding which also does not provide favourable conditions for no dual growth.

The northern boundary of the total claim area follows more or less the siliceous ooze-red clay boundary. The northward excursion of the boundary between 122° and 140°W is nearly parallel to the northward excursion of the calcareous ooze-siliceous ooze boundary, and most likely has the same origin.

The sub-parallelism of the “nodule belt” with the Clarion and the Clipperton fracture zones is just a coincidence, but it has geological relevance. Due to an eastward shift of the Molokai-Clarion ridge segment relative to the Clarion-Clipperton ridge segment, the seafloor north of the Clarion Fracture Zone is constantly older than in the area south of it; hence subsidence is more advanced in the north, and regional water depths are greater. This has led to a southward shift of the red clay-siliceous ooze boundary between longitude 140° and 150°W, a general decrease in deposition of calcareous as well as organic material, and greater influence of erosion-inducing Antartic Bottom Water altogether forming unfavourable conditions for nodule formation.

In conclusion, the model for the formation of the regional nodule facies which has been derived from the investigation of four areas by the Federal Institute for Geosciences and Natural Resources, as published by von Stackelberg & Beiersdorf (1991), seems to be applicable to the entire “nodule belt” in the CCZ.

Applicability of the model of von Stackelberg & Beiersdorf (1991) in terms of local nodule facies in the Clarion Clipperton Zone

The SO-25 and VA-18 areas are representative for the CCZ in terms of their basic geological properties: their sub-bottom consists of oceanic crust with a sediment cover. However, there are significant differences between areas within this region. With the increasing age of the oceanic crust away from the active seafloor spreading centre, the Pacific Rise, the relief of the crust and its topographic structure changes as a consequence of past changes in spreading rates (see Beiersdorf, 1987. *In*: Von Stackelberg, U. & Beiersdorf, H., compilers, 1987), subsequent crustal sagging, loading by sediments, erosion, and submarine weathering. The relief of the crust becomes “veiled” or obliterated by the sediment cover resulting in the present abyssal hill topography. This cover varies in thickness and lithologic composition. Both are related to changes of the depositional regimes and states of diagenesis in space and time.

Since economically valuable nodule deposits (high-grade, high abundance “Hamburger“-type nodules) are found throughout the “nodule belt”, which is associated with the northern part of the siliceous ooze zone, the depositional regime favourable for their formation must have existed ubiquitously throughout the “nodule belt” as explained in the previous chapter. Therefore, on a local scale, the model of von Stackelberg & Beiersdorf (1991) also seems to be applicable.

What is needed to delineate the nodule belt more precisely and to estimate the total size and value of economically interesting areas within “blocks”of the total claim area?

The formation and growth of manganese nodules in the CCZ is a function of availability of nuclei, particularly during times of very low or zero sedimentation rates, as well as:

- Subsequent accumulation of sediments attractive to benthic life as well as at rates which are in balance with benthic lifting
- Availability of metal and other ions in seawater and porewater needed in nodule formation
- Benthic lifting.

The ideal seabed-mining area needs to be large and have large nodules that are rich in copper and high abundance resting on a flat seafloor. Such areas are rare because of the geological complexity of nodule formation and preservation. An ideal area would require a sediment layer immediately underlying the seafloor with the following origin and history:

- Deposited on a flat “basement” of large areal extent
- Experienced at least one hiatus to have allowed nucleation and initiation of nodule growth
- Experienced a post-hiatal sedimentation for a long period of time to allow growth of large nodules,
- Formed by particles which were able to supply “building” materials for nodule formation to bottom water and during diagenesis to pore water
- Maintained, during the long time of nodule growth (several millions of years), the delicate balance between sedimentation and burial-preventing biogenic nodule-lifting
- Has escaped significant erosion and re-deposition.

The large size of the total claim area in the CCZ suggests that the ideal layer characteristics are met here frequently. Prospecting and exploration results confirm the existence of ideal but patchy conditions. However, patches of economically interesting nodule covers are difficult to predict. The prediction of patches ideal for seabed mining is the objective of modelling. For such modelling, the rules of correspondence between sets of variables involved in sediment-layer and manganese-nodule formation need to be known. Geological modelling needs to correlate those functions. Results of pure statistical evaluations of the total claim area, such as, for example, that carried out by the International Seabed Authority and the geological model, need to be compared for verification.

The above-stated reasons for the formation of the “nodule belt” in the Clarion-Clipperton Zone, and the delineation of the total claim area following it, are simplified and rather roughly defined in their relationship to underlying geological processes. For example, within the wide compositional range of siliceous ooze, such ooze types and sedimentary conditions, as well as their spatial distribution have still to be defined, which could have allowed the formation of the economically most valuable nodule deposits, a process which lasted millions of years.

The conditions for the formation of such sediments and in turn for the formation of their valuable nodule covers are the consequence of the complex interaction of many processes in the ocean, in the lithosphere and its sediment cover, in atmosphere and last but not least in the biosphere. The governing factors in the distribution of the nodule facies are composition and sediment accumulation rate, both strongly influenced by particle flux, post-depositional particle alteration, bottom currents and seafloor relief, and hence are very variable on a local scale. Therefore, any attempt to model the probability of nodule occurrences and their nature has to make predictions on particle flux and preservation, on seafloor topography, bottom currents, erosion and redistribution of sediments, for past as well as for present situations.

In order to define the boundaries of valuable nodule deposits precisely, work has to start with a comprehensive synthesis of existing data with the goal of determining the depositional and nodule growth history in the context of the following factors (*Figure 17*):

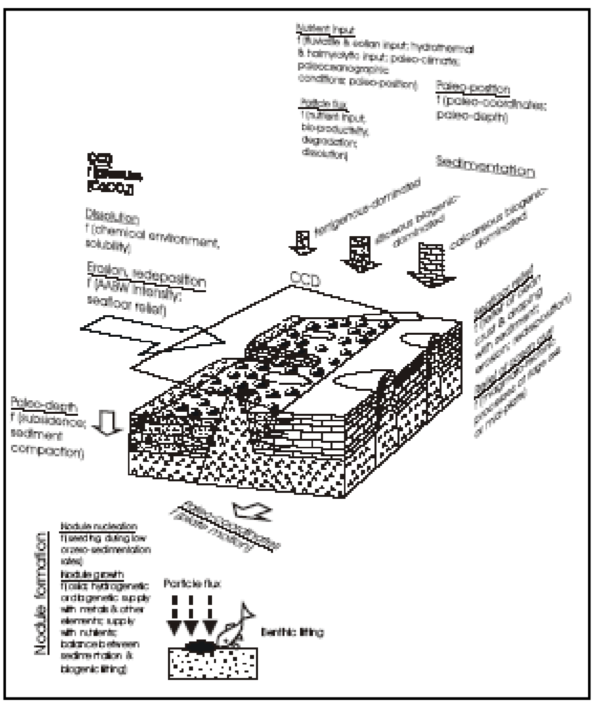

Figure 17 Variables (underlined) relevant to modelling of manganese nodule deposits. Note: The variables are functions of sets of other variables (e.g. the calcite compensation depth CCD is a function of water depth/pressure, and the concentration of calcium carbonate [CaCO3] expressed as CCD = f (pressure; [CaCO3]). Block diagram not to scale.

- Plate motion and subsidence history
- Evolution of regional water depths as well as regional seafloor relief (changes in grain direction & depth distribution)
- Present-day oceanographic conditions
- Paleoceanographic and paleoclimatic evolution

  - History of primary biological productivity and its zonation
  - Particle export history
  - Calcite compensation depth, and particle preservation history
  - Benthic activity
  - Sediment diagenesis.

From this synthesis, a model which allows delineation of the regional nodule facies and estimation of the total size of the economically interesting area can be developed. The total size and value of sub-areas within any defined “block” of the total claim area can then be estimated as well. In some cases, it may even be possible, based on the Authority’s POLYDAT database, to determine the exact location of such areas.

The first step in this process will be the identification of sources of information and data. Such sources will be found in academic institutions, governmental agencies and in industry. In particular, entities which have been active in nodule prospecting since the early seventies have to be considered. Industry and governmental entities can be deemed to be prime data holders.

In a second step, a concerted effort by experts in the fields listed above and by prime data holders is required to sift through the available data, to work on data standardization and homogenization, as well as towards the synthesis which, in the end, will serve as the basis for a comprehensive model.

In a third step, this synthesis, which may come as a digital atlas, will be used for modelling the manganese nodule deposits in the Clarion-Clipperton Zone. The model will serve the International Seabed Authority and other interested parties in their attempt to estimate the value of areas under their purview, but will also be of high scientific value.

For these activities experts will be required who know the Eastern Equatorial Pacific Ocean very well in terms of:

- Plate tectonics and evolution of regional water depths, as well as seafloor relief
- Paleoceanographic and paleoclimatic evolution
- Oceanography and benthic processes
- Primary biological productivity and particle export
- Benthic activity
- Sedimentary and geochemical processes
- Present-day nodule distribution, composition, and growth history.

For approaches to the problems arising in the fields of information and data handling, as well as of modelling, experts should be added to the expert group for:

- Data and information handling, hard-and software
- Mathematical modelling.

These experts should be invited by the International Seabed Authority as early as possible, because it will become increasingly difficult to have access to those who were active decades ago, but whose knowledge will be very important.

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SUMMARY OF THE PRESENTATION

Professor Beiersdorf informed participants that many years ago, the Federal Institute for Geosciences and Natural Resources in Germany decided to start deep-sea exploration for marine minerals including manganese nodules. He said that in 1970, he was fortunate to participate in a twenty-one day cruise aboard Deep-Sea Ventures' research vessel the R/V *Prospector*. Professor Beiersdorf said it was the very first time that he had seen manganese nodules lying on the seafloor. He said that at the time, he noted a great variation in nodule coverage on the seafloor, as well as differences in their sizes and shapes. He said that he also saw some curious creatures around the nodules that appeared at their edges, whose existence he could not explain. Professor Beiersdorf said that the sight of the nodules on top of sediments as shown by the television cameras on board was enough to visualize over 150,000 years of history. He said that upon his return to Germany, he had been curious about the age of the nodules and the role of the sediments in their formation. He noted that during this period, a great debate occurred among scientists, about these matters including that of nodule formation.

Professor Beiersdorf said that the Institute decided to focus its work on developing a rapid exploration vessel, using acoustics to facilitate adequate coverage of the huge areas where the nodules were found. Professor Beiersdorf said that through acoustics, the Institute was able to gather data and information based on profiles across the CCZ, which enabled it to select smaller areas for more focussed examination, and to address the question of how nodules are formed.

According to Professor Beiersdorf, it was generally accepted at the time that nodules were formed through the convergence of many processes. He said that he and his colleagues decided that their problem was how to combine the relevant parameters from these processes into a model. He said they designed a cruise which enabled them to acquire the relevant data and information on, *inter alia*, particle flux, the carbonate compensation depth (CCD) and seafloor evolution, starting from the ocean ridge (where nodule formation was initiated), to their present locations that result from plate motion and subsidence. Professor Beiersdorf said that their investigations also included biological processes, in particular their role in keeping the nodules afloat.

To facilitate the acquisition of a complete dataset, including a complete picture of progress from the ridge, plate movement over the past fifty million years, the accumulation of sediments, the production of the first set of nodules, and how nodules had managed to stay at the surface of the sediment column until today, Professor Beiersdorf said that four areas were selected for their investigations. He said that the four selected areas were on a single track in the CCZ.

Following their investigations in the CCZ, Professor Beiersdorf said a similar investigation was conducted in the Peru Basin, and the results compared with the CCZ study. He told participants that Professor Hoffert would address the results of the latter study during the workshop.

With regard to nodule surface types, Professor Beiersdorf said that based on their studies, three major types of nodule surfaces and associated characteristics had been identified. He said that these were rough nodules, which grew within the sediment and semi liquid layer; nodules which were partly resting in sediment but exposed to seawater, and smooth nodules which were surrounded mainly by seawater.

Professor Beiersdorf informed participants that his colleague, Dr. Ulrich Von Stackelberg, a pioneer in this field, had investigated 9,200 nodules to determine the internal structures of nodules. He apologized for his absence, which he said was for health reasons, and informed participants that Dr Von Stackelberg was a co-author of the paper for his presentation. He said that Dr Von Stackelberg's work confirmed the typology according to the surface type, and also provided knowledge on growth conditions.

The Professor said that rough surface type nodules were found in the bottom layer of the formation, in the sediments and the semi-liquid layer. He said that metals in nodules are provided by sediment pore water. He said that nodule growth that takes place within the sediment but close to the sediment-seawater interface is described as diagenetic, and nodules grown this way have a rough surface structure. He also said that these types of nodules are called r-type nodules. He said that nodule growth based on metals from seawater is described as hydrogenetic. He said that the surface structure of nodules formed this way was smooth. These types of nodules are called s-type nodules. Professor Beiesdorf said that many nodules, especially large ones, show diagenetic growth at the sediment-facing surface and hydrogenetic growth features at the seawater-facing surface. He said that these types of nodule are called r + s-type nodules or tempoarary shaped nodules.

Professor Beiersdorf said that part of Dr. Von Stackelberg's work on the internal structure of nodules resulted in the identification of three types of growth structures for nodules, each of which could occur in a nodule. He noted that prior to the workshop, they had succeeded in devising a classification of growth conditions and came up with several major growth types. Professor Beiersdorf informed participants that due to the different chemical environments in the sediments close to the seawater interface and in the seawater itself, different phases of manganese in minerals are precipated. In that regard, he said that in seawater, the predominant manganese phase in nodules is δ -MnO_2, while in sediments it is todorokite. He said that the δ -MnO_2 phase is iron (Fe) and cobalt (Co) rich and that the todorokite phase is manganese (Mn) rich, and accommodates copper (Cu) and nickel (Ni).

Professor Beiersdorf explained that each of the growth types had a particular growth rate. He said that in the Peru Basin, where the nodule growth type was called massive, the growth rate varied between 200 and 250 millimetres per million years. He also said that a particular range of growth rates could be assigned to all growth types such as hydrogenetically grown nodules, densely laminated or massive nodules, and pillow growth types. He said that the latter nodule growth types had a lower growth rate of about 5 millimetres or less per million years. Bearing this in mind, he said that one could check the cross-section of a nodule, and determine its history.

He said that in all the areas that they had investigated there was a great variation in nodule abundance, size and shape within 100m.distances. The Professor however stressed that while this was a general observation, it came from small areas in a particular region of the Clarion-Clipperton Zone.

Professor Beiersdorf emphasized the importance of sediments, saying that it was for this reason that so many cores had been taken during the Institute's cruises. He said that initially, scientists had tried to establish the stratigraphy of the areas, work he described as very tedious because of the variety of out-crops of different ages in the Clarion-Clipperton Zone. In this regard, Professor Beiesdorf said that they found the stratigraphy to stretch from the middle to late Eocene up to the Quaternary, and that it showed two distinct hiatuses in deposition. He said that the most remarkable haituses were the ones that occurred between the early to late Eocene, and between the late Eocene to the early Miocene.

The Professor said that the lithostratigraphy of the investigated areas was now well established, and that it had been supported by the results of work of the Ocean Drilling Program in these areas in 2000 and 2001. He indicated on a chart the area that he was talking about and said that there were now four drill holes from the Ocean Drilling Program, which supported his institute's lithostratigraphy license. What was important, he said, was that the hiatuses they had identified had also been found, and that was very important because nodule growth started at hiatuses.

Professor Beiersdorf indicated sediment colours on the chart and explained that what was seen was due to the hiatus formed between the early and late Miocene. On hilltops, he pointed out iron-rich nodules, small poly-nodules, and also thick manganese crusts. He further pointed out that the crust itself was more than seven centimetres thick; which meant that it had been accumulated over a long time.

Professor Beiersdorf said that in the second phase of their investigation, much more emphasis had been placed on studies of the nuclei of manganese nodules. He said that their invesitigation arrived at the following statistics: 54 per cent of the 9,200 nodules investigated consisted of indurate (hardened) sediment, surrounded by various layers of manganese oxide; 26 per cent of all nodules contained fragments of older nodules; 8 per cent consisted of basalt, while, around 5 per cent or less, contained organic debris.

Professor Beiersdorf said that the thickness of the post-hiatus sediment also determined the size of the nodules. He noted that the thinner the post-hiatus sediment, the smaller the nodules were in that sediment. He confirmed that these were relationships which had been found everywhere that they had investigated.

Professor Beiersdorf said that biologic activity on the seafloor could be clearly demonstrated with traces of holothurians and nest-like structures, wood-like structures, and the arrangement of nodules, indicating that nodules could be moved and altered. He showed photographs of sediments, explaining that each column was about ten centimetres thick, and pointed out traces of boring organisms. The Professor said that the boring organisms could reach the surface of the sediment column, and keep the nodules on top of the sediments. He further noted that in terms of pressure, it was easier to keep the nodule afloat, than to suppress them into the centre of the sediments.

Professor Beiersdorf turned his attention to hiatuses, recalling that he had spoken of the Eocene hiatus and the two major hiatuses that had been found in one core. He attributed the discovery to the systematic manner of digging through the sediments in the search for buried nodules. Professor Beiersdorf recalled that a succession of buried nodules from small to large, had been found, starting at the hiatus. He informed participants that the outer layer of the nodules at various depths had also been investigated. He said that the outer layer of a nodule, which represented one single growth type increased in thickness towards the top of the column. He said that this phenomenon had been observed at the depth of the second hiatus. He also said that this meant that the growth rate increased from top to bottom, and that the thickness of nodules was strongly associated with the type of growth, starting from diagenetic to hydrogenetic growth.

The Professor said that having reached the hiatus, the nodules cracked, became dehydrated and around the resulting fragments, new nodules had started to grow. Professor Beiesdorf said that the same trend had been observed immediately after the hiatus. He described the growth as diagenetic, in particular in relation to the sediments.

Professor Beierdorf said that in their investigations, three ash layers had been discovered. He said that the input of volcanic ashes appeared to create a regional nodule sub-facies. He said that the ash was infertile and unfavourable to life, thus impeding biogenic lifting of nodules. Upon investigation of the nodules that the researchers had found, he said that the succession was from small nodules to large ones, until arrival at the ash layers. He said that after the onset of sedimentation on the ash layers, a new generation of very small nodules had started to grow.

With regard to nodule abundance, Professor Beiersdorf said that on hilltops where there was little or no sediment, accumulation was almost zero. He said that in marginal basins, smooth nodules, or nodules which are transitional between smooth and rough were dominant. He said that these were mainly small nodules, and that their abundance was between 5 and 15 kilograms per square metre. In basins away from hills, he reported that they found nodules with relatively high accumulation rates. The Professor said that there were basin settings and low sedimentation rate areas. He said that in low sedimentation rate areas, relatively small, rough nodules buried in sediment could be found. He also said that in basin areas, which were strongly eroded by bottom water, no nodules were found.

According to Professor Beiersdorf, in the CCZ, there is a latitudinal zonation of sediments, which is a function of radiolarian inputs, and the primary productivity with its associated particle flux. He said that there is a decline of nutrients in the photic zone from the equatorial upwelling zone in the south towards the oceanic desert, where there is very low bioproductivity. As a result, Professor Beiersdorf said that sedimentation dominated differently; calcareous, near the equator and the upwelling zone, siliceous further north, and finally the red clay areas even further away. He said that the accumulation rates decreased accordingly, from south to north, greater than two grams per square centimetre per thousand years, to less than one gram per square centimetre per thousand years in the red clay area.

He stressed that this is associated with the equatorial distribution of bioactivity in the surface waters. He said that taking into account the fact that sediment in the middle areas of the CCZ had migrated from the ridge crest to their present positions, and had undergone subsidence along the way; one could understand what had happened with regard to the carbonate compensation depth. Professor Beiersdorf said that once a site had arrived in the equatorial region, where the carbonate compensation depth was depressed, due to the high supply of carbonate in the water column, a calcareous deposition started, and this was maintained until the site moved beyond this zone. He concluded his presentation saying that one had to consider the migrations as subsidence, until finally one ended up with a major nodule facies.

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CHAPTER 11 RELATIONSHIP BETWEEN MANGANESE NODULES AND THEIR SEDIMENTATION AND GEOLOGICAL ENVIRONMENT: PREDICTIVE APPLICATIONS FOR RESOURCES ASSESSMENTS

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(A formal paper was not provided to the Secretariat, therefore this chapter comprises a summary of Michel Hoffert's presentation and the discussions that followed the presentation

SUMMARY OF THE PRESENTATION

Professor Hoffert started his presentation saying that he would like to take participants on a field trip to the Peru Basin, and to provide them with an overview of nodule deposits that occur there. He said that his presentation would provide different details on nodules. He described the basic parameters that he would touch on as the bathymetry, the topography, the sediments, currents, surface productivity, and seeing that it was the Peru basin, the CCD.

Professor Hoffert explained that the Peru basin was several thousand kilometres away from the Clarion-Clipperton Zone, that is, to the east and south of the Equator, and close to a highly productive biological area. He said that because of the productivity, there was a lot of organic carbon and organic metal input in the sediment, which was probably different from the Clarion-Clipperton Zone. On the question of why the workshop should consider this basin; the answer, he said, would be that it had a lot of manganese nodules, and that it had generated quite a lot of interest in the seventies and eighties by industry. He said that the Peru basin could become a new target in the future. He showed participants on a chart the areas where some investigations had taken place and said that he would refer to information from area two and area five.

Professor Hoffert started with bathymetry, which he said was very important. Using a slide, he showed participants the 20-metre contour line of a small portion of the area that had been surveyed, and said that the results were different from their expectations. Professor Hoffert said that the overall relief of the area was about 400 metres and the depth range between 4,300 and 3,900 metres. He also showed images of large seamounts that he said were previously unknown and had now been mapped; the largest of which was about 2 kilometres high. He stressed the importance of mapping in the investigation of seafloor areas. He said that from seismic information that had been acquired, it was known that the sediment sequence was approximately 115 metres thick in this area. He said that with a relief of 300 to 400 metres, it was difficult to explain the sediment cover in the area.

Professor Hoffert said that the impact of the tectonic framework on the underlying basement was important because, it depended on whether one had large escarpments**,** in which case one had to deal with considerations such as sedimentary environments. He said that sedimentary environments were important because, they defined a large part of nodule growth in the area. He described unfavourable environments for nodule growth as inclusive of areas that resulted in down slope transportation of materials, which buried nodules, or did not allow them to grow at all. He also said that it was likely that such areas would not be available for mining, even if they had a nodule tonnage. In that regard, he said that ash areas were probably not mineable because of the inclination of the slope.

The second parameter presented by Professor Hoffert was the carbonate compensation depth (CCD). He said its importance had already been confirmed and that in their study, they had obtained the requisite data on this parameter at two sites. He said that within a distance of about 120 metres, a difference of about 150 metres was detected in the carbonate compensation depth. He suggested that with this kind of data, the importance of the CCD to nodule formation could be determined.

Professor Hoffert said that a comparison of the carbonate record for the two areas was undertaken. He said that the data used was standardized to 4,100 metres replicates, which was close to the carbonate compensation depth in that area. He said that the researchers had wanted to see the importance of the CCD for that area; and had observed that the abundance of nodules was highest in the immediate vicinity of the present-day CCD. He also noted that the highest values were found in areas where the carbonate compensation depth was 4,100 metres. In these areas, Professor Hoffert said that nodule abundance was between of 40 to 50 kilograms per square metres.

Professor Hoffert said that their study revealed that the size of nodules at locations above the carbonate compensation depth was uniform but small. In the basin close to the carbonate compensation depth, he said that there was a wide range of very large nodules with diameters ranging up to 13 centimetres, but that these nodules were few in number. He said that these findings indicated that there was a difference in the way nodules were formed. He suggested that it could be a special initiation process or phenomenon which generated a lot of nodules in this geographic setting. Professor Hoffert believed that the Tertiary sediments had been deposited under oxygenated conditions and that they contained, in the solid phase, manganese oxide. He said that there were hiatuses at the Tertiary boundary and also a part of the Quaternary above that. He also said that there was a sequence which was basically based on manganese, since manganese moved upwards when dissolved under sub-toxic or reducing conditions. Consequently, the Professor concluded that the change in cobalt and other manganese metals for them to be precipitated in the surface area, where there was oxygen available, was the basis for nodule growth. He described the layer of nodules in this area of the Peru basin as fairly thick. Professor Hoffert informed participants that once nodules reached a certain size, they tended to grow faster, because, they then enjoyed favourable growing conditions.

Professor Hoffert said that from the sediment eco-sampler data, researchers had observed significant differences in the sequence in this area. These included 12 metres of Quaternary sediments behind a seamount. He noted however that in general, a certain amount of carbonate was still present. He also asked participants to keep in mind two other parameters, erosion and currents.

Professor Hoffert showed participants a map of the seafloor from which a difference in reflectivity could be seen. He indicated an additional feature that they had found, which he said was completely unexpected, comprising small-scale relief cones between 15 and 25 metres in the area. He said that the cones could either be interpreted as volcanic cones with their basement coming up, which was somehow hard to believe or they could be interpreted in terms of a younger volcanic phase, which others did not know in that area.

Professor Hoffert invited participants to look at the scale of the map and to note that it was a very small area – he believed about 800 metres wide. He said that all the scale changes had been verified. He noted that within a distance of 10 metres or so, there was a change from a cobblestone pavement of nodules to a completely empty area. He said that he had wanted to investigate the area to look at the viability of the seafloor for mining, taking into account the impact of the carbonate compensation depth on nodule growth. Professor Hoffert concluded his presentation saying that one had to be aware of the very small-scale viability on a scale of hundreds of metres, with regard to mining. According to Professor Hoffert, the parameters to be examined for mining activities would be quite different from many of the considerations, which he had thus far heard in the workshop.

SUMMARY OF THE DISCUSSION

In reply to a question on whether the studies he had described were in the exclusive economic zone or in the Area, Professor Hoffert said that the studies were in the Peru Basin and in areas outside the exclusive economic zone.

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CHAPTER 12 RELATIONSHIPS BETWEEN NODULE GENESIS AND TOPOGRAPHY IN THE EASTERN AREA OF THE CLARION-CLIPPERTON REGION

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Introduction

The initiative of the International Seabed Authority (ISA) for the establishment of a geological model of the Clarion-Clipperton region is aimed at identifying and exploring regional and local patterns in distribution of nodules as well as those related to the presence and concentration of base metals in them. The long-term comprehensive geological studies, carried out to date in the region, have elucidated general relationships between distribution and conditions enhancing the presence of nodules, as well as relationships between base metal contents and specific morphotectonic features of the Clarion-Clipperton Zone (CCZ), the crystalline basement age and tectonic position, structure and development of sedimentary cover, depth and topography of the seafloor, subsidence and sedimentation rates, and the major environmental factors are of key importance for nodule formation (Cronan, 1977; Kazmin, 1984; Korsakov, 1987; Stackelberg, Beiersdorf, 1991; Kotliński, 1999; Andreev,Ed, 2000; Morgan, 2000).

The report of the ISA Secretariat and the results presented during the meeting of the Group of Experts, held in January 2003, demonstrate the diversity within the areas selected in the Clarion-Clipperton nodule region, of conditions enhancing nodule distribution, patterns in the distribution, and the nodule metal contents. The patterns of nodule distribution and of conditions enhancing their presence in the eastern, central, and western areas of the Clarion-Clipperton region show certain differences, expressed through certain area-specific features (Kazmin, Stackelberg, Beiersdorf, Wenzheng, Hoffert, and Kotliński).

Identification of the most characteristic parameters is of critical importance for development of the geological model. The present paper is aimed at highlighting the most important parameters (in the author's opinion), parameters and patterns typical of the eastern area of the Clarion-Clipperton region. The results obtained demonstrate certain specificity of the area, expressed, *inter alia*., in the basement age and structure and in the sedimentary cover development, in seafloor depth and topography, activity of the East Pacific Rise, level of the carbonate compensation depth (CCD), a high productivity and a relatively high sedimentation rate, distribution of nodules and conditions controlling their formation, and base metal content. The nodule patterns identified show a high variability of properties, manifested both at the local level and in comparison with other areas of the region in question (Kotliński, Zadornov, 2002; Kotliński, 2003).

Interoceanmetal Joint Organization as a contractor

The Interoceanmental Joint Organization (IOM), an intergovernmental consortium, was set up in April 1987 to survey and explore polymetallic nodule deposits in the eastern part of the Clarion-Clipperton nodule region (*Figure 1*) and to prepare their commercial development.

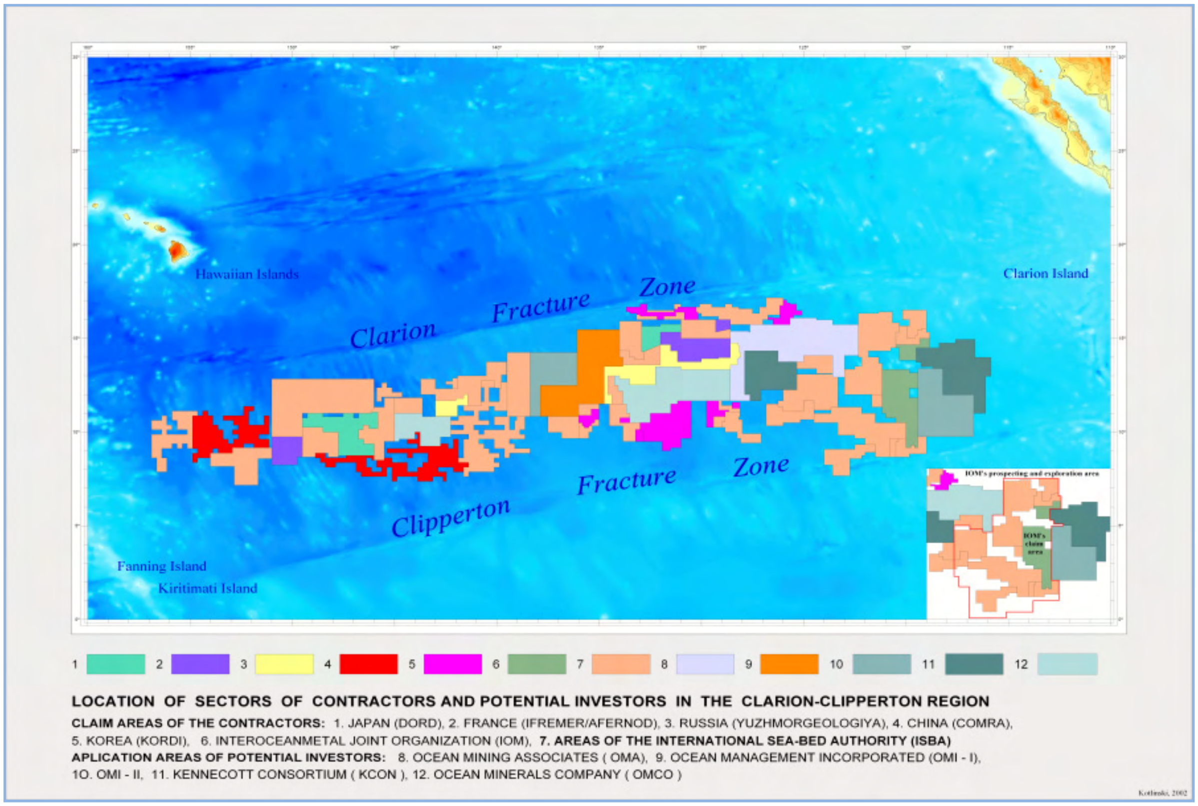

Figure 1: Location of sectors of Contractors and potential investors in the Clarion-Clipperton region.

Using the results of its comprehensive research and analysis of regional geological and geophysical data, between 1987 and 1990, IOM selected a prospecting area of about 553,000 km^2, within which to conduct multi-faceted geological and geophysical studies. The studies carried out in the eastern part of the Clarion-Clipperton nodule region were aimed at narrowing an application area down to 300,000 km^2 and to collect data necessary for IOM to apply to the Preparatory Commission of the International Seabed Authority (ISA) and International Tribunal for the Law of the Sea for registration and allocation of a 150,000 km^2 "pioneer area".

Based on the data submitted, in accordance with regulations of the United Nations Convention on the Law of the Sea and resolution II, in June 1992, IOM was granted pioneer investor status and a certificate of registration. Having fulfilled its obligations as a pioneer investor, IOM focused on comprehensive geological and environmental research and exploration, aimed at relinquishing to ISA parts of the registered pioneer area (in 1994, 1996, and 2001) and at collecting environmental data. In 1995, IOM carried out its Benthic Impact Experiment (IOM BIE) at an abyssal site located within the IOM claim area (Kotlinski *et al*, 1996, Kotlinski and Stoyanova, 1998; Radziejewska and Kotlinski 2002).

The long-term studies and regional analyses based on data collected during research cruises have made it possible to establish general patterns of nodule distribution and relationships between conditions controlling nodule formation processes in the eastern area of the Clarion-Clipperton nodule region.

As stipulated by the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area adopted by ISA in 2000, any activity within the pioneer area should be preceded by ISA approval of a 15-year plan of work for exploration and by conclusion, with ISA, of a contract for implementation of the plan.

The Authority approved the IOM plan of work for 2001-2015 in 1997. Subsequently, in March 2001, a contract between ISA and IOM for the implementation of the plan was concluded. According to the contract's provisions, the area intended for IOM exploratory activities covers 75,000 km^2. The contracted work has been conceived as an investigation of geological and mining conditions of the future mining area.

As a preliminary to the actual exploration, in 1999, the IOM pioneer area was surveyed using a SIMRAD multi-beam echo sounder. The survey resulted in the compilation of 1:200 000 maps of bottom relief, slope angles, and bathymetry; in addition, side-scan sonar images of the bottom were collated.

In May 2001, IOM embarked upon implementation of the first stage of its "Plan of Work for Exploration" by launching a cruise to its pioneer area on board the research vessel *Yuzhmorgeologiya*. During the cruise, the B-2 area was surveyed. The cruise was intended to acquire data with which to identify areas most suitable for more detailed geological exploration aimed at mapping potentially valuable nodule deposits, as well as at assessing spatial variability in nodule coverage and base metal contents in the deposits (Kotliński, Zadornov 2002).

Basement and seafloor topography

IOM's exploration area is situated on the western slope of the East Pacific Rise and extends longitudinally over 510 km between the Clarion and Clipperton fractures, the mean width of the area being 150 km.

Based on data collected during that and the preceding cruises, the seafloor of the area may be visualized as a series of longitudinal blocks of volcanic and tectonic origin, separated by sub-latitudinal and longitudinal fractures (including transform ones) (Jubko *et al*.,1990; Kotliński, 1992; Kotliński, Zadornov 2002).

Judging by the age of the seafloor basalts, the morphology and structure of the bottom dates back to early Miocene/late Oligocene. As volcanic and tectonic activity intensified in the late Miocene-Pliocene, sub-latitudinal volcanic massifs emerged, adding to the structural complexity of the area.

The seafloor within the boundaries of the IOM exploration area was found to be inclined N-S towards the centre; a slight inclination is observed in the E-W direction as well. The seafloor is a part of an undulating (4,300-4,400m below sea level) plain, its morphology being rendered more complex by a system of longitudinal horsts (4,100-4,300m) and graben (4,400-4,750m). The presence of volcanic massifs results in modification of the basic structural plan of the seafloor. The horsts and graben have emerged as a product of the seafloor fracturing.

The 4,300m depth contour seems to be the reference depth for the undulating horst-graben relief of the seafloor. The horsts vary in width from 1.0 to 15 km and extend for 5 to 70 km in length. The broadest and longest horsts are encountered in the central and southern part of the area surveyed and can be either symmetrical or asymmetrical on the cross-section. The slopes of the asymmetrical horsts are steeper (the slope angle exceeding 10^o). The horsts are 200m high at most (in the north), the minimum height (recorded in the central-western part) being 75m.

The 4,400m depth contour appears to be the reference level for the rifts (grabens). Along the 4,500m isobath, the rifts vary in width from 0.8 to 25 km and extend for 4.5 to 150 km in length. On the cross-section, the grabens are predominantly trough-like. They may contain depressions up to 210m deep, their size varying from 0.8 x 1.4 km to 3.0 x 18 km. The depression axes are curved in outline; certain wide grabens have several axes. The graben walls are steep, occasionally almost vertical. Most often, the grabens are symmetrical on the cross-section and their depth varies from 225 m (from the reference level) in the south to 310m in the central-western part. The axes of both the horsts and the grabens show a characteristic undulation.

The seabed over 30 per cent of the area slopes down at more than 7 degrees. Slopes of this kind are typical of volcanic structures, of the feet of horsts and of graben walls.

Sediments

In the eastern area, three sedimentary units were identified above the basement. They were termed 3.5 kHz seismo-acoustic facies: the upper transparent layer A (Unit A); the upper stratified layer B (Unit B); and the lower transparent layer C (Unit C); they correlate with the Deep Sea Drilling Project results (Drilling Hole No. 159; Kotliński 1992).

The basement composed of tholeitic basalt is Miocene in age, as concluded from the analysis of linear magnetic anomalies.

- Unit A is an acoustically transparent layer, Quaternary to late Miocene in age.
- Unit B is an acoustically semi-transparent layer, late Miocene to early Miocene in age.
- Unit C is an acoustically transparent layer, early Miocene in age.

Unit A is never thicker than 20m, its thickness averaging 10m. The unit's thickness in not only dependent on topographic variations of the seabed, but also on such factors as the deep-sea currents which can affect erosion processes. The seafloor sediments within the area surveyed consist of the Marquesas (early Miocene -Pliocene) and Clipperton (Pliocene-Holocene) formations within which 4 major layers can be identified (*Table 1*).

Table 1
Characteristics of bottom sediments within the IOM exploration area (Kotliński, Zadornov 2002)

Layer symbol	*Sediment type*	*Sediment origin*	*Layer sampled (cm)*	*pH range*	*Eh range*	*$SiO_{2amorph}$ (%) range*	*Moisture content range*	*Bulk density (g/cm^3) range*
IV_{CL}	Clay and siliceous ooze; geo-chemically active layer	Elluvial-deluvial	0-12	7.26-7.46	546-588	1.22-32.25	337-431	1.16-1.19
	Siliceous ooze (ethmodiscoid oozes)	Deluvial-solifluction produced	10-30	7.36-7.48	510-592	13.78-28.6	319-383	1.18-1.21
	Clay and siliceous ooze	Elluvial-deluvial	10-30	7.32-7.58	269-598	1.73-17.85	245-399	1.17-1.25
			35-350				231-310	1.21-1.25
III_{M}	Zeolitic clay	Elluvial	10-20	7.39-7.46	488-556	1.22-17.85	218-226	1.26-1.28
			35-135				198-240	1.26-1.29
	Zeolitic crusts		0-40	7.38-8.02	502-625	0.9-27.73	370-533	1.14-1.21
II_{M}	Radiolarian ooze	Elluvial	50-330	7.32-8.02	502-625	0.9-27.73	370-533	1.14-1.21
I_{M}	Calcareous ooze	Biogenic	215-300	7.57-8.09	543-573	1.36-7.75	152-208	1.22-1.37

The lowest layer (I), represented by calcareous, nanofossil-containing oozes, is characterized by an elevated bulk density as well as by reduced moisture and amorphous silica contents. The sediments are believed to be a product of the primordial biogenic sedimentation.

That layer is overlain by another (II), represented by siliceous ooze or a mixed sediment, a product of halmirolysis of the underlying deposits. The sediment is an elluvial formation characterized by a reduced bulk density, increased moisture content, and a high content of amorphous silica. The thickness of that deposit does not exceed 2.5m.

The overlying deposit (layer III) consists of the zeolitic red deep-sea clay and thicker zeolitic crusts characterized by a high bulk density, reduced moisture content, and the amorphous silica content reaching up to 18 per cent. This alluvial deposit is probably up to 3m thick.

The sediments making up the three layers described above belong probably to the Marquesas formation.

The uppermost layer (IV) belongs to the Clipperton formation. This sediment consists of alluvial-deluvial clays and oozes with montmorillonite and chlorite, and is mottled, patchy or smudgy in appearance. The amorphous silica content varies from 1 to 20 per cent. The layer may be up to 3.5m thick.

Some sites revealed specific sediment completely devoid of nodules. Such sediment is formed by reduced bulk density clays and aleuritic siliceous oozes the amorphous silica content of which reaches up to 30 per cent. That sediment is deluvial-solifluction in origin, a product of transportation and re-sedimentation in local, confined depressions (*Figure 2*).

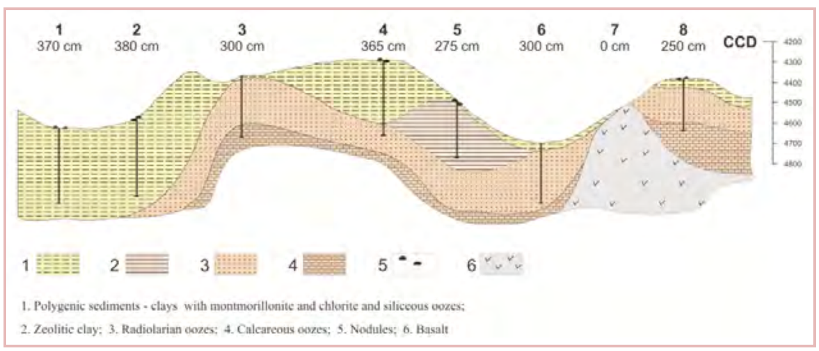

Figure 2: Distribution of sediments (according to Zadornov, 2001).

The seafloor sediment vertical profile is topped by clays and siliceous oozes of the geochemically active (2-12 cm thick) layer on which nodules are formed and in which they are partly embedded. Those sediments are characteristic in their reduced bulk density and increased moisture content. The layer discussed is known as the sediment–water interface boundary (SWIB) layer (see Sharma and Kodagali, 1992). The nodules are partially or fully buried, which results in nodule abundance estimates from bottom photographs being lower than those based on grab contents (Photo 1). The degree of embedding depends on the thickness of the (SWIB) layer. If it is thin, coefficient R assumes low values (< 1.5) because more nodules are exposed; whereas a thick layer and even larger nodules produce higher R values (>1.5).

Generally speaking, the sediments of the area belong to the polygenic type. Their granulometry places them on the boundary between clayey-aleuritic and aleuritic-clayey oozes, the <0.001 mm fraction making up 89-92 per cent; the median grain size is close to 4 µm.

The base metal contents in the sediments can be arranged in the following order:

Photo 1 – Typically sediment blanketed nodules

Fe > Mg > Mn to form a series of 5.97-6.61 > 3.0 – 3.1 > 0.13 – 0.67 per cent.

The low manganese content may be explained by diagenetic “scavenging” of manganese by nodules. The base metal contents are higher in nodule-bearing areas of the seafloor than in nodule-free patches. The metal contents decrease with increasing depth in the sediment, with a characteristic maximum within 3 to 6 cm in the sediment. The pore water shows a reverse relationship of metal content vs. depth in the sediment.

Distribution and characteristics of nodule in relation to geological settings

The complexity of the seafloor morphology is reflected in the nature of nodule coverage of the bottom. Although the IOM area may be generally regarded as a nodulized one, it contains, in fact, both nodule-bearing and completely nodule-free patches.

Notwithstanding the relatively constant base metal contents in the nodule deposits, nodule coverage varies widely (*Figure 3*).

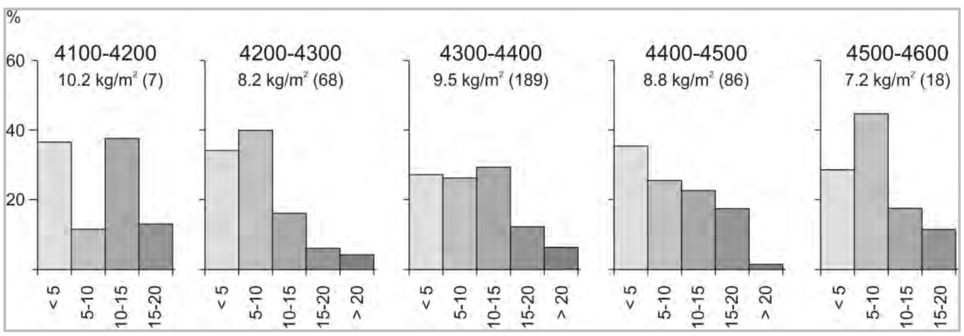

Figure 3: Distribution of nodule abundance

Within the IOM exploration area, sediment samples were collected (with a 0.25 m^2 box corer equipped with a photo-camera) from a total of 371 sites; nodules were present at 324 (87.3 per cent) of them, while at 154 (47.5 per cent) of them, the nodule abundance (wet weight-based) exceeded 10 kg/m^2 (Photo 2).

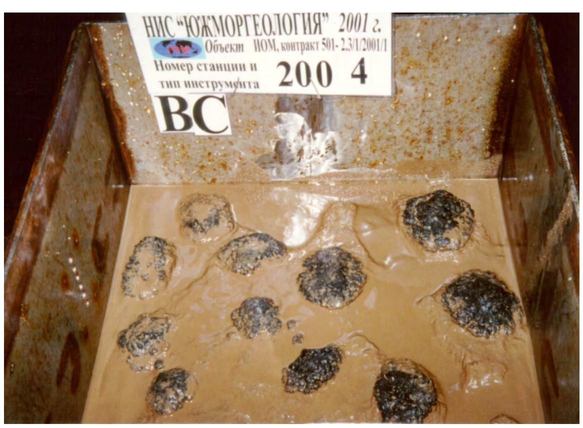

Photo 2- Discoidal (Dr) nodules in a boxcorer

No regular pattern could be observed in the distribution of polymetallic nodules in the area surveyed; in other words, no single morphological element of the seafloor relief tended to be more amenable to nodule aggregations than the remaining ones. Both nodule-rich and nodule-depleted patches of the seafloor could be found on the undulating abyssal plain, on tops and slopes of ridges (horsts), and on the walls of grabens.

Bulk mineralogy and chemistry

Although the crystallographic description and mineralogy of manganese nodules are still controversial, they are important because they reflect the origin of the nodule and to some degree determine their chemical composition (Usui, Someya, 1997; Kotliński, 1999). Minerals in the nodules are commonly identified by powder X-ray diffraction (XRD). Due to a low crystallinity and hydrous nature, the XRD diagrams are usually insufficient for more detailed analysis of nodule structure. In terms of mineralogical criteria and results of the analyses, the following three minerals can be assumed to be the major components:

1. 10 Å manganite (Cu-Ni rich busserite) the main mineral busserite forms probably from dissolved manganese in poor waters during early diagenesis;
2. Birnessite; its diagnostic reflection is 7 Å;
3. Vernadite, a hydrogenetic Fe-Mn oxide; it is poorly crystallized; while Fe- and Co-enriched, it contains negligible amounts of Cu and Ni.

The nodules contain also microscopic detrital silicates, feldspar, plagioclases, and quartz.

The mineral and chemical composition of nodules, particularly relationships between contents of hydrogenetic minerals (iron and manganese hydroxide, i.e., vernadite) and diagenetic-manganite-busserite, as well as the Mn/Fe ratio and concentrations of Ni, Cu, and Co reflect the major processes responsible for nodule formation, i.e., hydrogenetic or diagenetic processes (Usui, Terashima, 1997).

As a rule, larger nodules with rough surfaces are Mn-, Ni-, Cu-, and Mo-enriched, busserite being the major mineral component. On the other hand, smaller, smooth nodules are relatively rich in Co, Fe, and Pb and show a higher vernadite content.

Distribution and origin of the nodules

The area surveyed was observed to harbour all the known nodule genetic types: Hs, HD, and Dr (Kotliński, 1996; 1999; 2001; 2003). In terms of nickel content, a sub-type Dr_1 may be separated within the nodule type Dr, the Dr_1 nodules containing more copper than nickel (*Table 2*).

Table 2
Basic characteristics (mean values) of the diagenetic nodule types in the IOM exploration area (Kotlinski, Zadornov 2002)

Parameter	*Type*		*Entire exploration area (324)*
	Dr (148)	*Dr_1 (96)*	
Wet weight-based abundance (kg/m^2)	12.9	7.3	10.2
Dry weight-based abundance (kg/m^2)	8.8	5.0	7.0
Ni (%)	1.37	1.25	1.31
Cu (%)	1.26	1.34	1.23
Co (%)	0.18	0.16	0.18
Mn (%)	31.90	31.48	30.80
Moisture content (%)	31.6	32.0	31.7

*Number of sampling sites from which the data were acquired is given in parentheses

Distribution of the genetic types of nodules is controlled by the position of the CCD in relation to the seafloor, the CCD in the eastern region being located at a depth of about 4,200m. The hydrogenetic - smaller and smooth - nodules occur above and within the CCD depth interval, whereas the diagenetic - larger and rough - nodules occur, as a rule, below the CCD (*Table 3*). Differences in nodule sizes reflect their structural and textural features, which are related to their different growth rates (Kotlinski, 1999).

Table 3
Distribution of sediment sampling sites by nodule genetic types (Kotlinski, Zadornov 2002)

Location within the area surveyed	Nodule type				
	Nodule-free sites*	*Hs*	*HD*	*Dr*	*Dr_1*
Northern part	17.7’	6.2	21.5	46.2	8.4
Central part	9.6	4.2	13.3	39.4	33.5
Southern part	11.3	1.9	18.9	26.4	41.5
Total in the area surveyed	12.7	4.5	17.0	39.9	25.9

*Percentage of the total number of stations in the location.
- Northern part: 13°20’-12°00’N.
- Central part: 12°00-10°30’N.
- Southern part: 10°30’-9°10’N.

The richest deposits are formed by large (6-12 cm) type Dr nodules (weighing up to 2.6 kg), their abundance reaching 28.4 kg/m^2. Nodules of this type are encountered throughout the area surveyed and occur under various conditions in terms of seafloor morphology and depth. The large type Dr nodules, up to 10 cm in size, have nuclei made up of fragments of older nodules. Although the nodules are irregular in shape, they reveal some features of the primarily discoidal form. In a number of cases, large nodules are mushroom-shaped, with a “stalk” embedded in the sediment and a loose, easily chipping, rough surface. The upper surface of some large specimens is botroidal and smooth. The equatorial belt is usually well-developed and visible as large botroids. On the cross-section, those nodules show thick layers that, in certain largest specimens, are up to 10mm thick each. They usually show a radial, dendritic or colomorphic texture and are cracked. The nodules of this type are typically sediment-blanketed. In numerous photographs of the seafloor, taken at the moment of sampling, the nodules appear to occupy as little as a few per cent of the frame. A significant number of nodules remain buried in the sediment–water interface boundary layer and are revealed only when the sediment sample is being processed. The coefficient R (a ratio between the area of the bottom actually covered by nodules and the nodule-covered area as seen on the photographs) may be as high as 15 and averages 1-3 (*Table 4*).

Table 4
Distribution of ratio “R”

Index ”R”	*Stations (Percentage)*
1.0	29.1
1-3	56.4
3-10	11.6
>10	2.9

Small-type (up to 6 cm in size) Dr nodules are, as a rule, coreless (cross-sections show a single generation of concentric layers about 1 mm thick each; even a microscopic examination fails to reveal the presence of a core). The nodules are discoidal or ellipsoidal in shape, the smallest being spheroidal. They usually have rough surfaces.

Type Hs nodules are particularly abundant in the northern part of the area; they usually lie on the seafloor surface at water depths shallower than 4,200 m (CCD level) and are very visible in photographs of the bottom. A characteristic feature of their distribution, useful in interpretation of images, is their chain-like arrangement on the bottom.

Those nodules are usually small and spheroidal (not larger than 6 cm, most of them attaining 2-4 cm in size). They usually display a smooth surface; occasionally the surface shows large monocrystals and zeolitic accretions. Those nodules are porous and frequently cracked. Their nuclei are, as a rule, formed by concentrations of zeolites; more seldom are they made up by fragments of older nodules. The nodule cross-sections show the layers to be a fraction of a millimetre thick each. Those nodules occur in conjunction with calcareous oozes or calcium carbonate–poor siliceous clayey oozes.

Some sites located at depths shallower than 4,200 m show the presence of crusts up to 3 cm thick on more consolidated zeolitic clays.

The moisture content of those nodules varies within 28-40 per cent and averages 32 per cent; their density ranges from 1.75 to 2.06 g/cm^3, averaging 1.95 g/cm^3.

Most numerous in aggregations of those nodules are discoidal (morphotype D) ones and their regenerated fragments (fD); the summary contribution of other morphological types (ellipsoidal, spheroidal, accreted, and plate-like) does not exceed 13 per cent. The aggregations described extend both latitudinally and at various water depth ranges. The contribution of morphotypes D and fD increases from type Hs towards type Dr nodules, the share of other morphotypes decreasing.

In 95 per cent of the cases, the nodules have been formed around a nucleus of older ones. It is only among nodules of morphotypes S, R, and T that their cores are occasionally formed by sediment (primarily zeolitic clay) agglomerates (Photo 3).

Photo 3: [Sediment agglomerate cores]

A gradual increase in contribution of larger fractions, up to the maximum at fractions exceeding 8 cm (from 3.2 per cent contributed by 0-2 cm to 40.7 per cent of the >8 cm fraction) is observed. In the N-S direction, the contribution of >8 cm nodules is seen to decrease (from 52.5 per cent in the northern part to 5.6 per cent in the south). The nodules in the southern part of the area are mostly those 4-6 cm in size (38 per cent). As the depth increases, the amount of nodules >8 cm decreases (from 56 to 32.9 per cent), while the respective contributions of nodules 2-4, 4-6, and 6-8 cm in size increase. The most stable size distribution of nodules is observed within the depth range of 4,300-4,500m (Table 5).

Table 5
Characteristics of polymetallic nodules in the Interoceanmental Joint Organization exploration area by depth (Kotlinski, Zadornov 2002)

Depth range (m)	*Number of sampling sites*	*Mean abundance (kg/m^2)*		*Mean metal content (% by weight)*				*Mean moisture content (%)*
		Wet nodules	*Dry nodules*	*Ni*	*Cu*	*Co*	*Mn*	
3400-3500	1	0	0	-	-	-	-	-
4000-4100	2	5.0	3.3	1.05	0.86	0.20	24.02	34.0
4100-4200	7	10.2	7.0	1.22	1.01	0.20	27.45	31.3
4200-4300	68	8.2	5.7	1.3	1.16	0.18	29.77	31.2
4300-4400	189	9.5	6.5	1.32	1.24	0.17	31.08	31.9
4400-4500	86	8.8	6.0	1.32	1.27	0.17	31.31	31.8
4500-4600	18	7.2	4.9	1.24	1.19	0.19	30.47	32.5
Entire area	371*	9.0	6.1	1.31	1.22	0.18	30.79	31.8

*All sampling sites, including nodule-free ones, are included.

The nodule size increases from type Hs to Dr (the contribution of the >8 cm fraction increases from 37.9 to 43 per cent), while the respective contribution of the 0-2 cm and 2-4 cm fractions sharply decreases (from 17.5 to 2.0 per cent and from 19.0 to 10.3 per cent). The type Dr nodules have the most stable size distribution. The basic characteristics of nodule deposits in the IOM exploration area are summarized in Table 6.

Table 6
Characteristics of the genetic types of nodules in the Eastern Clarion-Clipperton region

Lithofacies	*Calcareous oozes and calcareous clayey silt within 4200m -CCD depth interval*	*Clayey silt (slightly calcareous and slightly siliceous) 4200-4500m*	*Siliceous oozes and brown pelagic clays below CCD 4300-4700m*
Genetic type	Hs	HD	Dr
Mean nodule abundance: kg/m^2	10.5	8.3	12.9
Co-occurrence on the genetic types	HS+HD	HS+HD-HD+DR	HD-DR DR_1
Size (cm)	<3.0	3.0-6.0	6.0-12
Average size (cm)	3.4	4.4	6.5
Mean diameter and percent contribution to fractions: >6 cm >8 cm	1-4 54.0 37.9	2-8 49.8 39.2	4-12 66.9 43.0
Index “R”	1.0	1.0-3.0	1.0- >10.0
Surface structure	s/r; s	s/r; r	r; s/r; r/s, s
Dominant morphotype D+fD %	D, fD, S, P, E, T 46.8	D, fD, E 83.4	D, fD,E 93.7

Nucleus type	clayey-zeolitic, more seldom volcanoclastic or bioclasts	clayey-zeolitic, bioclasts,	fragments of older nodules, micronodules
Fractures	radial	irregular	clearly radial
Lamination (mm) prevailing lamina thickness (mm)	thin (<1.0) <0.4	medium (1.0) 0.4-1.0	coarse (>1.0) >1.0
Textures	radial	radial-dendritic, concentric-laminated	massive, radial-dendritic, concentric- laminated
Dominant Mn minerals	vernadite	birnessite, vernadite	busserite, birnessite, vernadite
Average contents (per cent) of major metals:			
Mn	23.79	28.31	31.90
Fe	5.38	5.88	5.25
Cu	0.89	1.10	1.26
Ni	1.06	1.24	1.37
Co	0.20	0.20	0.18
Zn	0.10	0.12	0.14
Mo	0.044	0.065	0.062
Pb	0.025	0.035	0.032
Mn/Fe	<5.0	3.0-5.0	>5.0
Physical properties:			
- density of mineral part (g/cm^3)	3.35	3.35	3.34
- density (g/cm^3)	1.93-2.00	1.88-2.03	1.75-2.24
- volumetric weight (g/cm^3)	1.33	1.29	1.28
- moisture content (%)	31.0	32.3	31.6

Latitudinal variability in nodule abundance and related parameters is shown in *Table 7*.

Table 7
Latitudinal variability of nodule abundance and base metal contents (Kotliński, Zadornov 2002)

Part of the area explored	*Nodule abundance parameter*						
	Wet weight-based abundance (kg/m^2)	*Dry weight-based abundance (kg/m^2)*	*Ni (%)*	*Cu (%)*	*Co (%)*	*Mn (%)*	*Moisture content (%)*
Northern	11.3	7.6	1.32	1.17	0.19	30.31	32.9
Central	10.0	6.8	1.29	1.27	0.17	30.86	31.8
Southern	9.0	6.2	1.24	1.25	0.165	31.13	31.1
Total area	10.2	7.0	1.31	1.23	0.18	30.80	31.7

From the north to the south of the area, the mean abundance of the nodules and their Ni and Co contents are observed to decrease, the Cu and Mn contents increasing. The maximum contents of Ni and Co are typical of nodules in the northern part of the area, the highest Cu and Mn contents being found in the nodules occurring in the central and southern parts, respectively.

Furthermore, the respective contributions of type Hs and Dr nodules are seen to decrease in the N-S direction (from 7.5 to 2.1 per cent and from 56.1 to 29.8 per cent), while the contribution of type Dr_1 nodules increases (from 10.3 to 46.8 per cent). The abundance of type HD nodules shows a decreasing trend in the same direction, but their minimum abundance is found in the central part.

Variability in the nodule attributes increases in the following order: Co – Ni – Cu – Mn – abundance. It is only in type Hs nodules that Ni and Cu change places.

Formation of the deep-sea nodules involves complex, multi-stage processes of biogenic migration and hydro-diagenetic differentiation of Mn and Fe and trace elements, proceeding in the uppermost sediment layer, under specific conditions. Intensity of those processes is directly related to complex reaction between amorphous substances which form active colloidal complexes with Mn and Fe. Metal concentration in the nodules is also a multi-phase process the course of which depends on whether busserite or vernadite is being formed (Kotlinski, 1996; 1999).

In the entire area explored, the depth range of 4,300-4,500 m appears to be the most productive one, both in terms of nodule abundance and with respect to the base metal contents. This is the depth range that the basic nodule resources are concentrated in.

No clear-cut relationship between the nodule occurrence and the thickness of the seismo-acoustic complex A has been found either; the thickness of the complex varying from 0 to about 20 m. Changes in the thickness bear not relationship with nodule abundance on the seafloor. No relationship between domination of a particular genetic nodule types, or increased metal content, and the complex thickness has been found (*Figure 4*).

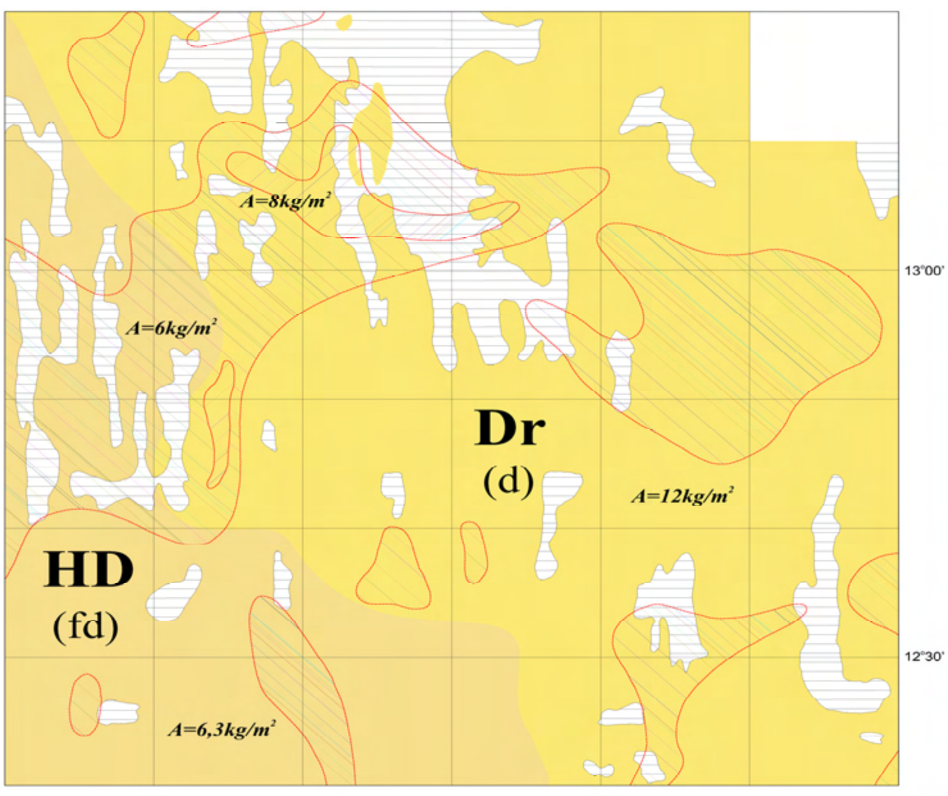

Figure 4: Relationship between thicknesses of the seismo-acoustic complex A, Nodule abundance and genetic nodule types

It was for the first time in the area explored that buried nodules, occurring at 8 – 27 cm in the sediment (average depth in sediment: 15-20 cm) were found. They were recorded at 15 sampling sites. At 5 sites, the abundance of buried nodules was comparable to that on the sediment surface. The buried nodules did not differ in morphology or size from those found on the surface. The buried nodules showed, as a rule, slightly lower contents of ore components.

It should be pointed out that increased resolution of surveying and exploration has changed our comprehension of the local nodule-bearing potential of the area. However, the increase in resolution was achieved without sacrificing the reliability and representatives of nodule sampling, which is of a particular importance at the exploration stage. Results of such finely tuned surveys are extremely valuable in that they broaden the existing knowledge on different spatial scales of natural variability in the potentially exploitable areas.

A characteristic feature in the eastern area of the CCZ nodule region is a relatively high Mn-Cu content at a lower Co concentration, compared to the central area the nodules of which show lower Mn-Cu contents and higher Ni and Co contents. A trend involving a westward increase in the contents of Co and Ni and a decrease in those of Mn and Cu is observed in the region (Kotlinski, 2003).

Conclusions

The structure and geology of the eastern area of the Clarion-Clipperton nodule region (Kotliński, 2003), is characterized by:

- The shallowest location of the crystalline basement, dated to Late Oligocene/Miocene, toleithic basalts being exposed at numerous sites on the seafloor. In Late Miocene/Pliocene, the eastern area experience intensified volcanic and tectonic activity, as evidenced by the presence of overlapping volcanic covers.

- Block basement structure, determining the seafloor topography, and a high variability of sedimentary cover thickness which is represented by sediments classified to three seismoacoustic complexes correlated to the Marquesas and Clipperton formations.

- Seafloor depth and topography determining the specific distribution and high variability (both vertical and horizontal) of surface sediment which are represented by various types of polygenic and biogenic sediments. At numerous sites on the seafloor, usually within local rises, older sediments (e.g., zeolite clay and calcareous oozes of the Marquesas formation) are exposed by erosional processes.

- Siliceous-clay oozes and siliceous oozes cover extensive parts and form a strongly hydrated, geochemically active, sediment-water interface boundary layer 2-12 cm thick. As shown by the results, the small thickness (up to 4 cm) of the layer corresponds to low nodule abundance. The increase in the layer's thickness is usually accompanied by the increasing abundance. No relationship between a specific genetic nodule type or their metal content and the active layer thickness has been found.

- No clear-cut relationship between the nodule occurrence and the thickness of the seismo-acoustic complex A has been found either; the thickness of the complex varying from 0 to about 20 m. Changes in the thickness bear no relationship with nodule abundance on the seafloor. No relationship between domination of a particular genetic nodule type, or increased metal content, and the complex thickness has been found.

- The eastern area of the Clarion-Clipperton nodule region carries nodules belonging to the two basic genetic nodule types, Hs and Dr, co-occurring with an intermediate types HD and Dr1. As a rule, the nodules are embedded in the sediment–water interface layer and partly blanketed by contemporary deposits. The presence of blanketed nodules was revealed at about 70% of the sites. The extent of blanketing (index R) was found to increase with depth from the north to the south, conforming to the change in CCD. At the CCD of 4,200 m, dominant are small (2-4 cm) spheroidal, smooth nodules belonging to type Hs. Below that depth, as a rule, discoidal, larger (6-12 cm) nodules with rough surface are found. The general north-south increase in depth is accompanied by a decrease in the proportion of Hs and Dr nodules of 8 cm modal diameter, the contribution of Dr_1 nodules of 4-6 cm modal diameter gradually increasing.

- The highest nodule abundance, at a high frequency of their occurrence, was recorded within the depth range of 4,300-4,500 m. The north-south depth increase is accompanied by a certain pattern of change in the nodule metal content. The maximum contents of Ni and Co are found in the nodules present in the north part (nodule types Hs and HD); increased Cu contents are observed in nodules present in the central part (nodule type Dr_1), the Mn content increasing clearly in the nodules present in the south part (nodule type Dr). Parameters of nodules present in the eastern area of the Clarion-Clipperton nodule region change in the following order: Co-Ni-Cu-Mn – abundance.

- Nodule distribution on the seafloor and their coverage are extremely diverse. Contours, size, and form of the deposits are determined by the seafloor relief. Borders of streaked deposits, 2 to 10 km wide, and up to several tens km long, coincide with contours of rises and depressions in the seafloor, usually with steep slopes. On the other hand, patchy deposits, about 70 km wide and up to 120 km long, occur on a level bottom. The deposit types are highly variable, both in terms of size and in terms of nodule distribution within them.

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SUMMARY OF THE PRESENTATION

Dr. Kotliński said that his presentation on the relationship between nodule genesis and topography in the Eastern area of the Clarion-Clipperton region would be based on the results of a cruise undertaken by his institute in 2001. Dr. Kotliński began by speaking about the rules and provisions governing contractors, noting that the United Nations Convention on the Law of the Sea treated mineral resources on the seafloor and the international seabed area as the common heritage of mankind. He said that on the open seas, prospecting had been conducted in accordance with the Convention and the Agreement relating to the implementation of Part XI of the Convention and the relevant regulations of the International Seabed Authority. He said that exclusive rights to analyze polymetallic nodule deposits, collecting systems and equipment, processing facilities, transportation systems, and studies of the environment within the registered claim area were vested in contractors. He also said that the nodules buried in the Clarion-Clipperton field extended over some 2,400 square nautical miles, and covered about 2.2 million square kilometres, and that the IOM prospecting area was in the eastern part of that field and covered 543, 000 square kilometres.

Dr. Kotliński explained that the Interoceanmetal Joint Organization (IOM) is an intergovernmental consortium that was set up in April 1987 to survey and explore polymetallic nodules in the eastern part of the Clarion-Clipperton Zone. He said that, during the period 1987-1990, IOM had prospected an area of about 543,000 square kilometres, conducting multi-faceted geological and geophysical studies. Dr. Kotliński said that in June 1992, IOM submitted an application for pioneer investor status to the Preparatory Commission. Based on the data submitted, and in accordance with the UN Convention on the Law of the Sea and resolution II, Dr. Kotliński said that IOM had been granted pioneer investor status following its submission of a 150,000 square kilometre application area. Dr. Kotliński said that the area allocated to IOM to conduct its exploration activities was 75,000 square kilometres. He further informed participants that following the establishment of the Authority, it had approved the IOM plan of work for 2001-2015 in 1997. Subsequently in March 2001, he said that a contract between the ISA and IOM for the implementation of the plan of work was concluded.

Dr. Kotliński told participants that as a preliminary to the actual exploration, the IOM pioneer area had been surveyed by means of a SIMRAD multi-beam echo sounder in 1999. He said that the survey had resulted in the compilation of much better bottom relief maps. He also said that in May 2001, IOM began to implement the first stage of its plan of work for exploration with the launching of a cruise to its pioneer area on board the research vessel *Yuzhmorgeologiya*. He noted that the cruise was intended to acquire data with which to identify areas most suitable for more detailed geological exploration aimed at mapping potentially valuable nodules.

Basement and seafloor topography in the Eastern Clarion

Dr. Kotliński said that the seafloor of the IOM pioneer area might be visualized as a series of longitudinal blocks of volcanic and tectonic origin, separated by sub-latitudinal and longitudinal fractures. He said that judging by the age of the seafloor basalts, the morphology and structure of the bottom dated back to early Miocene and late Oligocene. He said that the seafloor was part of an undulating plain, its morphology being rendered more complex by a system of longitudinal horsts and grabens. He noted that the presence of volcanic massifs had resulted in modification of the basic structural plan of the seafloor, with the horsts and grabens emerging as products of the seafloor fracturing. According to Dr. Kotliński, the 4,300-metre depth contour seemed to be the reference depth for the undulating horst-graben relief of the seafloor. He said that the horsts varied in width from 1.0 to 1.5 kilometres and extended from 5 to 70 kilometres in length. He also said that the 4,400- metre depth contour appeared to be the reference level for the rifts (grabens) and that along the 4,500-metre isobaths, the rifts varied in width from 0.8 to 25 kilometres and extended from 4.5 to 150 kilometres in length.

In describing the seabed, Dr. Kotliński said that over 30% of the IOM area sloped down at more than 7 degrees, adding that slopes of that kind were typical of volcanic structures, of the feet of the horsts and of the graben walls. He said that one could see in a part of the abyssal plain with slopes of more than 7 degrees, the horsts and grabens that had emerged as a product of that fracture. He also said that most often, the grabens were symmetrical on the cross-section; and that their depths ran from 225 to 310 metres in the central and western part.

Sediments

Dr. Kotliński said that in the eastern part of the IOM area, three sedimentary units had been identified above the basement. They had been termed 3.5 kHz seismo-acoustic facies: the upper transparent layer A (Unit A); the upper stratified layer B (Unit B); and the lower transparent layer C (Unit C); and they correlated with the Deep Sea Drilling Project results for Drill Hole No. 159. He informed participants that Unit A was rarely thicker than 20 metres, and said that its thickness averaged 10 metres. He said that the unit's thickness was not only dependent on topographic variations of the seabed, but also on factors such as deep-sea currents, which could affect erosion processes.

Dr. Kotlinski said that the uppermost layer belonged to the Clipperton Formation. He said that the sediment comprising this layer consisted of elluvial-diluvial clays and oozes with montmorillonite and chlorite, and was mottled, patchy or smudgy in appearance. He informed participants that the amorphous silica content varied from 1- 20 per cent. Dr. Kotliński said that some sites within the IOM area had revealed sediment, completely devoid of nodules. He said that this sediment was formed by reduced bulk density clays and aleuritic siliceous oozes. He informed participants that the amorphous silica content of the sediment was up to 30 per cent. He described the sediment as diluvial-solifluction in origin, a product of transportation and re-sedimentation in local, confined depressions. He noted that the distribution of the sediments was clearly visible.

He further noted that the vertical profile of the seafloor sediment was topped by clays and siliceous oozes of the geochemically active 2 to 12-centimetre thick layer on which nodules were formed and in which they were partly embedded. He said that this sediment was characteristically much reduced in density, and had increased moisture content. Referring to the IOM box core, Dr. Kotliński said that one could see that some nodules were not blanketed by sediment, although many were.

Dr. Kotliński informed participants that the layer being discussed was known as the sediment-water interface boundary. He said that nodules were partially or fully buried, which resulted in nodule abundance estimates from bottom photographs being lower than those based on the grab content. He observed that one could see in the photograph sediments which blanketed nodules. He said that the degree of embedding depended on the thickness of the sediment-water interface boundary layer. If it was thin, he said that the coefficient R assumed low values, because more nodules were exposed, whereas a thick layer and even larger nodules produced higher values.

Nodule distribution and characteristics in relation to geological settings

According to Dr. Kotliński, the complexity of seafloor morphology was reflected in the nature of nodule coverage. In addition, he said that the IOM area might be generally regarded as a nodulized one. He said it in fact contained both nodule-bearing and completely nodule-free patches. He said that no regularity in distribution of polymetallic nodules could be observed in the areas surveyed. In other words, no single morphological element of seafloor relief tended to be more amenable to nodule aggregation than the others. He noted that both nodule-rich and nodule-depleted patches of the seafloor could be found on the undulating abyssal plain, on tops and slopes of ridges and on the walls of grabens. He said that, notwithstanding the relatively constant base metal content in the nodule deposits, nodule coverage varied widely. He said that if one looked at the distribution of the nodule abundance, one could see that the area with the most promising concentration and abundance was between 4,300 and 4,500 metres water depth.

Dr. Kotliński drew attention to the relationship between the number and thickness of the acoustic complex. He said that the thickness of the complex varied from 0 to 20 metres. He also said that changes in the thickness of the complex bore no relationship with nodule abundance on the seafloor and that there was no relationship between particular genetic types of nodules to the increased metal content. He used a map to illustrate that point.

Bulk mineralogy and chemistry

Dr. Kotliński said that the mineral and chemical composition of nodules, particularly relationships between contents of hydrogenetic minerals (iron and manganese hydroxide, vernadite) and diagenetic-manganite-busserite, as well as the Mn/Fe ratio and concentrations of nickel, copper, and cobalt reflected the major processes responsible for nodule formation, hydrogenetic or diagenetic. He said that, as a rule, larger nodules with rough surfaces were manganese, nickel, copper, and molybdenum enriched, busserite being the major mineral component. On the other hand, smaller smooth nodules were relatively rich in copper and iron and lead, and showed a higher vernadite content.

Distribution and origin of the nodules

According to Dr. Kotliński, the area surveyed had been observed to harbour all the known nodule genetic types: Hs, HD, and Dr. In terms of nodule content, a sub-type Dr_1 might be separated within the nodule type Dr; the Dr_1 nodules containing more copper than nickel. Distribution of the genetic types of nodules was controlled by the position of carbonate compensation depth in relation to the seafloor. He said that the carbonate compensation depth (CCD) in the eastern region is located at a depth of about 4,200 metres. According to Dr.

Kotliński, the hydrogenetic, smaller and smooth nodules occurred above and within the calcium carbonate compensation depth interval, whereas the diagenetic larger and rough nodules occurred, as a rule, below the CCD. He said that differences in nodule sizes reflected their structural and textural features, which were related to their different growth rates.

Dr. Kotliński said that the large type Dr nodules, which were up to 10 centimetres in size, had nuclei made up of fragments of older nodules. He said that although the nodules were irregular in shape, they revealed some features of a primarily discoidal form. In a number of cases, Dr Kotliński noted that large nodules were mushroom-shaped, with a "stalk" embedded in the sediment and a loose, easily chipping, rough surface. The upper surface of some large specimens was bothroidal and smooth. The equatorial belt was usually well developed and visible as large bothroids.

He said that Hs nodules were particularly abundant in the northern part of the area; they usually lay on the seafloor surface at water depths shallower than 4,200 metres, and were very visible on photographs of the bottom. He said that these nodules were usually small and spheroid; not larger than six (6) centimetres,and that most of them attained two (2) to four (4) centimetres in size. He also said that they usually displayed a smooth surface and that occasionally they showed monocrystals and zeolitic accretions. Noting that these nodules were porous and frequently cracked, Dr. Kotliński said that their nuclei were, as a rule, formed by concentrations of zeolites. He said that more seldom, they were made up of fragments of older nodules. The nodule cross-sections showed the layers to be a fraction of a millimetre thick, each. Dr. Kotliński showed participants a table which presented characteristics of all those types of nodules: Hs, HD, Dr and Dr_1.

According to Dr. Kotliński, from north to the south of the area, the mean abundance of nodules and their nickel and cobalt contents were observed to decrease, while the copper and manganese contents increased. He said that the maximum content of nickel and cobalt were typical of nodules in the northern part of the area, the highest copper and manganese content being found in the nodules occurring in the central and southern parts, respectively.

Furthermore, he said that the respective contribution of the Hs type nodule was seen to decrease in the N-S direction, from 7.5 to 2.1 per cent, and from 56.1 to 29.8 per cent, while the contribution of Dr_1 nodules increased from 10.3 to 46.8 per cent. Dr. Kotlinski said that the abundance of HD type nodules showed a decreasing trend in the same direction, with their minimum abundance to be found in the central part. He also said that the variability in the nodule attributes increased in the following order: cobalt-, nickel-, copper-, manganese- abundance. He pointed out that it was only in Hs type nodules that nickel and copper changed places. Dr. Kotliński presented the results in a table.

Dr. Kotliński also pointed out that increased resolution of surveying and exploration had changed the comprehension of the local nodule-bearing potential of the area. Moreover, he said that the increase in the resolution had been achieved without sacrificing the reliability and representatives of nodule sampling, which was of particular importance during the exploration stage. He also said that the results of such finely tuned surveys were extremely valuable in that they broadened the existing knowledge of different spatial scales of natural variability in the potentially exploitable sites.

Conclusions

In the final part of his presentation, Dr. Kotliński said that siliceous-clayey oozes and siliceous oozes covered extensive parts of the IOM area and formed a strongly hydrated geochemically active, sediment-water interface boundary layer that was between 2 and 12 centimetres thick. He said that the results had shown that the limited thickness (up to 4 centimetres) of the layer corresponded to low nodule abundance. The increase in the layer's thickness was usually accompanied by increased abundance. He noted that no relationship between a specific genetic nodule type or its metal content, and the thickness of the complex had been found.

Dr. Kotliński said that the eastern area of the Clarion-Clipperton nodule region carried nodules belonging to two basic genetic nodule types, Hs and Dr, co-occurring with intermediate types HD and Dr_1. As a rule, he said that the nodules were embedded in the sediment water interface layer and partly blanketed by contemporary deposits. He said that the presence of blanketed nodules had been revealed at about 70% of the sites. The extent of blanketing (index R) had been found to increase with depth from the north to the south, conforming to the change in CCD. At the CCD of 4,200 metres, small (2-4 cm), spheroidal, smooth nodules belonging to Hs type nodules were dominant. Below that depth, he said that as a rule, discoidal, larger (6-12 cm) nodules with rough surfaces were found. He informed participants that the general north-south increase in depth was accompanied by a decrease in the proportion of Hs and Dr type nodules of 8 centimetre modal diameter, and that the contribution of Dr_1 nodules of 4 to 6 centimetre modal diameter gradually increased.

According to Dr. Kotliński, the highest nodule abundance had been recorded within the depth range of 4,300 to 4,500 metres. He noted that the north-south depth increase was accompanied by a certain pattern of change in nodule metal content. He stated that the maximum contents of nickel and cobalt were found in the nodules present in the north part (nodule types Hs and HD); increased copper contents were observed in nodules present in the central part (nodule type Dr_1),and manganese content increased clearly in the nodules present in the south part (nodule type Dr). With regard to abundance, he said that nodules present in the eastern area of the Clarion-Clipperton nodule region changed in the following order: cobalt-, nickel-, copper-, manganese-.

In closing, Dr. Kotliński said that nodule distribution on the seafloor and their coverage was extremely diverse. Contours, size, and form of the deposits were determined by seafloor relief. He said that the borders of streaked deposits 2 to 10 kilometres wide, and up to several tens of kilometres long, coincided with contours of rises and depressions in the seafloor, usually with steep slopes. On the other hand, he observed that patchy deposits about 70 kilometres wide and up to 120 kilometres long occurred on a level bottom. He concluded his presentation saying that the deposit types were highly variable, both in terms of size and nodule distribution within them.

SUMMARY OF THE DISCUSSIONS

There were no discussions after Dr. Kotliński's presentation.

§

CHAPTER 13 REGIONAL AND LOCAL TRENDS IN THE FORMATION OF POLYMETALLIC NODULE DEPOSITS IN THE CLARION-CLIPPERTON ZONE

Dr. Valeri Yubko, Deputy-Director, Okeangeofizika Research Institute, Yuhzmorgeologia, Russian Federation

As we know the Clarion-Clipperton ore province is one of the intensively studied regions of the seabed. In particular, in the preparation of the present report, the data from the multi-tier graphical database containing information about the measurements of the ore potential of the Clarion-Clipperton Zone was used. The measurements were assessed after taking samples from 10,236 points. Simultaneously, in the form of digital layers, the base contains bathymetric maps, geologic maps, the maps of predicted metallogenic potential etc., for the regions of ore bodies classified in order of their magnitude.

In our analysis and systematization of such huge amounts of geological data, we were primarily interested in the quantitative and qualitative characteristics of regional and local spatial distribution of nodules. For estimation of the regional mechanism of nodules distribution we used a method of trend analysis.

The essence of the method is in separation of total variability of the studied spatial variable into two components: regular and random.

Z(X, Y) = F(X, Y) + ø(X, Y)
F(X, Y) – Regular component of spatial distribution (trend)
Ø(X, Y) – Random component of spatial distribution
Simple planar surface (first-order trend)
F(X, Y) = A00 + A01 Y + A10 X
Quadratic surface (second-order trend)
F(X,Y) = A00 + A01 Y + A02 Y2 + A10 X + A11 XY + A20 X2

Both components were considered as functions of coordinates. There are different mathematic techniques of regular component selection. In our case we used a technique of approximation of regular components by algebraic polynoms of the 1-2 order. Calculations of trend surfaces were done with SURFER –7 Software.

The following figures will demonstrate the results obtained with use of the described technique. Each slide represents:

- A diagram of isometric lines showing different features of manganese nodules, calculated for inverse quadratic distances method;
- A diagram of isometric lines for the second level trend of the given feature

In the case of *Figure 1,* we studied nodules abundance. As can be seen, both diagrams represent the same pattern in regional distribution of abundance, controlled by presence of a sub-latitudinal zone, where nodules abundance have maximum values, decreasing to the south and north directions.

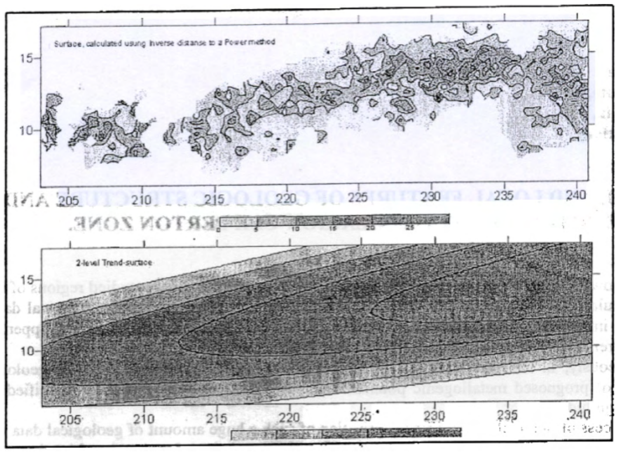

Figure 1: Map of nodule distribution and a scheme of the level 2 trend surface of nodule abundance in the Clarion-Clipperton Zone

Figure 2, demonstrates the regional variability of Manganese (Mn) concentration in nodules. We can see here how the Mn concentration demonstrates a stable tendency to increase from the south to the north.

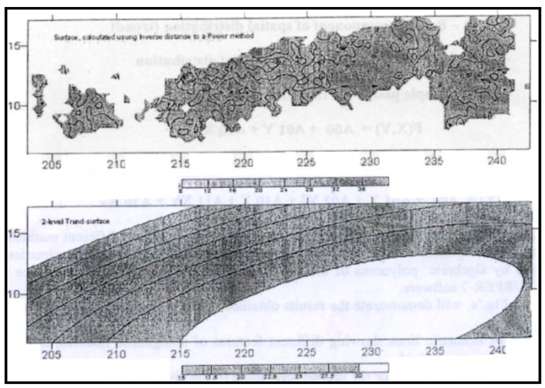

Figure 2: Map of nodules distribution and a scheme of the level 2 trend surface of Mn concentration in nodules of the Clarion-Clipperton Zone

Unlike Mn, Iron (Fe) concentration is characterized by the opposite tendency (*Figure 3*) reflecting its increase from the south to the north.

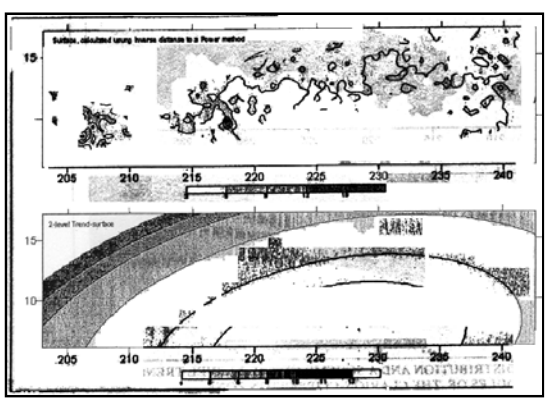

Figure 3: Map of nodule distribution and scheme of the level 2 trend surface of Fe concentration in nodules of the Clarion-Clipperton Zone

The types of regional zoning made according to the distribution of Nickel (Ni) (*Figure. 4*) and Copper (Cu) (*Figure.5*) concentrations are close to the zoning according to Mn distribution.

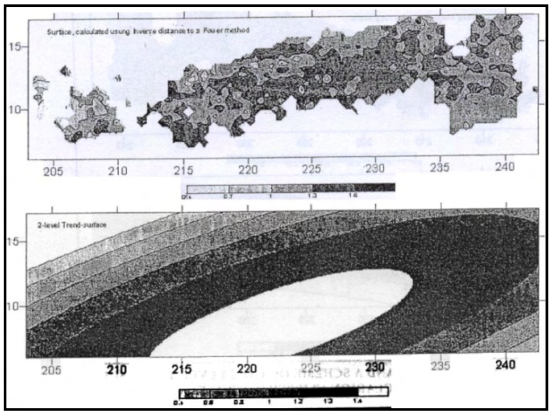

Figure 4: Map of nodule distribution and a scheme of level 2 trend surface of Ni concentration in nodules of the Clarion-Clipperton Zone.

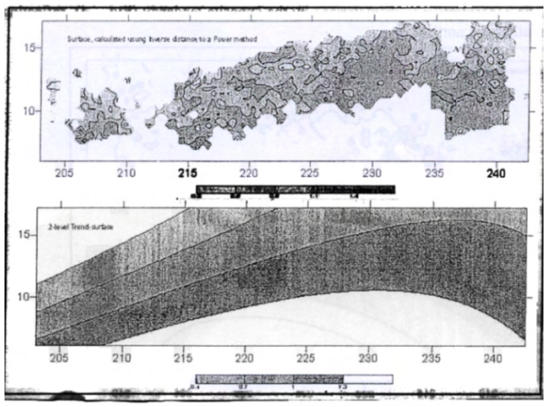

Figure 5 Map of nodules distribution and a scheme of the level 2 trend surface of Cu concentration in nodules of the Clarion-Clipperton Zone.

At the same time, the tendencies in regional variability of Cobalt (Co) concentrations (*Figure 6*) are practically similar to the corresponding tendencies in Fe: their values increase from the south to the north.

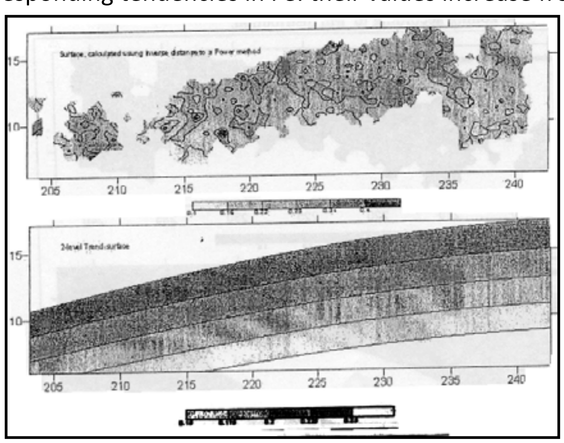

Figure 6: Map of nodule distribution and a scheme of the level 2 trend surface of Co concentration in nodules of the Clarion-Clipperton Zone.

Regional geochemical zoning of ore accumulations in the Clarion-Clipperton Province are represented in the most explicit way by a distribution of Mn/Fe ratio (*Figure 7*)

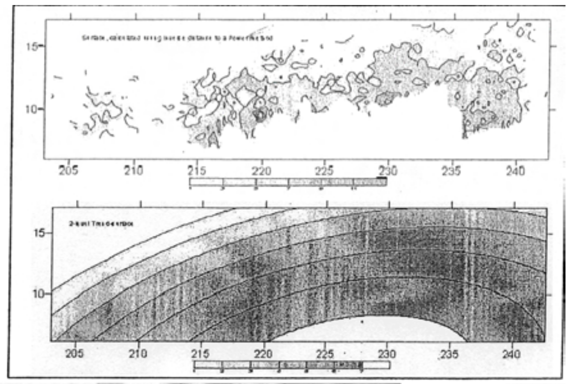

Figure 7: Map of nodule distribution and a scheme of the level 2 trend surface of Mn/Fe in nodules of the Clarion-Clipperton Zone

In the diagram, a distinct sub-latitudinal zoning, characterized by Mn/Fe ratio increasing from north to south can be observed. It is noteworthy, that Mn/Fe ratio is considered as a typical feature showing nodule composition. It is well known that the main ore components of nodules are well correlated with the values of Mn, Ni and Cu in a positive way, but with Fe and Co in a negative way.

Finally, in the last of this series, *Figure 8a* demonstrates a combination of nodule abundance trend surfaces and their Mn/Fe ratio, calculated for six different fragments of the Clarion-Clipperton Province. As can be seen, all the basic features of regional zonality typical for the Clarion-Clipperton Province are represented in each fragment.

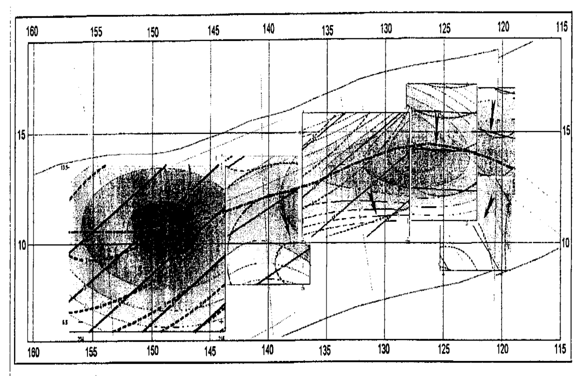

Figure 8a: Cumulative diagram of the trend 1 and 2 surfaces for abundance and Mn/Fe in Manganese nodules composition of the Clarion-Clipperton Zone

The results of our analysis showed that the regional distribution of quantitative nodule abundance and the concentrations of ore elements are controlled by sub-latitudinal zoning (*Figure 8b*)

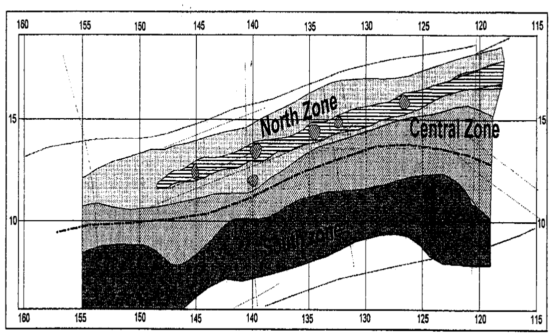

Figure 8b: Scheme of ore accumulations facial zonality in the Clarion-Clipperton Zone

The pattern of zoning is connected with the existence of the axial area inside the nodule-bearing province where the values of quantitative nodule abundance are maximized. The values of nodule abundance decrease in the south and north directions from that area.

The spatial distribution of nodule composition has another specific feature. In this case, the Mn/Fe ratio has a tendency to increase in the north-south direction.

It may be assumed that such quantitative and qualitative regional parameters of nodule distribution reflect regional facial variation of nodules in the Clarion-Clipperton field, where three facial zones can be distinguished: northern, central and southern (*Figure. 9*).

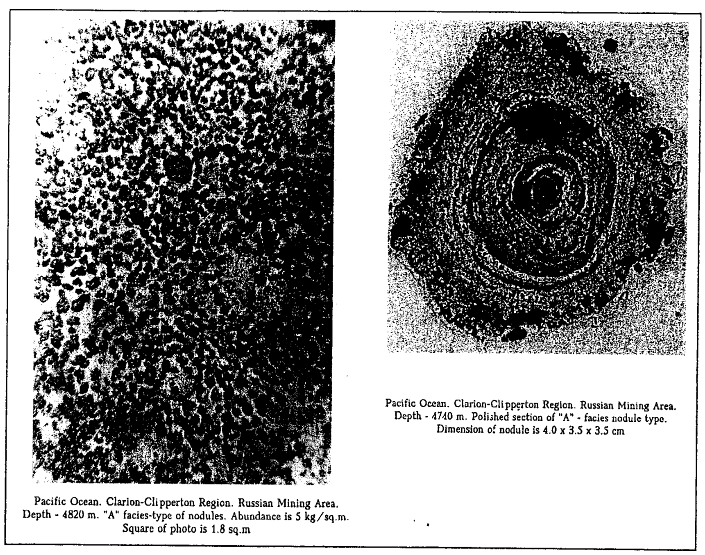

Figure 9: CCZ Nodules "A" facial type

The northern zone is characterized by a prevalence of nodules that are small-sized (2-5 cm) with a smooth surface, and often accrete. The average nodule abundance in this zone is relatively low. The nodules are relatively poor in manganese (19-26 per cent), rich in iron (6-10 per cent), poor in nickel and in copper and (relatively) rich in cobalt (0,25 to 0.45 per cent). Such facial type of nodules was referred to type "A" (*Figure. 10*).

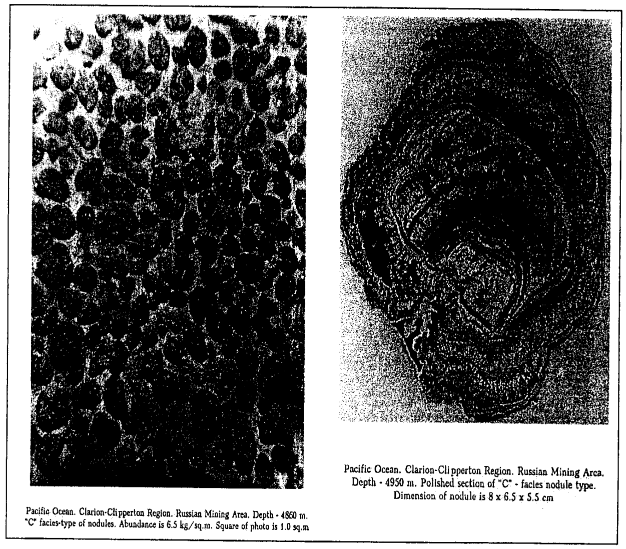

Figure 10: CCZ Nodules "C" facial type

Within the central zone, the disc-shaped and ovoid large-sized (8-12 cm) nodules with a smooth upper and rough lower surface are predominant. Such nodules are characterized by the highest Ni (1.3-1.5 per cent) and Cu (1.1-1.4 per cent) content. Such types of nodules facies were classified as type "C" (*Figure. 11*). Average abundance of nodules in the northern zone is the highest.

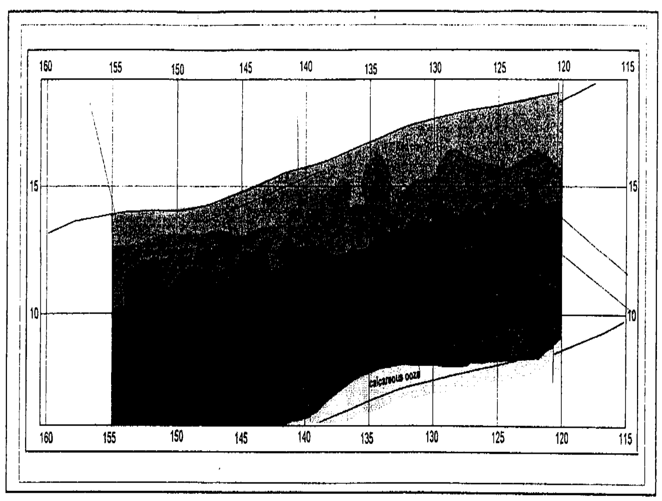

Figure 11: Scheme of seabed surface sediment types in the Clarion-Clipperton Zone

We considered "A" and "C" facial types of nodules as extreme in the facial series. A relatively large group of intermediate members of the series were referred to the facial type "B", which is distributed in the northern and central zones.

In the southern zone, only nodules of the facies "C" type are distributed. Although nodules of the southern zone are richest in Mn (40 per cent and more), their average abundance is not large. Furthermore, large nodules fields of commercial value are quite rare in this zone.

It is noteworthy that the elements of sub-latitudinal zoning are well seen in the distribution of the seabed sediments of the Clarion-Clipperton Zone (*Figure 12*). As can be seen from the scheme, the zones alternating each other from the north to the south are filled with red deep-water clays, silicious-argillaceous and argillaceous-silicious oozes and carbonate oozes in the southernmost area.

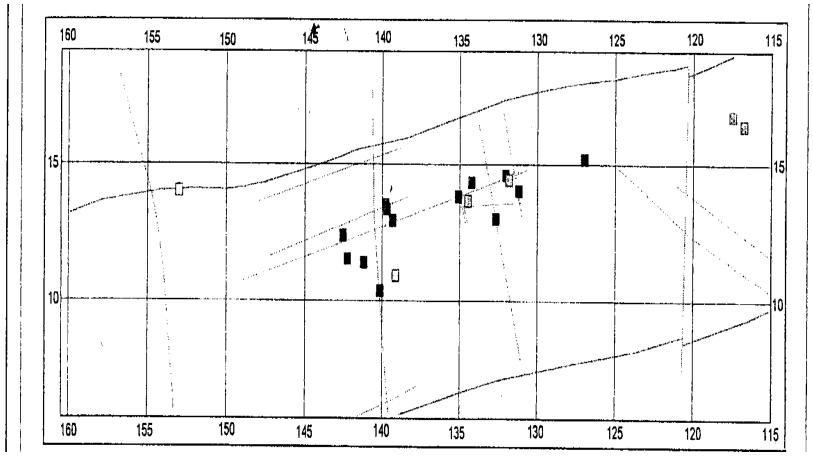

Figure 12: Plan of sampling points of magmatic, hydrothermal-sedimentary and hydrothermal-metasomatic formations

It is noteworthy that within the northern zone there is a linear area, characterized by intensive magmatic and hydrothermal activity (*Figure 13*).

Figure 13: Recent basaltic flows

That zone is position controlled by the Bezyimiyannyi fracture zone, along which recent metalliferrous sediments, basaltic flows (*Figure 14*) and also massive sulphide ores of monomineral, chalcopyrite compositions were discovered.

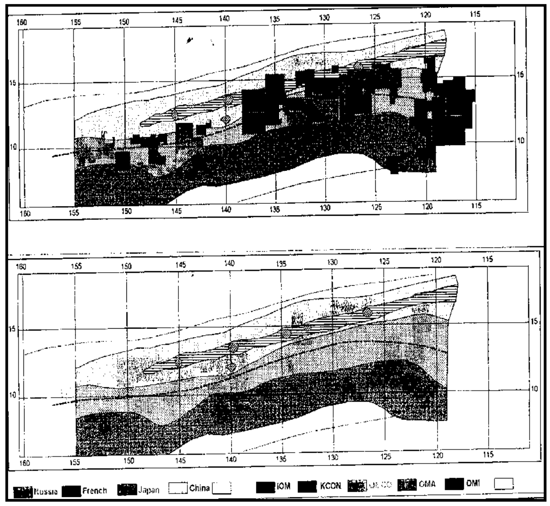

Figure 14: Scheme of the licensed and reserved areas based on the metallogenic zonality in the Clarion-Clipperton Zone.

In the North Zone there is an East KCON Area, the entire OMA Area and the northern parts of the IOM, eastern French and the western OMI areas, the entire eastern and the north parts of the western Japanese area, northern part of the Korean area, the entire western part of Russian area and northern part of the western part of the OMCO.[1]

The entire eastern part of OMI, the central part of IOM, the entire western part of KCON, and practically all eastern parts of the Russian and the OMCO areas are located in the Central Zone. There are also the southern parts of the French area, the western zones of the Japanese and OMI areas, a western part of the French area, and the entire Chinese area. Only the southern parts of the Korean areas are located inside the South Zone.

We believe that such a specific layout of areas represent the differences between average values of nodule composition in different zones. We can provide data about average concentrations of Co and Ni illustrating such differences: the highest average values of Co are in the OMA area (0, 26), which is entirely located inside the North Zone; the lowest values are in nodules of the IOM (0, 19) area. The highest average of Ni concentrations are in nodules in the eastern part of the OMCO (1, 43) and the western part of the Japanese area (1, 48) is entirely located inside the Central Zone. Hence, we think that regional seabed morphology and water depth are not the main factors controlling nodule composition.

But if we apply the results of our investigations to each area and field, we can see that in each case every nodule field reflects the local seabed features and morphology and is a very important factor of nodule distribution. Our studies proved that the Clarion-Clipperton seabed morphology is characterized by a similarity irrespective of the areas. It is represented by a combination of long hills, abyssal valleys and inter-valley plateaux from the North to the South (*Figure 15*).

1 KCON – Kennecott Consortium; OMA – Ocean Mining Associates; OMCO – Ocean Minerals Company; OMI – Ocean Management, Inc, and IOM – Interoceanmetal Joint Organisation

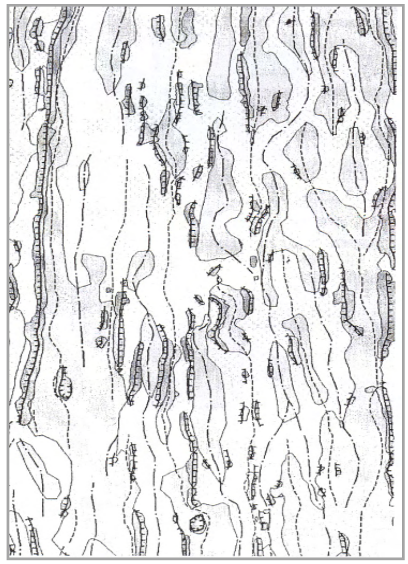

Figure 15: Geomorphological scheme of the local area inside the Clarion-Clipperton Zone

The lateral size of those morphological structures ranges from 1 to 5 km. The extent of structures varies from a few tens to sometimes a few hundred km. with crestal amplitude ranging between 50 and 300 metres (*Figure 16*).

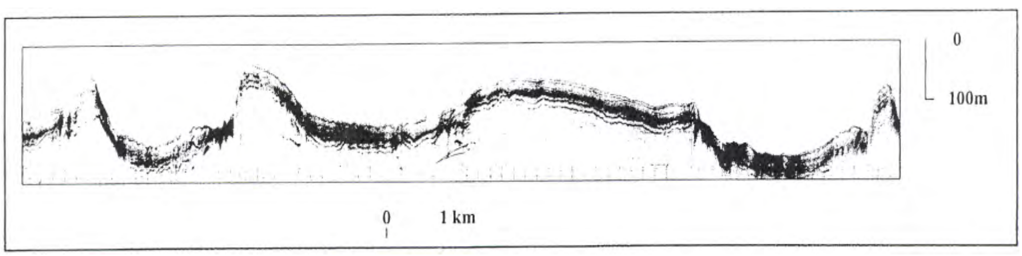

Figure 16: Structure of the relief and the sedimentary cover in the Clarion-Clipperton Zone

Apical surfaces of hills, bases of valleys and inter-valley plateaus are mainly gentle. They are separated by steep slopes (10-15^{o}) and scarps where ancient sediments and basaltic substrates are exposed (*Figure 17*).

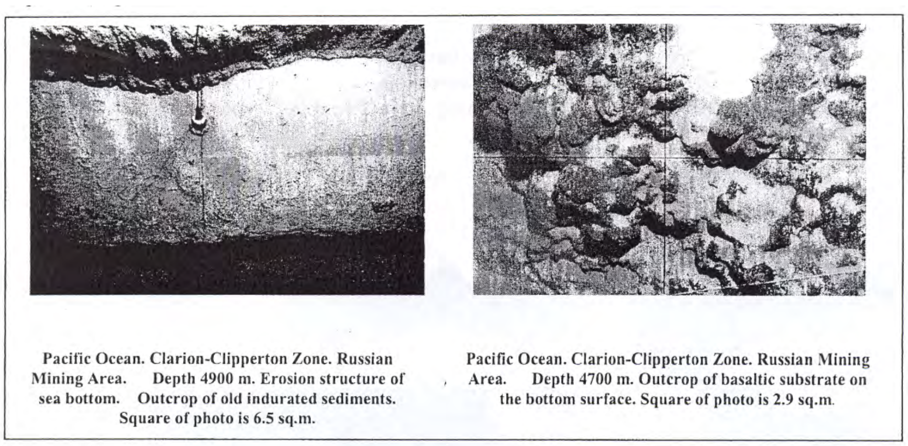

Figure 17: Exposed old (pre-middle Miocene) sediments and basaltic substrate on the ocean floor (seabed)

It is noteworthy that eastwards from the 140° E sedimentary structure consists of two lithologic sequence pre-Middle Miocene carbonates and post middle Miocene silicic clays (*Figure 18*)

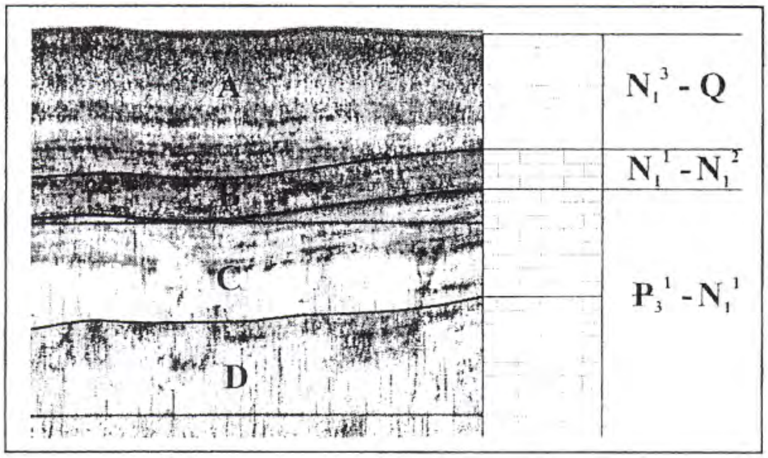

Figure 18: Stratigraphic column of the Clarion-Clipperton Zone sedimentaty section

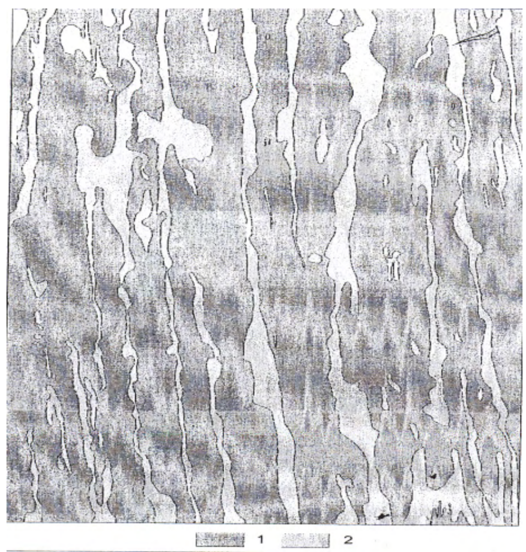

Figure 19: Scheme of the local structure of the ore field in the Clarion-Clipperton Zone (1 – ore body; 2 – inter-orebody areas)

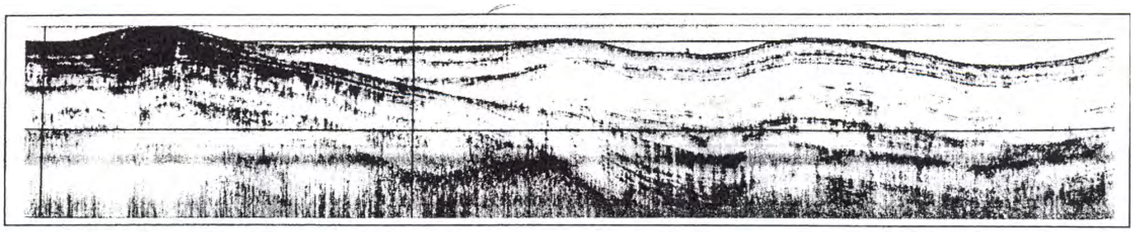

Figure 20: Buried downcuttings, stratigraphic and angular unconformities in the sedimentary cover structure of the Clarion-Clipperton Zone

During that period the process of erosion had a fluvial nature forming erosional channels. Later the channels were filled up by thick siliconus-argillaceous sediments (about 60m thick). Even at present the erosional activity is quite intense, having both fluvial and isolated nature, forming erosional "funnels (*Figure 21*) or isometric basins.

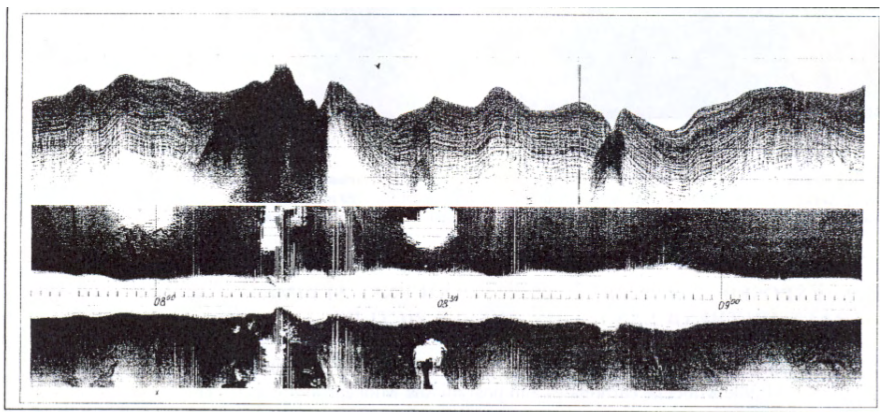

Figure 21: Local erosional structures on the ocean floor of the Clarion-Clipperton Zone

Analysis of acoustic data and seabed photos showed that obligatory local features for nodules occurrence are:

- Gentle seabed dip (less than 6^{o}) irrespective if it is a valley, a hill or inter-valley plateau and
- Presence of post-Micocene siliceous-argillaceous sediments.
- The denuded basement and ancient sediments, as well as the slope with steepness of more than 6^{o}, are devoid of nodules.

We can see that there are very strong dependencies between seabed morphology and the structure of nodules accumulations called ore bodies. Thus, the ore bodies have a band-like pattern with between 1 and 5 km transversal size and a few tens of km extent. Inside the ore bodies are nodule-free patches usually associated with modern erosional activity.

We are of the view that all nodule fields in the Clarion-Clipperton Zone are characterized by a similar structure of ore bodies. The only difference between the fields is their bathymetry. It is a well-known fact that the difference between the average depths in the western and eastern parts of the Clarion-Clipperton Zone is about 1 km. So, our idea is that the main principle for developing a CCZ nodule accumulation model should be a combination oriented towards sub-longitude direction band-like ore-bodies, in which the shape, size, composition and abundance of nodule deposits depend on their placement in relation to the northern, central and southern facial zones.

§

CHAPTER 14 CHARACTERISTICS OF THE DISTRIBUTION AND CONTROL FACTORS OF POLYMETALLIC NODULES IN THE WESTERN REGION OF THE CLARION-CLIPPERTON FRACTURE ZONE (CHINESE PIONEER AREA)

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Introduction

The tectonic setting of the reserved area for the International Seabed Authority resulting from the allocation of an exploration area to China is the same as that of the Chinese pioneer area; they both have similar topographic characteristics and nodule distribution. Research and analysis of these characteristics and control factors of nodule distribution could help in the establishment of a geological model and the assessment of polymetallic nodule resource.

From 1991 to 2000, COMRA carried out phases 1 and 2 of its exploration and resource assessment project on polymetallic nodules in the Chinese pioneer area, using geological sampling and the new multibeam, deep-tow and autonomous underwater vehicle techniques.[1] There is a clearer understanding of the topographic and geologic features and the distribution of polymetallic nodules and control factors. The results show that the formation and types and spatial distribution of abundance and grade of nodules are the result of several factors; tectonic (volcanism and faulting) and seafloor topography play an important role in the geological process of the formation of polymetallic nodules.

Topographic features of the Chinese pioneer area

The water depth in the Chinese pioneer area is generally from 4,900 to 5,400m, with the average depth in the western region being about 100m deeper than the eastern region.

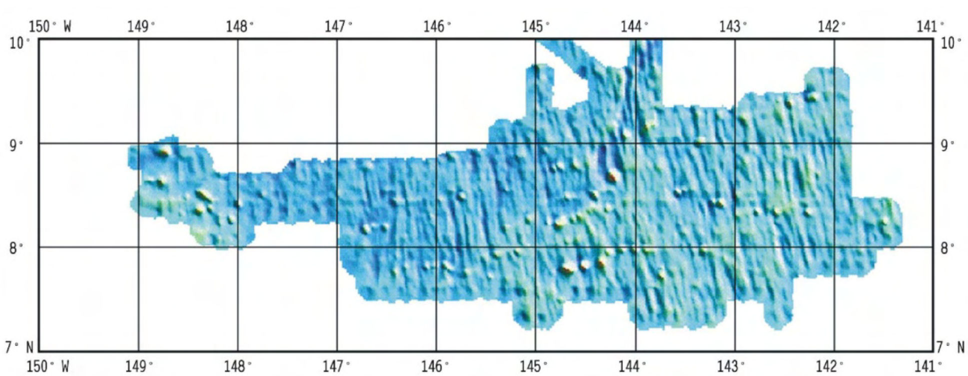

Figure 1 Map of 3D topography in the eastern region of the China pioneer area

The Eastern Region

Widespread linear furrows and isolated seamounts are the main features of the topography of the eastern region. The furrows extend NNW; the slope of the sides of the furrows is about 5^{o} to 10^{o}. The feature of the furrow topography in the north is more developed and deeper than that in the south. Low hills are the main

[1] COMRA – China Ocean Mineral Resources Research and Development Association (registered on 5 March 1991)

topographic feature in the south, where the furrows are less and shallower. The isolated seamounts are scattered like a string of beads, which extends NEE, and stretches in the same direction as the faults NEE across the whole area.

The Western Region

Seamounts and seamount chains are the main topographic features in the western region, which extends approximately eastwards. There are intermountain basins and furrow areas between the seamount chains. The whole region has five seamount chains, with heights that are generally about 500 to 1,000m. The topography of the intermountain basins and furrow areas is relatively smooth, and undulates less than 100m. The slope is generally less than 2^{o}.

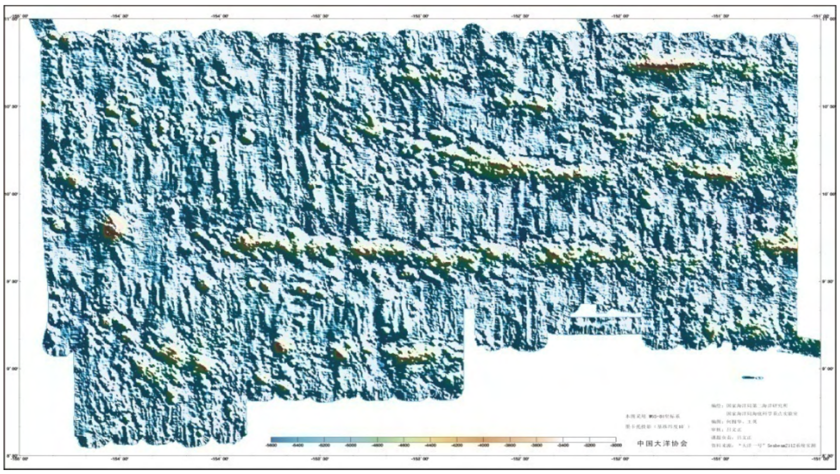

Figure 2: Chart of 3D topography in the western region of the China pioneer area

The results of a deep-tow survey show that in the eastern and western regions there are many abrupt furrows and sills, with heights varying from several meters to tens of meters. These abrupt sills and furrows will be topographical obstructions to mining.

Tectonic characteristics

The east and west regions of the Chinese pioneer area are located in the western part of the Clarion-Clipperton Fracture Zone (CCFZ) between the Clarion and Clipperton fractures of the East Pacific basin. The basement of the CCFZ is the oceanic crust consisting of basalt, which is the product of the spreading of the East Pacific Rise. The thickness of the sediment layer ranges from tens of metres to several hundred metres, and gradually decreases from the west to the east.

The sediment layer on the basalt is controlled generally by the original topography of the basement.

According to the results of the Deep Sea Drilling Project and the identification of lineation magnetic anomalies, the age of the basement is lower Campanian of Late Cretaceous in the west, and the Paleocene in the east. Obviously, the age of formation of the west was earlier than that of the East, so that the water depth in the west is greater than in the east (Beiersdorf, H., 1992).

The tectonic activity in the western region was mainly volcanism. The fractures by faulting have formed the passageway of volcanism, which constructed the seamounts and seamount chains in the various scales along the transform fractures. The tectonic activities in the east were quite different from that in the west, and were mainly faulting and block faulting; volcanism was secondary. Seismic reflection profiles show that transform faulting and block faulting are strong and widespread in the eastern region. The faulting system can be divided into two groups: one is a NNE fault system, and the other is near the EW fault.

These characteristics show that the eastern and western regions are obviously the geological unions in the different tectonic features.

Characteristics of polymetallic nodule fields

1. Types of polymetallic nodules

The nodules in the Chinese pioneer area have various shapes including ellipsoidal, spherical, cauliflower, dumb-bell, irregular linked bodies, discoidal and strawberry. The shape feature of nodules is different in each area. In the eastern region the main type of nodules are cauliflower, but smaller linked bodies and spherical nodules predominate in the west.

According to the surface features of the nodule, there are three nodule types in the Chinese pioneer area:

(a) Type s nodule (smooth surface): the surface of the nodule is smooth with a mostly, spherical or irregular shape. This kind of nodule is found in the western region;

(b) Type r nodule (rough surface): the size of the sand is usually 1 to 2mm. When touching it, the hand is always stained with particles. This kind of nodule usually has a spherical, ellipsoidal or strawberry shape. They are predominantly distributed in hilly areas;

(c) Type s+r nodule (smooth top surface and rough bottom surface): this kind of nodule usually has a cauliflower, ellipsoidal or discoidal shape. The internal lamination is sparse and irregular. They are mainly distributed in the east and are far away from seamounts in the west.

2. Variation features of nodule abundance

Nodule abundance in the China pioneer area varies greatly from 0.37 kg/m^2 to 23.50kg/m^2. Stations of more than 5 kg/m^2 occupy 74.6% of the area in the west and only 30.4% in the east. So, the west region is obviously higher than the east in terms of mean abundance in the Chinese pioneer area.

3. Variation features of nodule grade

Nodule grade in the eastern region is higher than that in the western region. The mean grade is 2.86 per cent in the east and only 2.20 per cent in the west. *Figure 3* shows that nodule grade in the eastern region is distributed basically as a normal function, but in the western region, it is distributed as double peaks, of 1.8 per cent and 2.6 per cent, respectively. The result shows that nodules of high grade are predominantly found in the eastern region. The western region has a large quantity of high-grade as well as low-grade nodules.

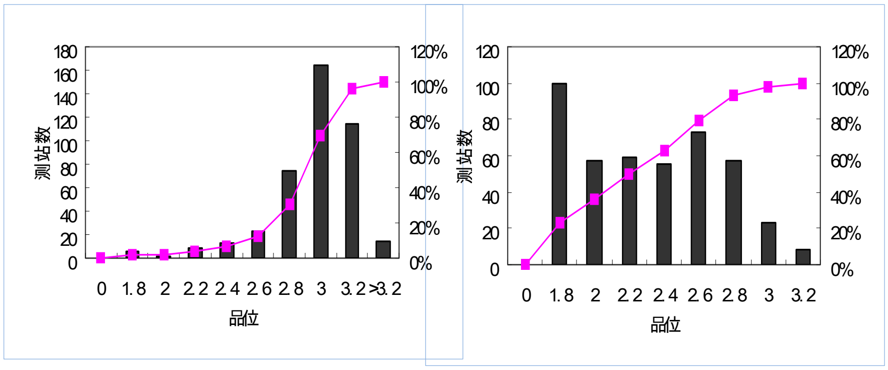

Figure 3: Distribution of nodule grade (L= the east region; R= the west region)

Features of the spatial distribution of polymetallic nodules

The results of the deep-tow survey show that, whether in the eastern or the western regions, the ore fields of nodules appear to be distributed in blocks, with the trend of mineral blocks consistent with the trend of the furrow topography. The varying topography has obviously controlled the spatial distribution of type, abundance, grade and coverage of nodules.

The coverage of nodules in the east is lower, with less than 10 per cent coverage to be found in 58.8 per cent of the area and coverage of more than 30 per cent in only 2.8 per cent. The coverage of nodules in the furrows is very low. Low hills have a relatively continuous distribution of nodules. Nodules are distributed mainly at the top and at the foot of the slope of hills, and at seamounts. The average length of nodule phases is only 418 m, and the nodule phases vary greatly.

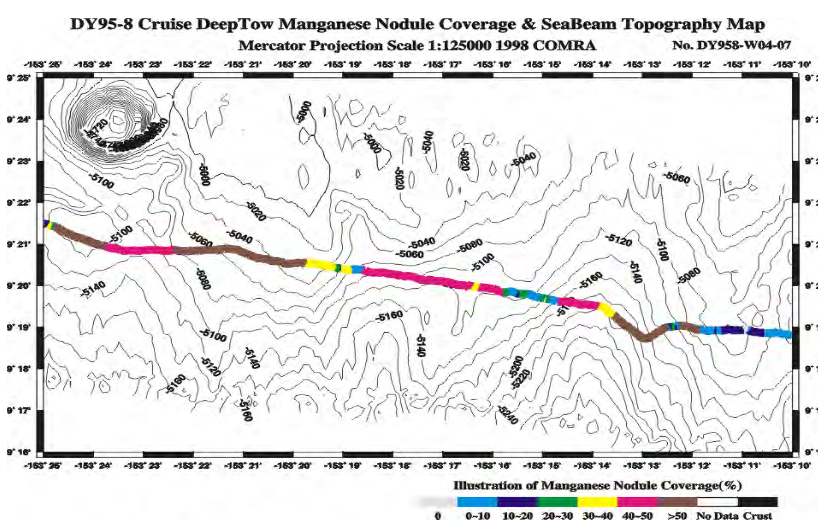

Figure 4: Spatial distribution of nodules in the Chinese pioneer area

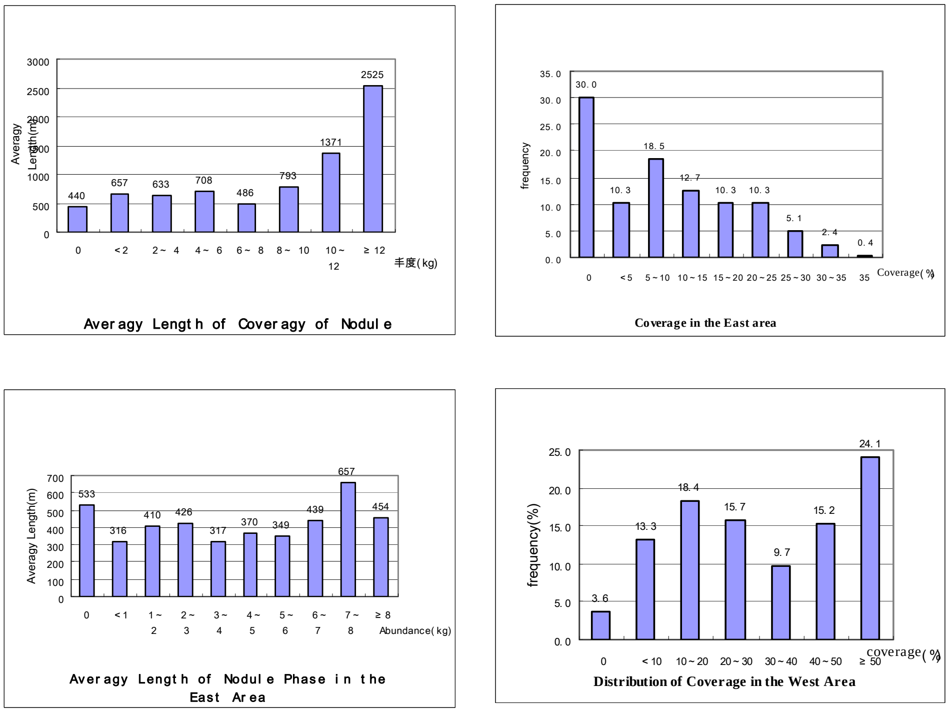

Figure 5: Spatial distribution of polymetallic nodules in the Chinese pioneer area

The slope and relief of the topography are smaller in the intermountain basins of the west. The lengths of the coverage phases of less than 10 per cent occupy only 16.9 per cent of total lengths; coverage of more than 30 per cent occupies 49.0 per cent. The average continuous length is about 798m in the west, so the continuity of coverage distribution is obviously better than that of the east.

Controlling factors of mineralization of polymetallic nodules

1. Tectonic factors

Judging from the temporal and spatial distribution of nodules in the Pacific Ocean, they were formed in late Oligocene, or a little bit later, and developed in great amounts in the Miocene epoch. The nodules are predominantly distributed in the Clarion and Clipperton Zones. In Oligocene, Australia left the Antarctic and moved northward and the waterway between South America and the Antarctic opened (Barker 1977). This led to the formation of the Antarctic glacier and the glacial water resulted in the sinking of cold (1^{o}-3^{o}C) oxygen-rich water of high density, forming the Antarctic Bottom Water expanding northward, which flowed into the Mid-Pacific Basin.

2. Influence of the Antarctic Bottom Current

The nodules that were formed in the oxidative weak-alkaline environment of low temperature and the Antarctic Bottom Current had the features of low temperature, rich dissolved oxygen and CO_2, and weak alkalinity.

3. Volcanic activities

The main contributions of volcanic activities to the mineralization of nodules are:

(a) Large amounts of basic volcanic rocks and effluence of thermal fluid on the seafloor containing rich metal elements of Manganese (Mn), Iron (Fe), Copper (Cu), Cobalt (Co) and Nickel (Ni), which are the main mineralizing elements of the nodules. Thus, magma eruption brought huge amounts of the mineralizing materials of the nodule;

(b) There is a solid core in all the nodules. Large amounts of rock debris and fragments from volcanic eruptions provided the source for the core materials.

4. Water depth and topography

In the CCFZ, polymetallic nodules are predominantly distributed on the seafloor below the carbonate compensation depth (CCD) boundary (4,900m). The areas 100-300m below the CCD are the most favourable for nodules.

Topography also has evident influence on nodule types. The nodules in seamount areas are mainly of type s; type r and r+s are far away from seamounts.

The formation, distribution and enrichment of nodules result from a number of factors. Except for those mentioned above, they are also closely related to the geochemical environment, biological action and sedimentary environment, which are not discussed here**,** but tectonics (volcanism and faulting) and seafloor topography play an important role in the geological process of the formation of polymetallic nodules.

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SUMMARY OF THE PRESENTATION

Professor Lu said that the tectonic setting of the western region of the area reserved for the International Seabed Authority was the same as that of the Chinese pioneer area; they had similar topography and nodule distribution.

He said that from 1991 to 1998, COMRA had carried out eight cruises to explore and undertake resource assessment of the Chinese pioneer area. Based on the resulting data, he said that analysis of the features and control factors of nodule distribution in the Chinese pioneer area might be helpful in the establishment of the geological model.

Professor Lu said that the main work done from 1991 to 1998 included a multibeam survey of 180,000 km^2; geological sampling; deep tow (video system) to survey a total of 1,850 km; seismic, gravity, magnetic and multi-frequency data. He said that the work had resulted in a clearer understanding of the topographic and geological features, and the distribution of polymetallic nodules together with control factors.

Professor Lu explained that the Chinese pioneer area was divided into two parts, namely the western area and the eastern area, which were two neighbouring areas. He said that the type and spatial distribution of nodules in the two areas were quite different. He informed participants that the water depth of the Chinese pioneer area was generally between 4,900 to 5,400 m; the average depth of the western area was 100 m greater than that of the eastern area. He further informed participants that the carbonate compensation depth was about 4,800 m in the Chinese pioneer area. In terms of nodule types, Professor Lu said there were three. Type s (smooth surface) was richer in the western area; Type r (rough surface) was predominantly distributed in the hilly areas; and type r + s (smooth top surface and rough bottom surface) was mainly distributed in the eastern area, far away from seamounts (3 miles) in the western area.

With regard to the distribution of abundance and grade of nodules, Professor Lu explained the differences between the eastern and western areas, highlighting the fact that manganese and nickel were quite different in the western area. In speaking about the spatial distribution of nodules (nodule facies), he said that with the image processing method, the sampling interval was about 40 m and that the average length of nodule facies in the east was very interesting in that there was both low and high coverage. In the western area, the abundance of larger nodules was greater.

Topographic features

Professor Lu said that, while in the eastern area, seamounts and seamount chains were predominant, intermountain basins and furrow areas were the main components of the topography in the western area. He said that their heights were between 500 and 1000m. The topography of intermountain basins and furrow areas was relatively smooth, undulating less than 100m. In the western area, he said that there were widespread linear furrows, while isolated seamounts were the main feature of the topography of the eastern area. He also said that the trend of furrows was NNW and that isolated seamounts, which were scattered like a string of beads, extended NEE.

Tectonic characteristics

According to Professor Lu, the age of the basement was lower Campanian or Late Cretaceous in the west and Paleocene in the east. The main tectonic activity was volcanism in the west, and faulting in the east. He used diagrams to show the seismic profiles of the eastern and western areas and also the coverage, geological stations, abundance and type of nodules. He summarized the main features of the Chinese pioneer area as follows:

	East area	***West Area***
Water depth	4,900 - 5,400m	4,900 to 5,400m
Average depth	100 m deeper	
Topography	Hills	Seamounts
Type of nodules	r + S	S, r + S
Abundance	Relatively low	High
Grade	High	relative low
	(Normal function)	(Two peaks)
Spatial distribution of nodule facies	Short	Long
Age of basement	Paleocene	Late Cretaceous
Tectonic activity	faulting	Volcanism
CCD	4800 m	4800 m
Sediment	Siliceous ooze & clay	siliceous ooze & clay
Thickness of transp. layer	30 - 40 m	40-50 m

Professor Lu identified the main control factors of mineralization of nodules as: tectonic factors (volcanic activities and faulting); influence of the Antarctic Bottom Current; the sedimentary environment; water depth, (CCD); topography; geochemical environment; and biological action.

He said that tectonic factors (volcanism and faulting) and seafloor topography played an important role in the geological process for polymetallic nodules formation.

SUMMARY OF THE DISCUSSION

When asked whether he saw any real evidence of Antarctic Bottom Water features with deposits, such as those spoken about by Dr. Beiersdorf, Professor Lu replied in the affirmative.

A participant asked whether Professor Lu had seen any evidence of it in the bottom topography and whether there had been signs of benthic currents in the bottom topography that he had investigated, such as erosion surfaces that had looked as though they were associated with currents. Professor Lu said that it had indeed looked like that.

The same participant commented that he would expect them to be most evident there, since those currents were coming from the western side.

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CHAPTER 15 BIOLOGICAL FACTORS RELATED TO FORMATION OF HYDROGENOUS FERROMANGANESE NODULES

Philomene Verlaan, Department of Earth Sciences, Imperial College,United Kingdom

Introduction

This paper focuses on the biological factors related to the formation of hydrogenous ferromanganese nodules (hereinafter called nodules) that may assist in identifying potential locations of nodules enriched with commercially significant quantities of valuable metals, in particular Nickel (Ni), Copper (Cu) and Cobalt (Co). The actual biological mechanisms, by which this enrichment is thought to occur, albeit fascinating in their own right, are addressed here only in so far as necessary to contribute to an efficient prospecting model.

Nodule formation and metal enrichment result from the interaction of numerous factors, many of the principal geological, geochemical, geophysical and oceanographic factors have been described in the preceding papers. Biological factors are recognized as likely to be significant, but have received little specifically focused research attention, principally for operational and logistical reasons.

With regard in particular to Co, Ni and Cu enrichment in nodules, a relationship with the biological factor or productivity of the surface waters of the open ocean has often been postulated. This paper briefly outlines the background to this hypotheses, describes recent work undertaken by the present writer to test it throughout a large region, and concludes by suggesting prospecting criteria that may be derived from the body of research developed so far by linking the enrichment of these metals in nodules not only to surface productivity but also to two other related biological factors, the carbonate compensation depth (CCD) and the oxygen minimum layer.

Background

In the open ocean, primary producers are primarily responsible for concentrating the metals of interest here (and others) out of their dissolved state into particulate forms by which the metals can eventually be exported from the surface and transported to the seafloor (see, e.g., review by Whitfield, 2001). A potential relationship between surface productivity and metal enrichment in nodules was suggested by observations that, in the pelagic Pacific, concentrations of Manganese (Mn), Ni, and Cu in nodules tend to increase, and of Fe and Co to decrease, as the equator is approached, and that surface productivity increased equator-ward (see, e.g., Exon, 1983).

Further support for linking nodule metal enrichment to surface productivity was found in observations of the same metal enrichment dichotomy in relation to the calcium carbonate compensation depth: Mn, Ni and Cu tend to be enriched and Iron (Fe) and Co to be depleted near the CCD (Cronan & Hodkinson, 1994; Miller & Cronan, 1994). These workers conducted a detailed study of the relationship between surface productivity, the CCD and nodule composition was conducted in the central South Pacific from the equator to 18^{o}S at 160^{o}W along the Aitutaki-Jarvis Transect. The Aitutaki-Jarvis Transect study confirmed the latitudinal variation in nodule composition as described above in relation to surface productivity and the CCD from productive to oligotrophic pelagic waters.

The CCD is the depth at which the supply rate of biogenic Calcium (Ca) carbonate equals its dissolution rate, such that at the CCD little or no biogenic Ca carbonate is found in the sediments. In the pelagic Pacific, the CCD deepens equator-ward as surface productivity increases (Berger, 1978). Although the biogenic Ca carbonate dissolution rate is governed principally by pressure and temperature, its supply rate to the seafloor is related to surface productivity. Surface productivity also affects the supply rate and hence the proportion of labile organic material to biogenic carbonates reaching the seafloor (Berger & Wefer, 1992). In the open ocean, the depth at which the ratio of the former to the latter is greatest is thought to be at the CCD; it is here that Cronan et al.

suggest that the organic matter concentration is high enough to drive diagenetic reactions leading to Mn, Ni and Cu enrichment in nodules.

Recent work

In research undertaken by their work, the regional applicability in the study area (the central south Pacific (135°W-175°E, 0°-25°S) of this relationship between nodule compositional variation, surface productivity and CCD found along the Aitutaki-Jarvis Transect was among the questions examined. The study area is suitable for such work because it is subject to neither continental nor significant hydrothermal influences. This research was recently completed (Verlaan, 2002); the aspects relevant to the objectives of this workshop are discussed below.

Method of approach

The compositional variation in nodules of Fe, Mn, Co, Ni, Cu and Zinc (Zn) was determined geographically for the study area and with depth. Analyses for these metals in dry weight percent were conducted on whole or vertically sliced half bulk nodules.

Surface water productivity and CCD in the study area were determined and their value at the nodule sample locations was calculated. The surface productivity data were derived from the 7.5-year average of chlorophyll data for the study area collected by the Coastal Zone Colour Scanner between 1987 and 1986 and analyses of sediment core samples from the study area for presence and concentration (%) of calcium carbonate were used to determine the CCD. The depth of the CCD at a given location was estimated from the shallowest depths at which trace (<=2%) quantities of calcium carbonate were found in the sediments.

The regional variation in nodule composition, surface productivity and CCD was contoured and depicted on maps of the study area; for nodules the regional variation for each of the six elements of interest was depicted on a separate map. The values of the nodule element content and the values of surface productivity and CCD at the coordinates of the nodule sample locations were compared to assess the regional relationships between nodule compositional variation, surface productivity and CCD. Linear regression correlation analysis was used to determine whether statistically significant associations exist between regional variation in nodule composition and, respectively, surface productivity and CCD. This study is the first to quantify these parameters such that direct comparisons between them can be made visually and statistically at the nodule sample locations.

Results

Surface productivity. From a maximum at the equator, surface productivity declines regionally southward in the study area to a minimum at 25°S. However, productivity peaks around island groups, irrespective of their locations, are attributed to an "island mass effect" which can result in productivity enhancement up to as much as 1000 km downstream of the islands (Signorimi *et al*., 1999; Coutis & Middleton, 2002). Local surface productivity enhancement is also thought to occur in association with seamounts (Boehlert & Genin, 1987; Roden, 1987), although these are not discernible from the Coastal Zone Colour Scanner data used to establish the overall regional productivity picture. Apart from the influence of island groups, overall the isolines of surface productivity tilt from southeast to northwest and narrow westward, such a westward decline in surface productivity is discernible, albeit less pronounced than the strong southerly decline.

The CCD. The CCD is estimated to lie between 5,400 and 5,500m at the equator and between 4,750 and 4,850m at 16°S throughout the study area. It shallows to 4,600 m at 20°S between 165°-155°W. The CCD deepens latitudinally towards the equator for each 10° column of longitude in the study area. Longitudinal differences in the depth of the CCD at any given latitude are no greater than 100-200 m.

Discussion

Relationship of surface productivity and CCD to nodule composition

The composition of nodules in the study area is significantly related to surface productivity and the CCD. These parameters are shown to influence nodule composition more strongly latitudinally than longitudinally, probably because their latitudinal variation is greater.

In nodules near the CCD, enrichment in nodules of Mn, Ni and Cu increases with increasing productivity and decreasing latitude. Their values decrease both above and below the CCD and with increasing latitude. Their maximum enrichment is found near the equator. By contrast, Fe and Co enrichment in nodules increased as surface productivity declines and with increasing latitude. The role of the CCD in Mn, Ni and Cu enrichment and Fe and Co depletion remains discernible under oligotrophic waters in the south of the study area.

The persistence, even under low-productivity waters, of Ni- and Cu-enriched nodules near the CCD, is interpreted as related to locally enhanced productivity regimes associated with nutrients from island runoff and, more speculatively, with upwelling around seamounts. It is therefore suggested that Ni- and Cu-enriched nodules may be found under locally enhanced productivity regimes, even where overall productivity in the area is low.

Nodule composition and depth

With depth, Mn, Ni and Cu content in nodules is positively and Fe and Co content is negatively correlated. These correlations are consistent with the relationship between nodule composition of those elements and surface productivity and CCD.

The CCD. For Co however, it was observed that Co enrichment, as well as increasing with decreasing depth, is also found in nodules above the CCD under high-productivity waters. In a related study (Verlaan, 2002), it is observed that, the composition of these Co-enriched nodules to be similar to the overall composition of Co-enriched ferromanganese crusts from similar depths and latitudes. This finding is interpreted as being related to these nodules being located in an environment similar to that where Co-enriched crusts are found: i.e., the metal-accreting surface is exposed mostly to overlying seawater rather than to sediments.

The oxygen minimum layer. More speculatively, the depth range within which Co-enriched nodules may be found under high-productivity waters may be further refined by analogy with another finding from the Co-crust study referred to above (Verlaan, 2002). In crusts Co enrichment was significantly negatively related to the concentration of oxygen in and the depth of the oxygen minimum layer.

The oxygen minimum layer is an identifiable zone in the water column with a quantifiable parameter, oxygen concentration, whose level is correlated with the intensity of surface productivity. Oxygen concentration in the oxygen minimum layer is the lowest where the layer is shallowest, and these conditions obtain where surface productivity as a biological factor on water column conditions below the surface. The oxygen minimum layer may, as with the CCD, be considered a biological factor associated with surface productivity underlining the importance of surface nodule compositional variation.

It is therefore suggested that Co-enriched nodules may be found above the CCD and below the oxygen minimum layer under high-productivity waters where local topographic and current regimes reduce bulk sedimentation, such that the predominantly hydrogenetic processes necessary for Co-enrichment can occur.

Prospecting criteria

Prospecting criteria developed so far to locate economically interesting nodule deposits have been summarized as follows for Ni- and Cu-enriched nodules:

- Elevated biological productivity (>50 g C/m^2/yr (Cronan, 1984)
- Absence of turbidite sedimentation (Cronan et al., 1991)
- Within 200 m above or below the CD (Cronan & Hodkinson, 1994)

The present work shows the criteria of surface productivity and CCD listed above to be applicable throughout in the study area. Prospecting criteria directly related to grade, that is, element content can be further developed based on the results of the work presented here, as follows:

<u>For Ni- and Cu-enriched nodules</u>:

These are potentially likely to be found near the CCD under locally enhanced productivity regimes associated with nutrients from island runoff and, more speculatively, with upwelling around seamounts, even if overall productivity levels are low (e.g., <50 x C/m^2/yr).

<u>For Co-enriched nodules</u>:

An additional area which may have been somewhat overlooked to date where economically interesting deposits may be found is under high-productivity water at depths above the CCD and, more speculatively, below the oxygen minimum layer, where local topography and current regimes are sufficient to reduce bulk sedimentation.

Conclusion

Surface productivity, the CCD and the oxygen minimum layer are proposed as biological proxies for important regionally operative exploration criteria for locating nodules enriched in Ni and Cu or in Co. These three proxies are easily measurable and suitable for an initial, readily accessible, assessment of potentially economically interesting nodule grade.

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SUMMARY OF THE PRESENTATION

Dr. Verlaan said the area that was currently being studied was in the South Pacific Ocean. She said that as Professor Cronan and various speakers had talked about the previous day, it was thought that work from other regions could be used to illuminate factors which might be used for the development of prospecting proxies in the Clarion-Clipperton Zone. Dr. Verlaan said that the approach taken had been to identify regional biological factors which could explain the considerable nodule compositional variability in the region, in particular for the elements that she was going to focus on, i.e, nickel, copper and cobalt, which were also the metals of commercial interests in the Clarion-Clipperton Zone nodules.

According to Dr. Verlaan, the starting point had been surface productivity because, for a very long time, it had been postulated as being a very relevant factor in nodule composition and variability. But other than the initial detailed study on the Aitutaki-Javis Transect, which Professor Cronan and his colleagues had done way back in the early nineties, there had not been any studies to try to test surface productivity in any detail. In particular there had been no studies that tried to quantify the levels of primary productivity with the observed nodule composition variability in the region. Dr. Verlaan said that she had undertaken work on the subject at Imperial College during the past four years, and that she had brought that work out to show how she thought that some of the findings could be translated to the Clarion-Clipperton Zone.

She pointed out that an attempt had been made to quantify the regional coverage of primary productivity in the South Pacific by taking ocean colour data from the coastal zone scanner which had been flying from a satellite from 1979 to 1986. She said that data had been taken and contoured to reflect, essentially, high productivity at the equator, which decreased as one moved further away from the equator. She pointed out that the productivity isolines tended to trend upwards to the north-west from the south-east, noting that that was important for the conclusions that she would derive for the purposes of the biological proxy investigation later. Dr. Verlaan also noted that there were some peaks associated with some of the islands, in particular the Marquesas and Fiji.

Dr. Verlaan said that an element related to surface productivity that had also been tested was the depth of the carbonate compensation depth in the region. She said that the carbonate compensation depth had been identified as an element that was related to surface productivity. Dr. Verlaan said that one of the major products of her study had been to see whether the findings reported by Professor Cronan could actually be translated to the entire region. In this regard, she said that the first thing had been to see whether there was a deepening of the CCD towards the equator, as discovered by Wolfgang Berger back in the early 80s, and later confirmed by Cronan and Miller. It had been found that, essentially, in an east-west direction, the CCD did not vary more than 100 to 200 metres; it varied significantly from north to south, but deepened significantly as one approached the equator. One of the initial conclusions that had been drawn was that in terms of explaining nodule composition variability with regard to the CCD, the east-west variation was likely to be much less significant than the north-south variation which was a new information that had not been presented anywhere else.

Dr. Verlaan said that the CCD and the primary productivity criteria had been investigated with the help of Dr Morgan. She said that all the available nodule sample stations data, including much of the SOPAC and Polish data, had been put together. She said that Dr. Morgan had written a computer programme that had been able to pinpoint for each nodule sample location the value of primary productivity and the depth of the CCD at those locations. She noted that this was the first time that the distribution of the variability in nodule composition for iron, zinc and manganese had been quantified statistically and examined visually. It had also been the first time that one had been able to identify whether there were any statistically quantifiable relationships as well as visual ones. Dr. Verlaan said that using the kriging method, it had been possible to plot the distribution of the metal composition for each of the methods on a map of the region, in terms of their concentration. She also noted that this had also made it possible to compare the metal concentrations and the distribution throughout the region with the variability of the primary productivity and of the CCD in the area.

Manganese

Through a colour chart, Dr. Verlaan showed that there was high manganese near the equator, a little bit near the Astral Tubuai islands, a little bit of an increase in manganese just west of Tubuai, an essential decrease of manganese as one went further south, and an increase as one went north to the equator. This had been done for each of the metals of interest in the study.

Nickel

Dr. Verlaan said that again, there was a progression of nickel, which was higher towards the equator, and lower as one moved away from the equator. She noted that there was quite an interesting relationship, which, by regression/correlation analysis, had been determined to be quite significant between the trends in the productivity lines and the trends in manganese, nickel and copper.

Dr. Verlaan clarified that the sample base was quite significant - about 1,000 samples were utilized.

Copper

According to Dr. Verlaan, copper was quite comparable to the others and quite comparable with the primary productivity lines, although the variability was not that great from the east to the west.

Iron and cobalt

Dr. Verlaan said that for these two metals, by contrast, the completely opposite relationship had been found with primary productivity.

Iron was low near the equator and increased as one went south. Maps had been drawn of the Mn/Fe ratio which showed a very, very strong, high Mn/Fe ratio in the north towards the equator, which decreased as one moved further south.

There was high cobalt in the south and low cobalt in the north; similar to that of iron.

Dr. Verlaan said that when this had been analysed in detail, it had been discovered that one could topographically come to some very interesting conclusions to explain some of the anomalies that were not very visible from the maps, but were visible when one started looking in great detail at the way the nodules were distributed within particular areas. In terms of the work that was being done with regard to biological proxies, Dr Verlaan said that it had been discovered that, with regard to nickel and copper enrichment, there was enrichment at the CCD, literally throughout the region, not only in the high productivity areas, but even in low productivity areas, where there was still discernible CCD. She said that at that depth, there would be nickel and copper enrichment and its comparative would be found. She also said that here was much more nickel and copper enrichment near the CCZ under the high productivity zones, and that even in the low productivity zones, the CCD was the level at which one could anticipate finding additional copper and nickel enrichment.

Another point made by Dr. Verlaan was that with regard to cobalt and its relationship to the CCD was its depletion at the CCD throughout the region. However just above the CDD, under higher productivity waters, she said there was cobalt enrichment, and that was the conclusion through extrapolation because there were fewer data on nodules at higher levels. The least depth for nodules was about 3,000 metres. Dr. Verlaan mentioned that, in a related study, which had looked at a similar set of methods but for cobalt-enriched crusts in the region, it had been discovered that above the CCD, there was cobalt enrichment in crusts, comparable to that of nodules from similar depths. She said that the tentative conclusion arrived at, for the purposes of the workshop was that if one looked above the CCD and if one had the appropriate sedimentation regime (it had to be the same type of sedimentation regime that was going to be conducive to the formation of cobalt-enriched crusts), one might well find cobalt-enriched nodules in that area. According to Dr. Verlaan, this was a new area to be researched, either in the South Pacific or in the Clarion-Clipperton Zone. Dr. Verlaan said that she wanted to leave participants with the thought that when model development started, elevations within the area where the sedimentation regime was quite low should also be looked at to see whether they might not be a good source for cobalt-enriched nodules.

The final element discussed by Dr. Verlaan was also related to cobalt enrichment in nodules. She said that it was also an extrapolation from a related study with regard to ferro-manganese crusts in the region, and that was the effect of the oxygen minimum layer. In the region, Dr Verlaan said that the oxygen minimum layer was a biological factor, because it was very much related to the level of surface productivity. She said that in the same way that surface productivity had been modelled, the regional presence of the oxygen minimum layer had been modelled, in millimetres per litre. She also said that the depth of the oxygen minimum layer decreased as one approached the equator, and increased as one moved further south. In other words, the surface productivity was negatively correlated, both with regard to the oxygen concentration and the oxygen minimum layer, and in the depth of the oxygen minimum layer. Again extrapolating from the crusts data and the very few nodule data that were available from higher depths, Dr. Verlaan suggested that, in the Clarion-Clipperton Zone, the inclusion of the oxygen minimum layer should be explored as one of the biological factors to be considered, because it might narrow the depth in which it might be possible to find cobalt-enriched nodules within the layer.

Dr. Verlaan said that the biological proxies, which she suggested to be investigated for the CCZ, as derived from the work done in the South Pacific, were as follows: there were three criteria that she had been able to get from the literature for nickel and copper-enriched nodules that had come mostly out of work done by Professor Cronan and colleagues in the ‘80s and ‘90s. First was elevated biological productivity. It had been shown that, at least in the South Pacific, biological productivity was a criterion that could be extended regionally throughout the South Pacific, because of the absence of turbulent sedimentation. Dr. Verlaan said that the sedimentation regime was an important one, particularly with regard to the cobalt enrichment of nodules. She said she would be interested in seeing whether that could be narrowed down and said that she believed that one could probably get right down to the CCD level, in so far as that could be determined quite precisely, in order to enhance the prospecting possibilities.

Dr. Verlaan said that when the areas had been looked at in detail, productivity enhancement had been found in relation to the Tuamotos, in relation to the Cooks, in relation to the Marquesas, where it was very obvious, and there was a certain amount of work, unfortunately not quite enough yet, which showed that the productivity was enhanced around seamounts. Dr. Verlaan believed that enhanced productivity around seamounts was quite important; certainly to the fishermen around her home state of Hawaii, who spent a lot of time around seamounts there, where they had a little more fish, but it was interesting that a lot of the seamounts also had significant deposits of manganese crusts.

Dr. Verlaan said one needed to look for locally enhanced productivity regimes in the Clarion-Clipperton Zone, in order to find areas where one was liable to find nickel and copper-enriched nodules. Where the sedimentation regime was sufficiently reduced, one was also likely to find cobalt-enriched nodules. She was of the view that, under that high productivity, it would be more likely above the CCD, below the CCD, and below the oxygen minimum layer.

In closing, Dr. Verlaan said that the other advantage to using the three criteria was that they were very easily measurable, very easily accessible, did not require an enormous amount of dredging, and would provide an indication as to whether it was likely to find economically interesting nodule grades. What the criteria did not was give any indication of abundance. She had not been able to make any links to the abundance. Dr. Verlaan said that when she had put together the dataset, she had not looked at it with a view to determining a relationship with abundance. But in terms of nodule grade, she believed that those three prospecting criteria, from a biological standpoint, could be of use in the Clarion-Clipperton Zone.

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CHAPTER 16 CURRENT RESEARCH ACTIVITIES RELATED TO THE BIODIVERSITY AND TO THE WATER COLUMN COMPOSITION AND STRUCTURE AROUND NODULE DEPOSITS

Craig R. Smith, Department of Oceanography, University of Hawaii at Manoa

(Dr Smith did not provide a formal paper for the workshop.
He made a powerpoint presentation, which is reproduced in full below)

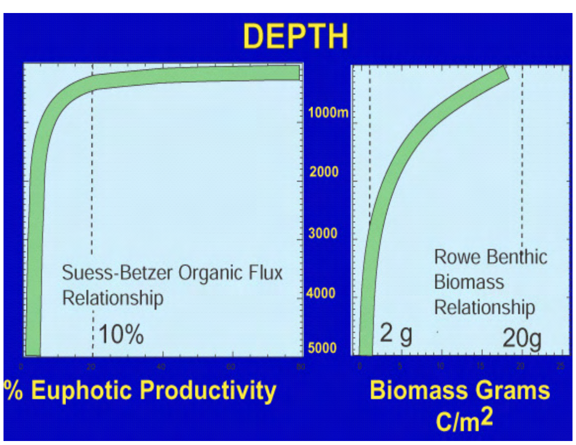
Outline

1. General ecological characteristics of Clarion-Clipperton Fracture Zone (CCFZ) floor
2. Studies of biodiversity and species ranges in the CCFZ – the Kaplan Project
3. What biology can do for the geological model and vice versa?

Ecological characteristics of abyssal seafloor

- Most sediment covered (~90%)
- Vast, largely continuous habitat (often 1000's km)
- Low temperature (<4◦C)
- High hydrostatic pressure
- Physically very stable (much structure biogenic)

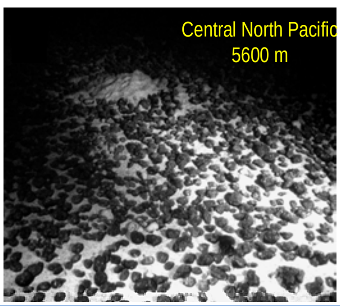
5600 m Central North Pacific — *4500 m Equatorial Pacific*



Productivity, biomass, popul ation densities, growth rates, recolonization rates all very low. Ecosystem typically is "food-limited"

EXAMPLES OF LOW RATES –

- infaunal community may require years to recover from 2-4 cm of sediment burial on ubiquitous biogenic mounds (Kukert and Smith 1992)



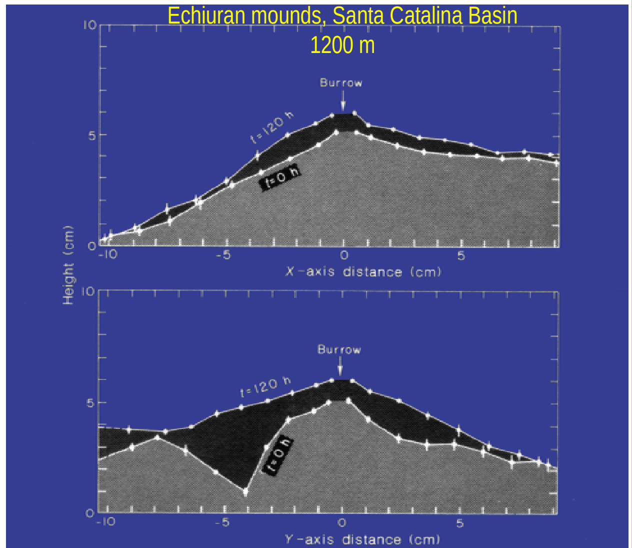


Fig. 1 Cross-sectional profiles through the peak of an echiuran mound, drawn from stereo photographs using a stereocomparator. Sets of profiles are drawn along two normal axes, from photographs taken shortly after the camera was emplaced ($t = 0$ h) and 120 h later ($t = 120$ h). Each point represents the mean (±s.e.) of five replicate runs with the stereocomparator. Heights are referenced to an arbitrary base level. (Smith et al. 1986)

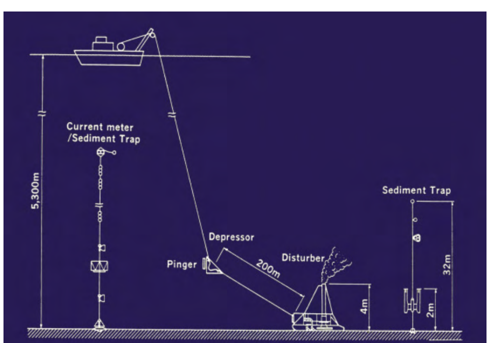


Fig.2. Schematic arrangement for disturber towing (after Fukushima, 1995).

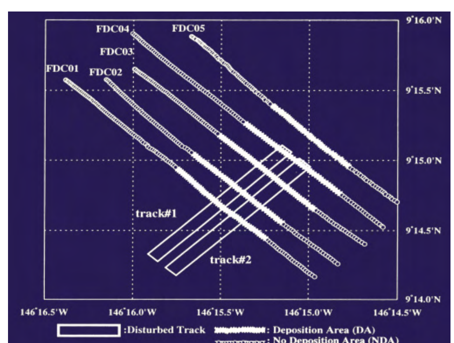
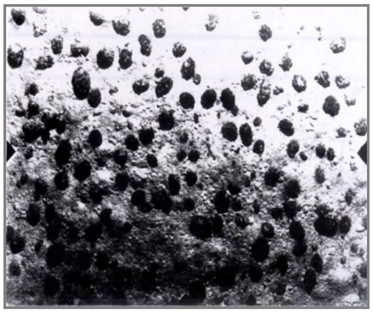
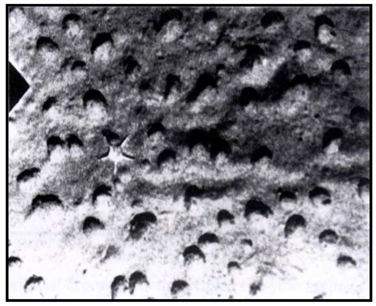


Fig.3. The locations of the 5 FDC (Finder-installed Deep-sea Camera) survey lines in the JET 4 cruise.

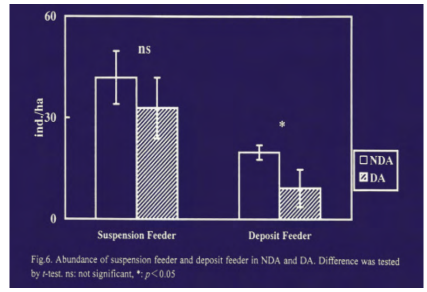
Deep-sea megabenthos slow to recover after artificial deposition



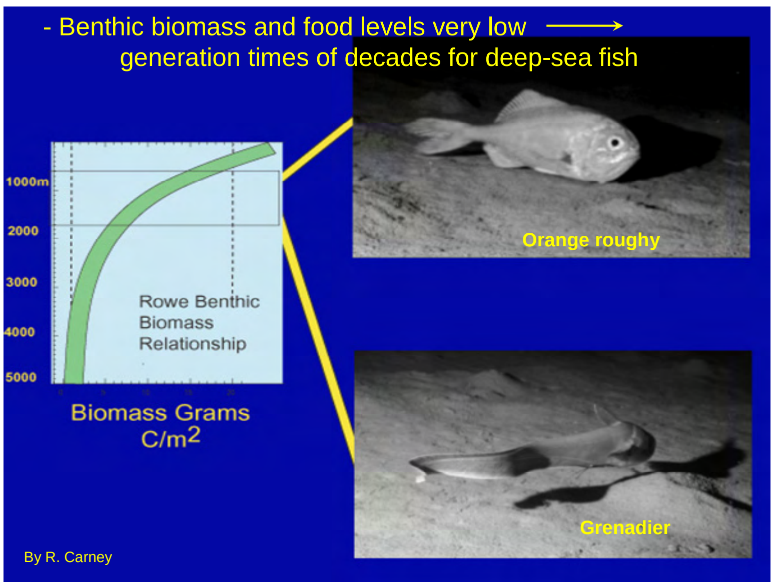
No deposition area



Deposition area

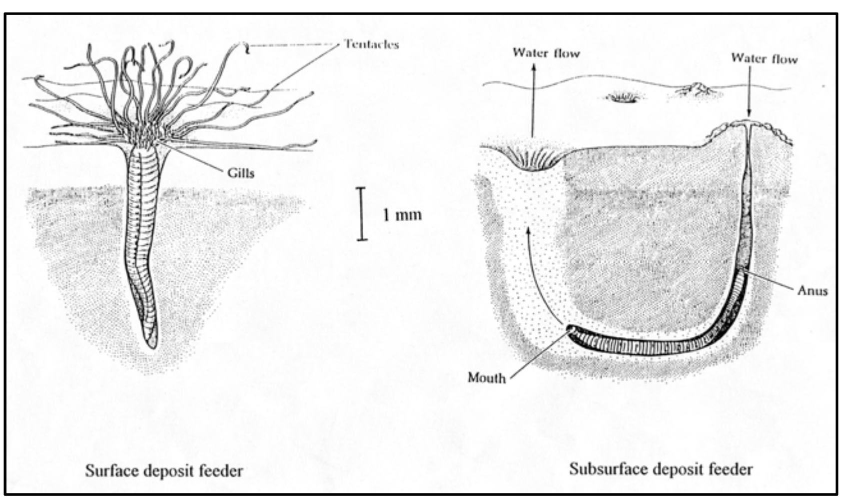


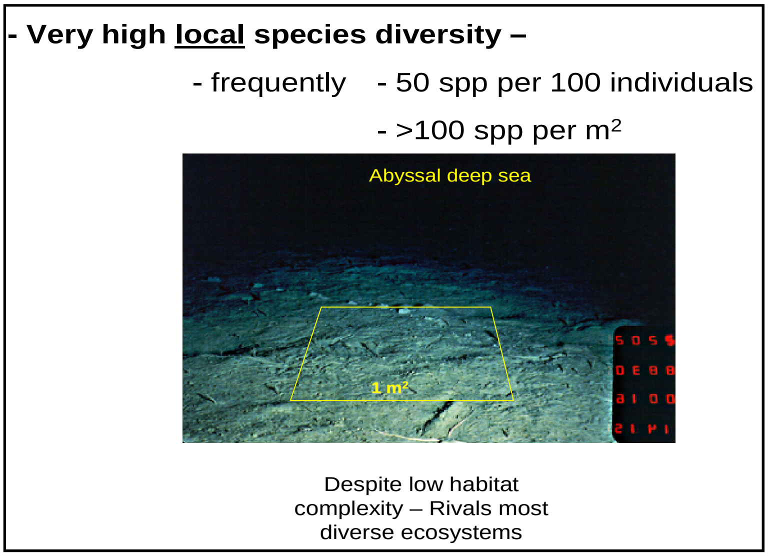
2 years after deposition

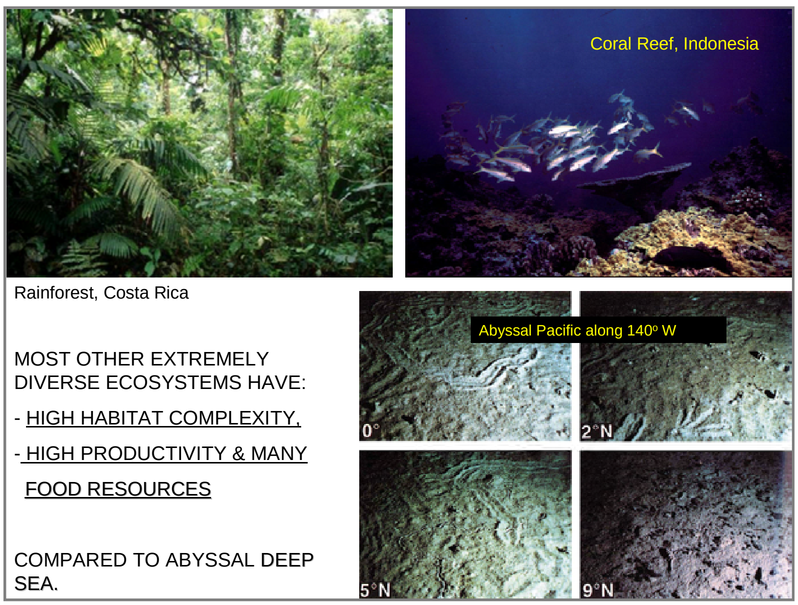


(Fukushima et al., 2000)

Most CCFZ macrofaunal species are small, delicate deposit feeders (esp. surface deposit feeders)







Processes promoting local species coexistence in the deep sea

(from Snelgrove and Smith, 2002)

1. Habitat partitioning
2. Nonlinear responses to changing resources
3. Intermittent disturbance with competitive/colonization tradeoffs
4. Disproportionate predation on competitive dominants
5. Competitive convergence
6. Source-sink effects in a heterogeneous landscape

Note: Underlined processes are especially sensitive to large regional species pools.

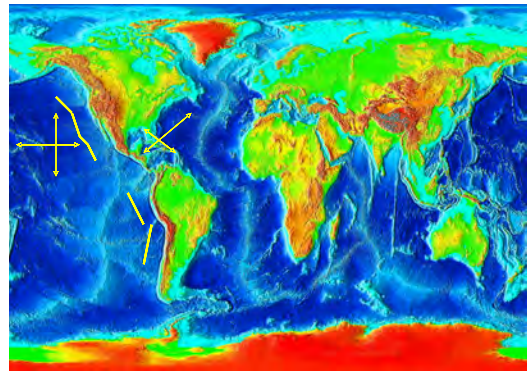
Conclusion

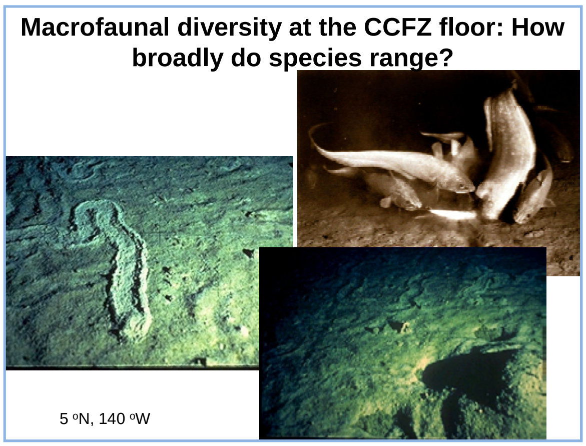
Soft-sediment, deep-sea communities are *easily disturbed* by, and *very slow to recover* from:

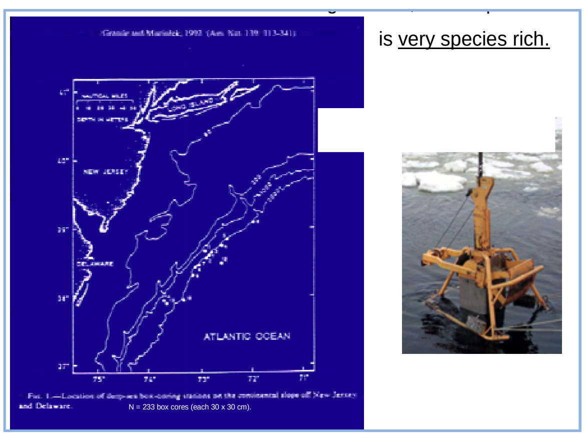
- Extraneous mortality (*fishing, lethal pollution*)
- Physical disturbance (*trawling, mining, dumping*)
- Changes in POC flux to seafloor (*global climate change*)

However, vast habitat size may → broad species ranges

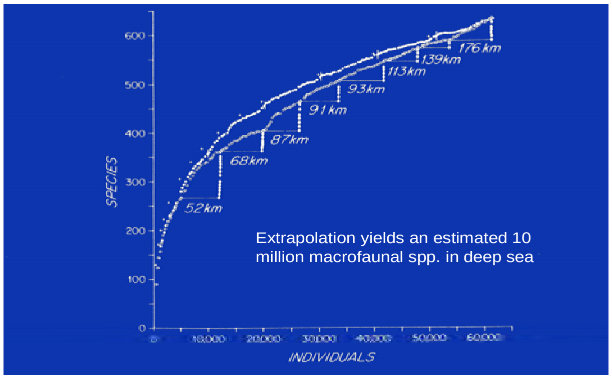
Extinctions relatively unlikely?

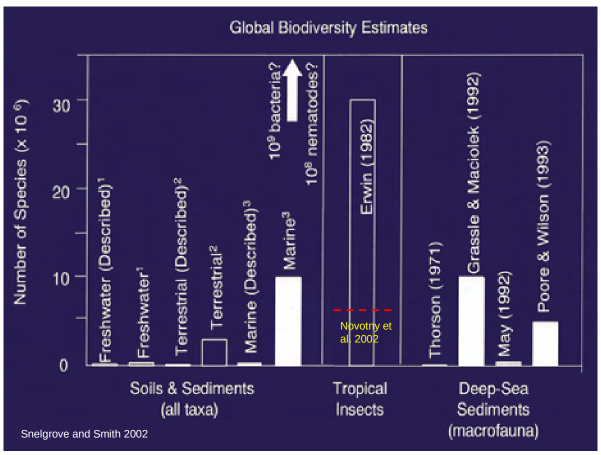




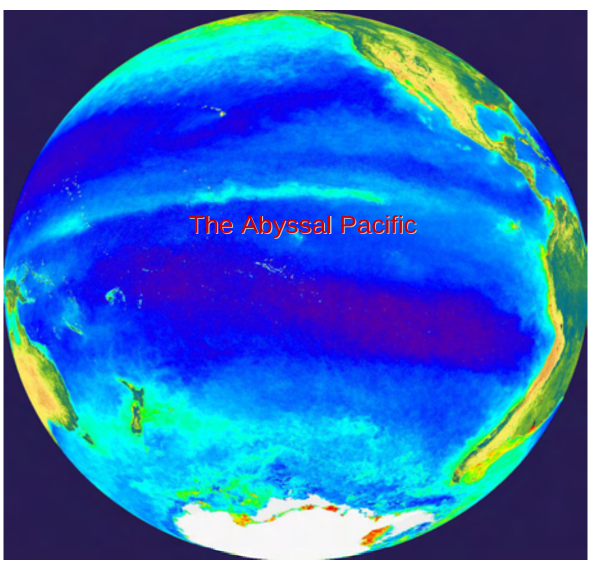


There is some evidence that on large scales, the deep-sea is very species rich

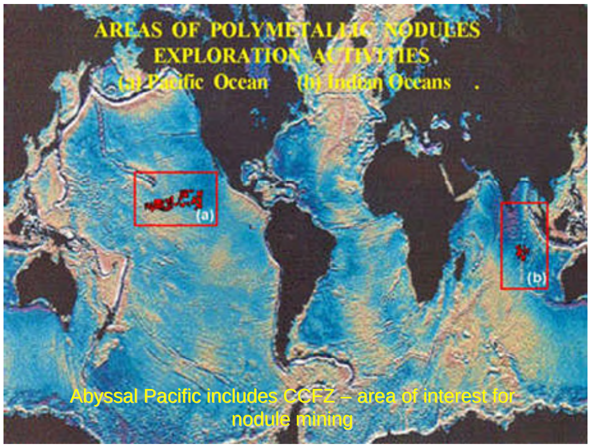




High global deep-sea diversity?



The Grassle extrapolation ignores the largest potential species reservoir in the deep sea

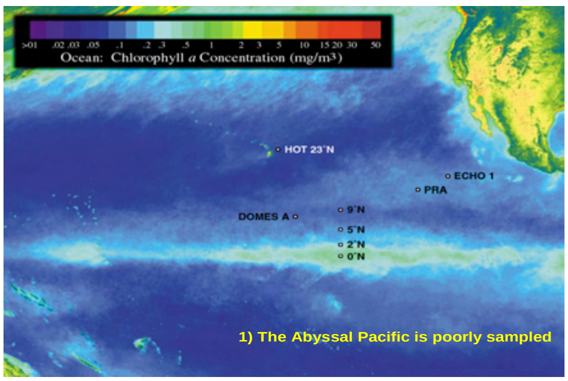


To predict risks of species extinctions from mining, it would be extremely useful to know:

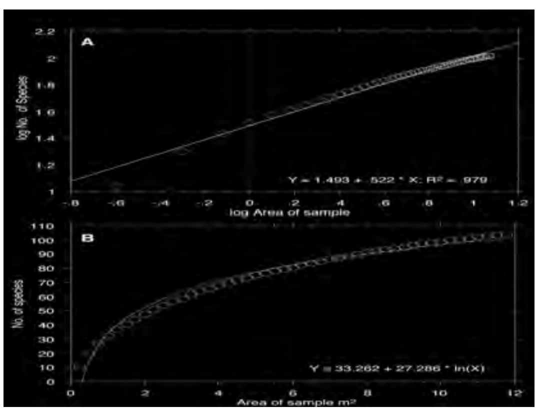
1. The number of species living within an area potentially impacted by mining.

2. Species ranges and scales of gene flow within the nodule provinces ("Are species ranges greater or smaller than the potential area of mining impact?").

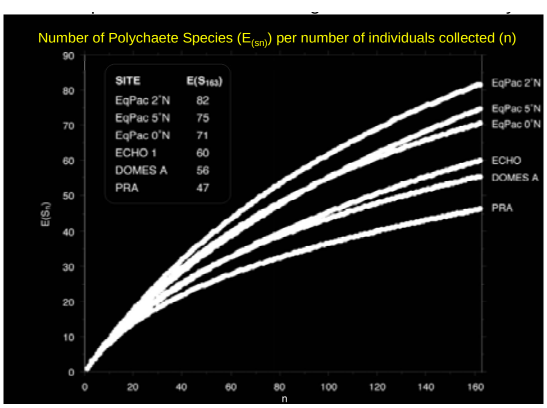
We know relatively little about diversity levels and species ranges in the Pacific Abyss. Why?



Biota at all these sites is still far from fully sampled

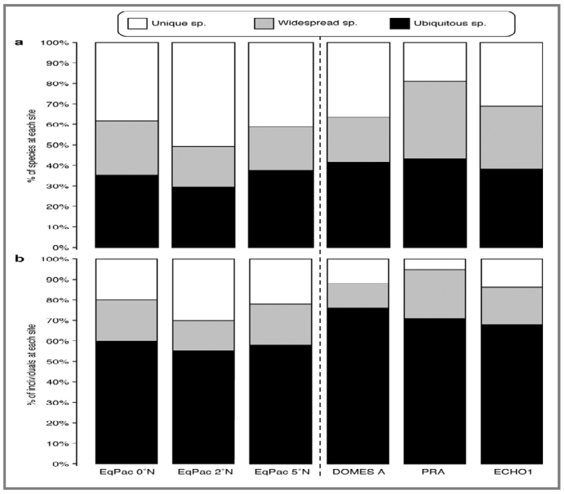


Linear regression of species-area curve in log space



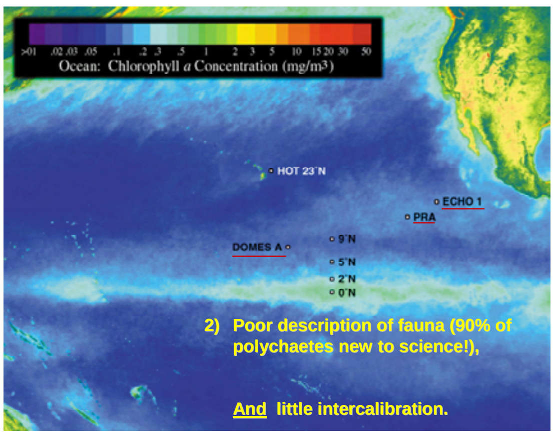
Non-linear regression of species-area curve

All sampled sites seem to have high macrofaunal diversity



Apparent ranges of polychaete species in the CCFZ region from Glover *et al* (2002)

Need more samples



Taxonomy based only on morphological analyses

- Recent DNA based analyses suggest many cryptic species in deep sea
- E.g. based on morph. Chaetozone setosa is cosmopolitan
- Common in CCFZ, Cal., Slope, NE USA and European zones

Summary

Major gaps in knowledge of macrofaunal diversity in the CCFZ result from:

1. Undersampling: we need substantially more samples collected across region to resolve presence/absence of rarer species;
2. Lack of intercalibration (and species descriptions): we need to cross reference taxonomic collections to resolve species ranges;
3. Lack of molecular (DNA-based) data: this is needed to resolve cryptic species and elucidate patterns of gene flow.

NB: The Kaplan Project is designed to begin to fill these major gaps in the CCFZ.

The Kaplan Project

Biodiversity, species ranges, and gene flow in the abyssal Pacific nodule province: predicting and managing the impacts of deep seabed mining

Principal Investigator:	Dr. Craig R. Smith, University of Hawaii at Manoa
Co-Investigators**:**	Drs. Gordon Paterson and John Lambshead, Natural History Museum of London, United Kingdom
	Dr. Alex Rogers, Fritish Antarctic Survey
	Dr. Andy Gooday, Southampton Oceanograhy Center, United Kingdom
	Dr. Hiroshi Katazato, Shizuoka Universitym Japan and JAMSTEC
	Dr. Myriam Sibuet, IFREMER, France
	Dr. Karsten Zengker, Diversa Corporation, United States of America

The problems

The Abyss. Deep-sea sediments may be major reservoirs of biodiversity, but regional species richness and species ranges are very poorly known.

Nodule Mining. At present, seven contractors are licensed by the International Seabed Authority to explore nodule resources and to test mining techniques in claim areas, each covering 75,000 km^2 (an average area ½ the size of Florida).

When mining begins, each operation is projected to directly disrupt ~300-800 km^2 of seafloor per year, and to disturb seafloor biota over an area 2-5 times greater due to sediment redeposition.

Over a 15-year period, two to three nodule mining operations might severely damage abyssal seafloor communities over areas of 18,000 to 180,000 km^2 (an average area ½ the size of Germany).

It is virtually impossible to evaluate the threat of nodule mining to biodiversity (in particular, the likelihood of species extinctions) without estimates of the following:

1. The number of species residing within areas potentially perturbed by single mining operations;
2. The typical geographic ranges of species (and rates of gene flow) within the general nodule province.

The Kaplan Project

With funding by the Kaplan Fund and the International Seabed Authority, the primary goals of the project are to:

1. Estimate, using, molecular methods and rigorous statistical techniques, the number of polychaete, nematode and foraminiferal species at three stations spaced at ~1500- km intervals across the Pacific nodule province;
2. Evaluate, using state-of-the-art molecular and morphological techniques, species overlap and rates of gene flow over scales of 1500 - 3000 km for key components of the polychaete, nematode and foraminiferan fauna;
3. Broadly communicate our findings to the scientific and mining-management communities, and make specific recommendations to the International Seabed Authority on minimizing risks to biodiversity resulting from mining;

In addition to studying the three faunal groups mentioned above, we will explore patterns of diversity within sediment microbial assemblages across the nodule province, using DNA sequencing approaches.

Project execution

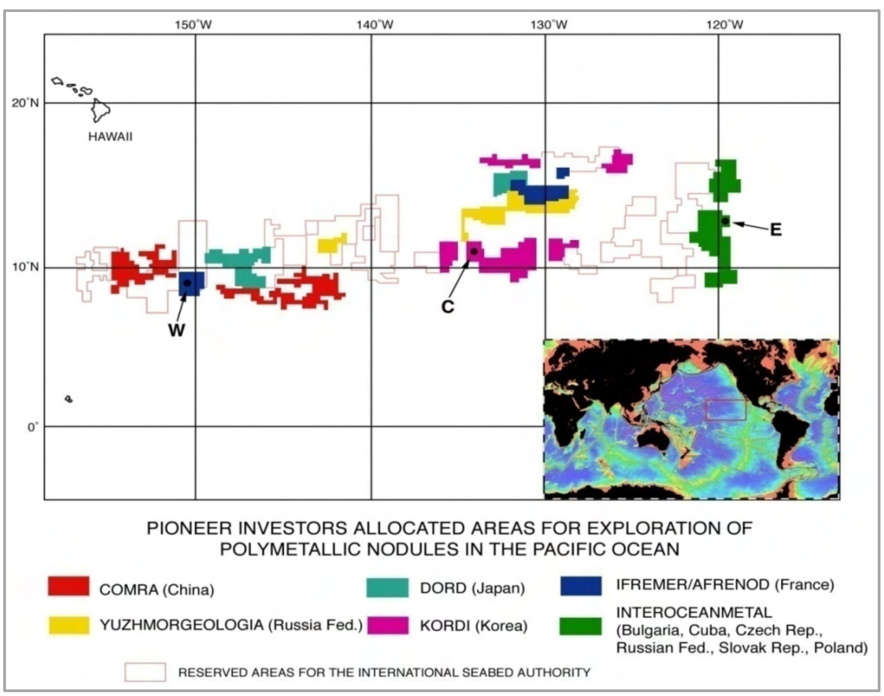
There are three major components, as follows:

1. <u>Field sampling</u>

Collect "DNA-friendly" samples at ≥ three stations separated by ~1500 km spanning the areas in the abyssal Pacific potentially impacted by nodule mining.

USNEL box core

Megacorer or multicorer



At each station, collect 14-20 box cores macrofauna,
6-10 multicores for meiofauna and microflora,
1-2 epibenthic sleds for more mobile macrofauna

- Samples are to be kept cold and rapidly processed with chilled seawater (2-4°C) to prevent damage to the DNA of the targeted organisms;

- Parallel samples of macrofauna and meiofauna from each station will be fixed in 4% formaldehyde-seawater solution (for morphological versus DNA comparisons);
- First cruise was completed aboard *RV New Horizon (*4 Feb-7 Mar 2003) and sampled the eastern station (8 multiple cores and 14 box cores);

Additional sampling was done near the central and western stations in collaboration with Japan in Feb 2004 (St. W), and with IFREMER in summer 2004 (St. C and W).

Additional sampling is expected in collaboration with KORDI and COMRA in 2004 and/or 2005.

2. Laboratory and planned traineeship programme

(a) Macrofaunal Sorting and Preliminary Identification, C. Smith, University of Hawaii;

(b) Polychaete Identification and Taxonomic Analyses, G. Paterson and A. Glover, Natural History Museum;

(c) Nematode Sample Processing, J. Lambshead, Natural History Museum;

(d) Foraminiferan Sample Processing and Identification, H. Kitazato, JAMSTEC & A Gooday, National Oceanography Centre , Southampton

(e) Molecular Genetic Analyses, A. Rogers, British Antarctic Survey, & K Zengler, Diversa

(f) Traineeships possible on molecular techniques at BAS, on-field and sorting techniques at UH, on taxonomy NHM.

3. Communication of results:

- Archive a “DNA-friendly” collection of deep-sea biota,
- Produce web page describing our “DNA-friendly” archive and illustrating the common polychaete species in the CCFZ;
- Presentations on our findings at international scientific meetings and to the International Seabed Authority;
- Publish results in peer-reviewed scientific literature.

Additional highly desirable collaborations (and funding)

- Megafauna, PI. Gerd Schriever;

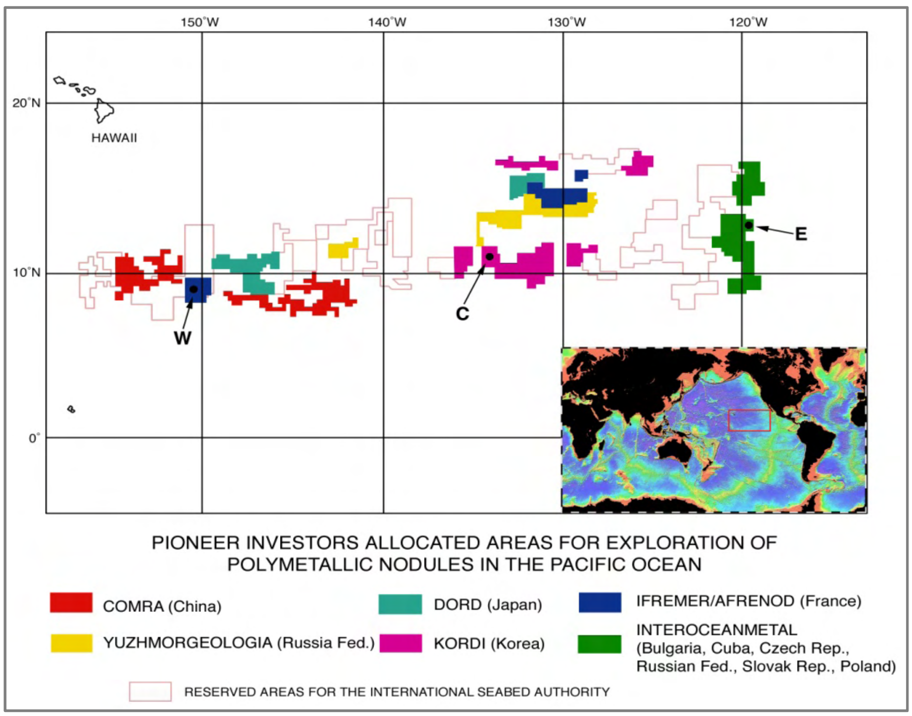
- Distribution and diversity of megafauna from vast collections of photographs from pioneer investors and others in CCFZ;
- Additional fauna groups (harpacticoids);
    - Additional sampling cruises or sites?;
    - Equipment, scientific or data exchanges with other biodiversity programmes?

Potential collaborations to be discussed at CoML Workshop on Deep-Sea Biodiversity in August in Oregon – (esp. collaborations with taxonomists and additional funding)

Water column research programmes collaborating with the Kaplan Project

1. COMRA: "Natural Variability of Baseline (NaVaBa)"

- Begun in 1996 to investigate and study the natural spatial and temporal variability in deep-ocean ecosystem in COMRA's contract areas.

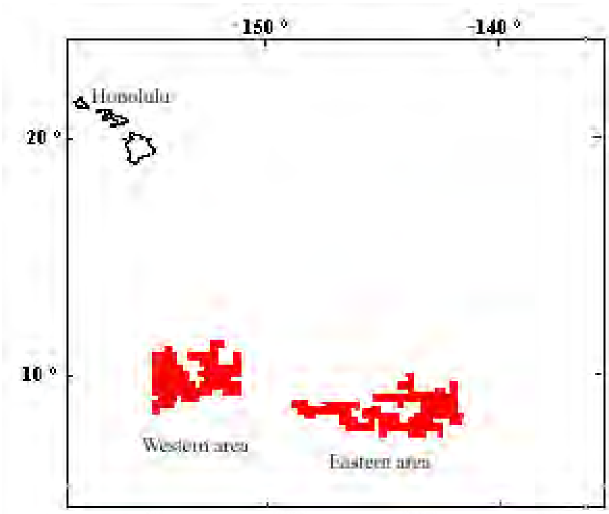


- Entails biological, chemical, physical and geological surveys.
- Four cruises over the past five years (1997 – 2001).

Future NaVaBa programme:

- At least three cruises in time frame 2003-2007.
- Sample transects and reference stations along 154o and 145o W.
- Measuring many water column biological and chemical variables, and seafloor geotechnical data.
- Eager for collaboration with Kaplan

2. KORDI: Baseline studies in CCFZ

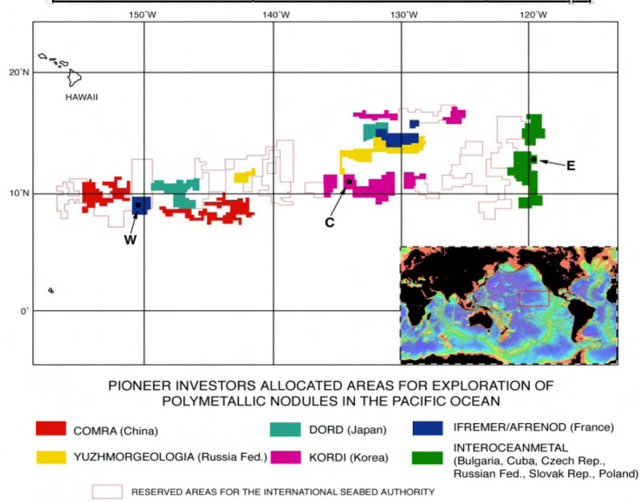


- Extensive water column and seafloor studies since 1991

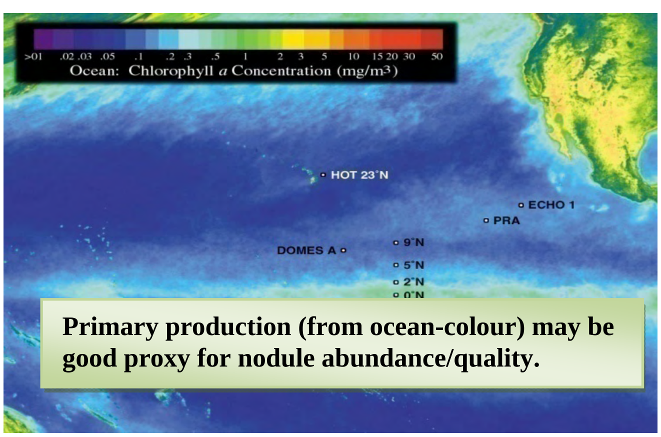
Many physical, chemical, biological geological variables measured

Continue baseline studies through 2005, with survey cruises for water column and seafloor in 2003 and 2004.

Interested in collaborations, but space and time on ship limited.

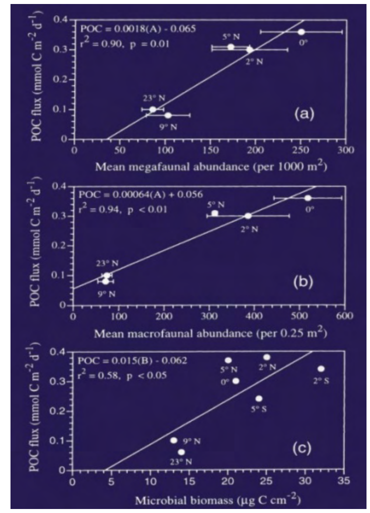


What can benthic biologists do for you (or for the geological modeling effort)?



Because deep-sea benthos are food-limited:

- Benthic biomass/abundance integrates export flux over large areas (>1000 km2) and time scales of months to years



Conclusion:

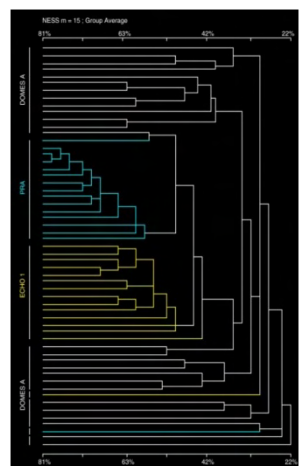
Benthic standing crop helps ground truth the productivity (i.e., export flux) versus nodule relationship in CCZ geological model.

"Is productivity controlling nodule abundance/quality in the way we think it is?"

What can the geological model do for seafloor biologists?

Provide distribution of key habitat variables that control species distributions and community structure in the CCFZ, including:

*Substratum type	- presence and abundance of nodules (hard substrata)
	- sediment type (grain size, % Corg)
*Flow regime	- mean and maximum near-bottom currents, frequency of sediment transport
*Bottom topography	- current intensification, frequency of slumping
*Bottom-water O2	- oxygen penetration into sediments
Sinking POC flux	- annual rate and variability



<u>Multivariate analysis</u>

Kulczynski similarity index:

sites are 50-65% similar

% similarity is more closely related to sampling intensity, not distance.

NESS similarity index (sensitive to both dominant and rare species)

sites are 60-80% similar, with weak evidence of geographical isolation

Example: submarine canyons as landscape heterogeneity with source population

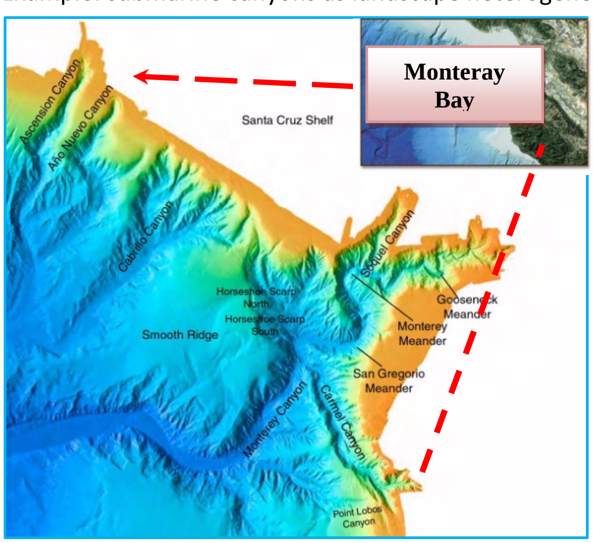
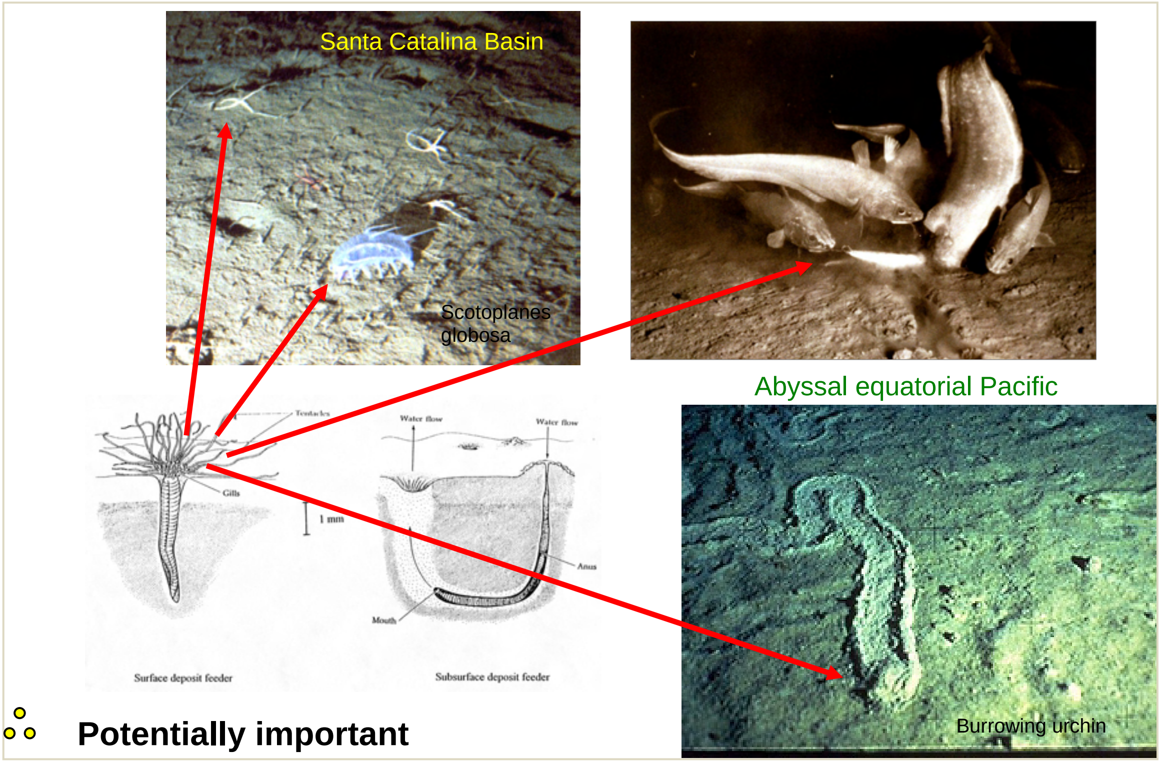
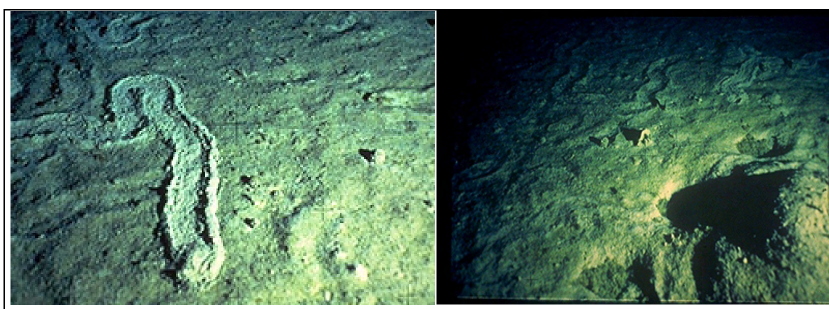


Image from MBAR1

STILL UNTESTED! Many possible examples:
Predation by megabenthos on surface deposit feeders (under test by Thistle and Eckman)



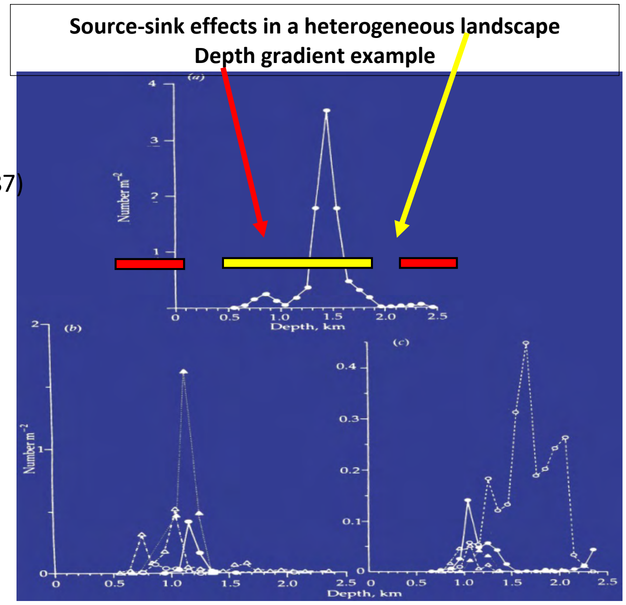
	
Example: physical disturbance from scavenger aggregation (Smith, 1986)	*Abyssal plain, 4,500 m equatorial Pacific*

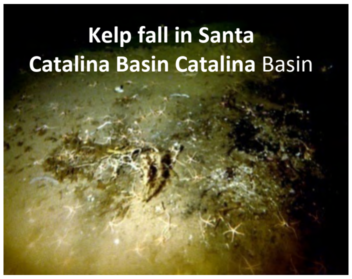
Yields –

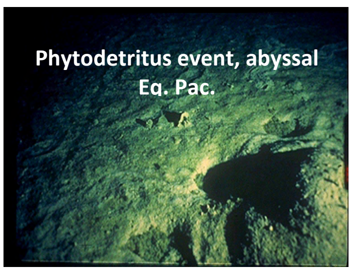
- interactions between local & regional processes
- long list of rare species

Megafauna, NW Atlantic slope:

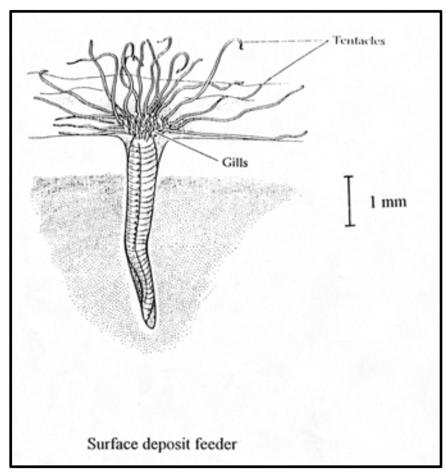
(a) Xenophyophore, *Reticulammina?*;
(b) 4 species of gorgonian;
(c) 3 species of pennatulid. (Maciolek et al. 1987)







Examples include:



Surface deposit feeder

- Enhancement of macrofaunal species in *Sargassum* falls and algal enrichments (Grassle and Morse-Porteous, 1987; Snelgrove et al., 1992, '94,' 96)
- Enhancement of foraminiferan and nematode spp. in phytoplankton-bloom fallout ("phytodetritus") (Lambshead and Gooday, 1990; Brown et al., 1999)
- Deep-sea factors leading to *competitive convergence* and very long exclusion times:

  (a) Selective pressure on surface deposit feeders to exploit the same thin veneer of recently settled, organic-rich particles;
  (b) Very low population densities (*Interference competition unlikely*)
  (c) Very low population growth rates

Comp. Conv. not yet directly tested (and remains difficult to test in the remote deep sea), but **potentially important!**

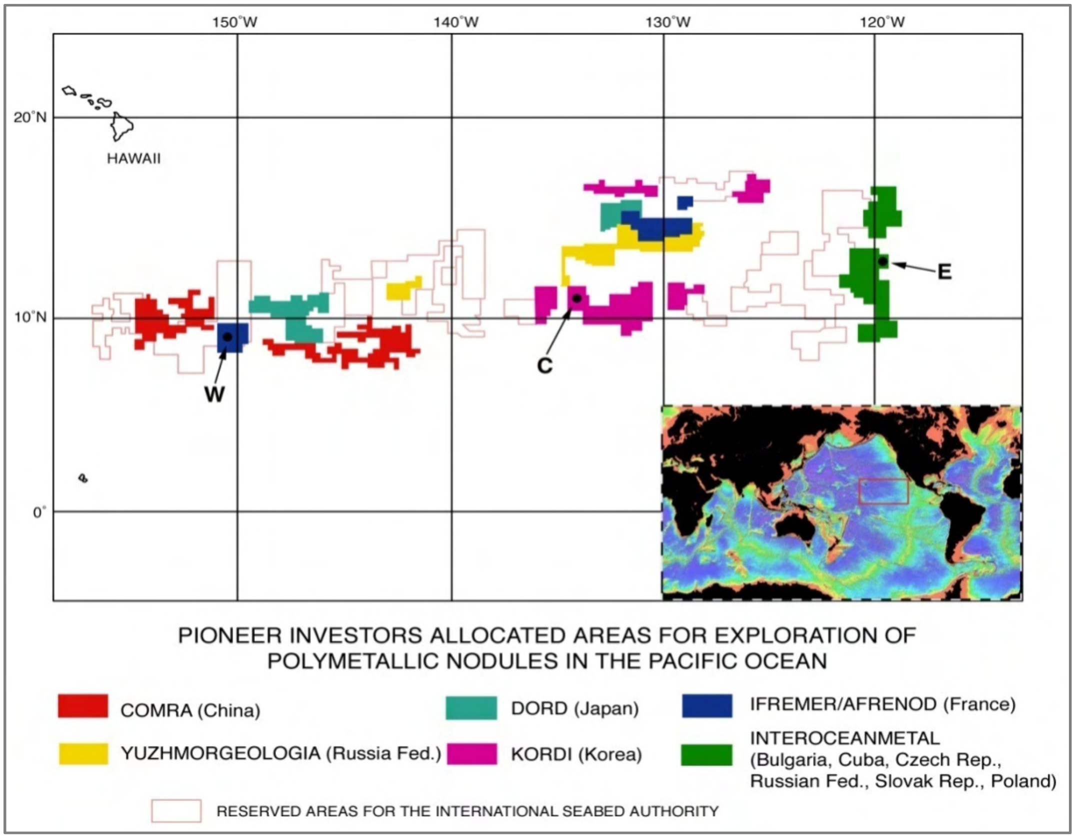


Figure 1: The region of maximum commercial interest in the Pacific nodule province (box in inset) and claim areas licensed to exploration contractors. The proposed sampling sites for the Kaplan project are indicated by E, C and W.

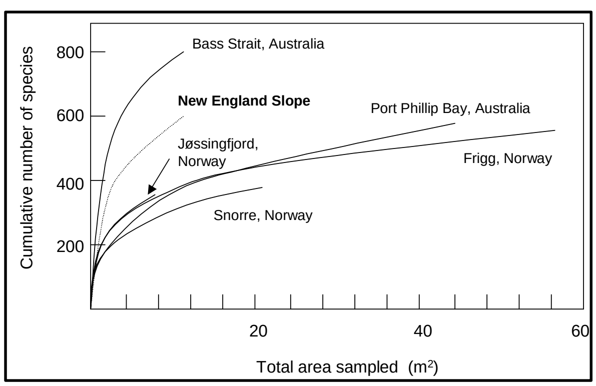
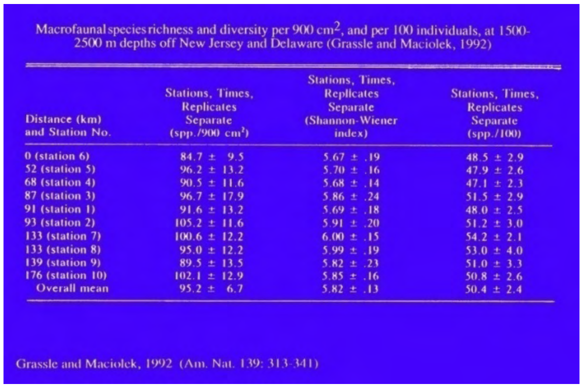


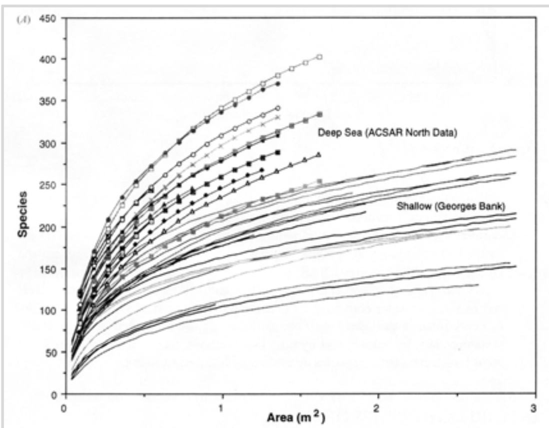
Figure 2: Snelgrove & Smith


Macrofaunal species richness and diversity per 900 cm^2, and per 100 individuals, at 1500-2500 m depths off New Jersey and Delaware (Grassle and Maciolek, 1992)

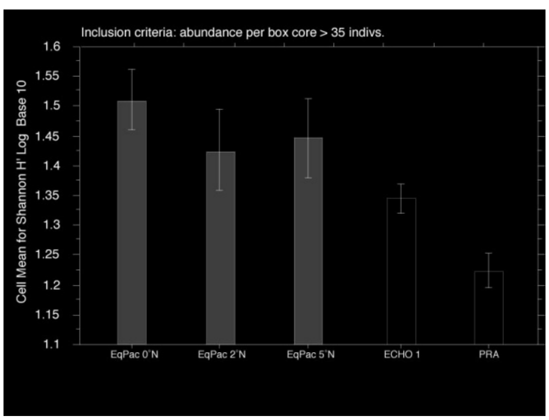
Distance (km) and Station No.	Stations, Times, Replicates Separate (spp./900 cm^2)	Stations, Times, Replicates Separate (Shannon-Wiener index)	Stations, Times, Replicates Separate (spp./100)
0 (station 6)	84.7 ± 9.5	5.67 ± .19	48.5 ± 2.9
52 (station 5)	96.2 ± 13.2	5.70 ± .16	47.9 ± 2.6
68 (station 4)	90.5 ± 11.6	5.68 ± .14	47.1 ± 2.3
87 (station 3)	96.7 ± 17.9	5.86 ± .24	51.5 ± 2.9
91 (station 1)	91.6 ± 13.2	5.69 ± .18	48.0 ± 2.5
93 (station 2)	105.2 ± 11.6	5.91 ± .20	51.2 ± 3.0
133 (station 7)	100.6 ± 12.2	6.00 ± .15	54.2 ± 2.1
133 (station 8)	95.0 ± 12.2	5.99 ± .19	53.0 ± 4.0
139 (station 9)	89.5 ± 13.5	5.82 ± .23	51.0 ± 3.3
176 (station 10)	102.1 ± 12.9	5.85 ± .16	50.8 ± 2.6
Overall mean	95.2 ± 6.7	5.82 ± .13	50.4 ± 2.4

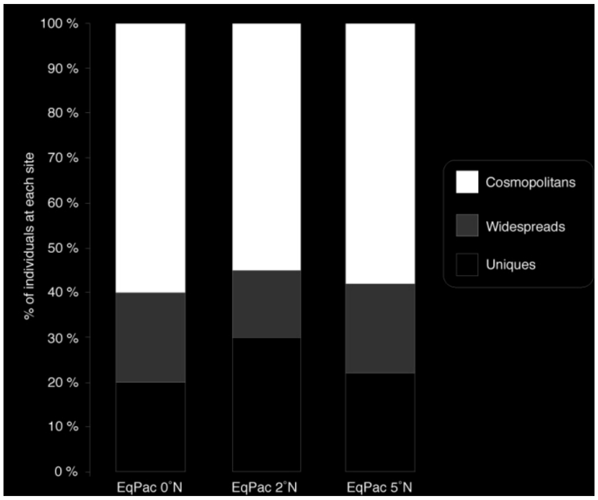
Grassle and Maciolek, 1992 (Am. Nat. 139: 313-341)

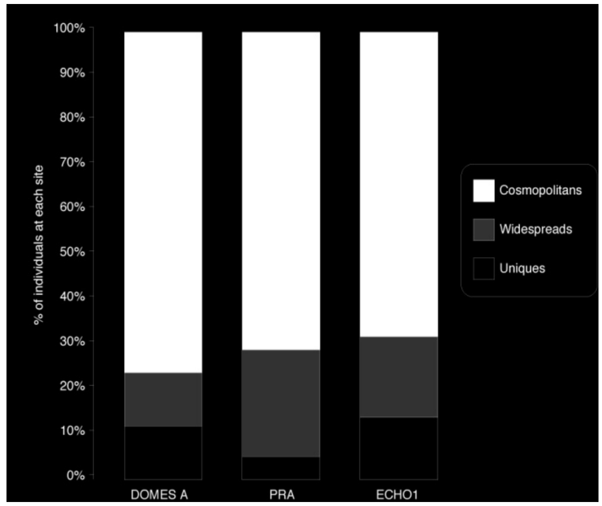
"Macrofauna" = animals retained on a 300 μm sieve.



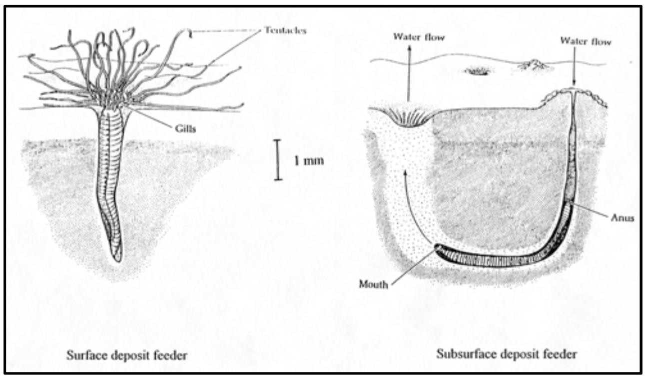
Randomized species accumulation curves for all North (ACSAR) and Georges Bank stations as a function of (A) area sampled and (B) number of individuals. The Georges Bank curves lack symbols while the North stations have symbols. Data are from Maciolek et al (1985) and Maciolek et al (1987b)







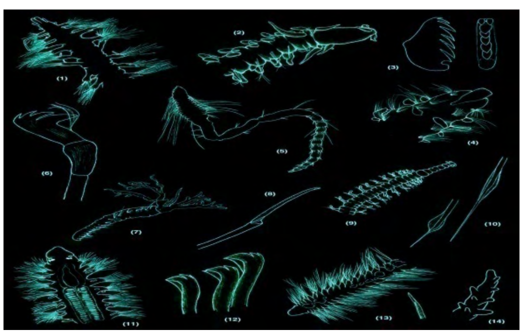
Most macrofaunal species are deposit feeders (especially surface deposit feeders)



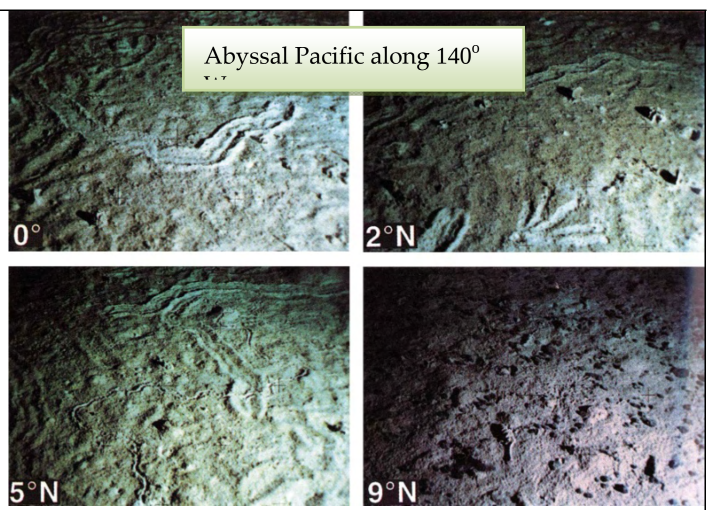
Macrofaunal species richness and diversity per 900 cm^2, and per 100 individuals, at 1500-2500 m depths off New Jersey and Delaware (Grassle and Maciolek, 1992)

Distance (km) and Station No.	Stations, Times, Replicates Separate (spp./900 cm^2)	Stations, Times, Replicates Separate (Shannon-Wiener index)	Stations, Times, Replicates Separate (spp./100)
0 (station 6)	84.7 ± 9.5	5.67 ± .19	48.5 ± 2.9
52 (station 5)	96.2 ± 13.2	5.70 ± .16	47.9 ± 2.6
68 (station 4)	90.5 ± 11.6	5.68 ± .14	47.1 ± 2.3
87 (station 3)	96.7 ± 17.9	5.86 ± .24	51.5 ± 2.9
91 (station 1)	91.6 ± 13.2	5.69 ± .18	48.0 ± 2.5
93 (station 2)	105.2 ± 11.6	5.91 ± .20	51.2 ± 3.0
133 (station 7)	100.6 ± 12.2	6.00 ± .15	54.2 ± 2.1
133 (station 8)	95.0 ± 12.2	5.99 ± .19	53.0 ± 4.0
139 (station 9)	89.5 ± 13.5	5.82 ± .23	51.0 ± 3.3
176 (station 10)	102.1 ± 12.9	5.85 ± .16	50.8 ± 2.6
Overall mean	95.2 ± 6.7	5.82 ± .13	50.4 ± 2.4

Grassle and Maciolek, 1992 (Am. Nat. 139: 313-341)



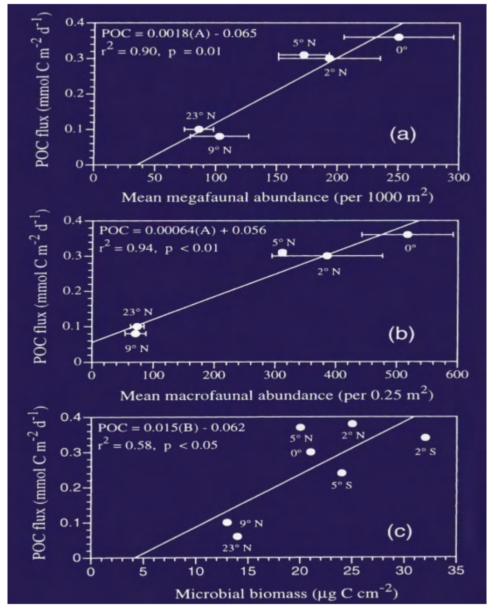
(From Glover, 2001)



Expected Species of macrofauna & meiofauna per 100 individuals, & species per 0.25 m^2 in deep-sea, soft-sediments.

Faunal Group	Site	Depth (m)	Species per 100 indiv.	Species 0.25 m^{-2}	Reference
MACROFAUNA					
	San Diego Trough (NE Pac)	1230	42	144	Jumars, 76; Jumars & Hessler, 76
	Santa Catalina Basin (NE Pac)	1240-1300	24-34	>70	Smith, 86; Kukert &Smith, 92
	North Carolina Slope	583-3015	15-63	~50-250	Blake &Grassle, 94
	NW Atlantic Slope	1800-2100	52	127	Grassle &Morse-Porteous, 87; Grassle &Maciolek, 92
	Rockall Trough (NE Atlantic)	2875		110	Gage, 79
	NW Atlantic Slope	3600	56	148	Grassle &Morse-Porteous, 87
	Central North Pacific	5500-5800	38	21	Hessler &Jumars, 74; Jumars &Hessler, 76
	Volcano 7 (Trop Pac)	770-1000	10	-	Levin et al., 94
	Fieberling Guyot (E Pac)	580-635	35-40	-	Levin et al., 94
MEIOFAUNA **					
Harpacticoids	San Diego Trough	1220	45-48	*	Thistle, 83
Harpacticoids	HEBBLE Area (NW Atlantic)	4626	43-51	?	Thistle, 83
Nematodes	San Diego, Rockall Troughs	200-2000	37-43***	?	Boucher &Lambshead, 95
Nematodes	Porcupine, Madeira, Hebble	2000-6000	35-39***	?	Boucher &Lambshead, 95
Nematodes	Puerto Rico Trench	> 6000	26-34***	?	Boucher &Lambshead, 95
Nematodes	Equatorial Pacific	4200-4800	43-52	?	Brown, 98
Foraminifera****	NE Atlantic Slope	1350	28-50	?	Gooday et al., 98

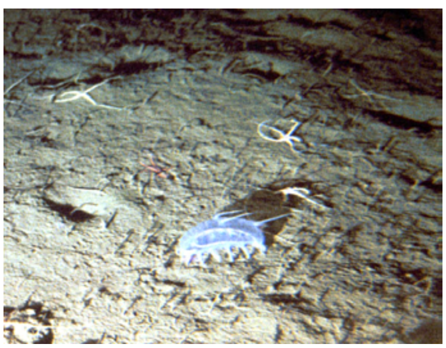
* Thistle (1978) collected 140 harpacticoid species in a total sample area of 0.14 m^2.
** Tietjen (1992) collected an average of 70.1 species of meiofaunal *nematodes* per 0.0060 m^2 at three abyssal stations (3520-5050 m) in the Venezuela Basin. Only one of the 136 total species was known to science!
***Based on only Expected Species for 91 individuals and may therefore underestimate by ~5%
****Includes macrofaunal and meiofaunal sized individuals



Characteristics of Deep Seafloor –

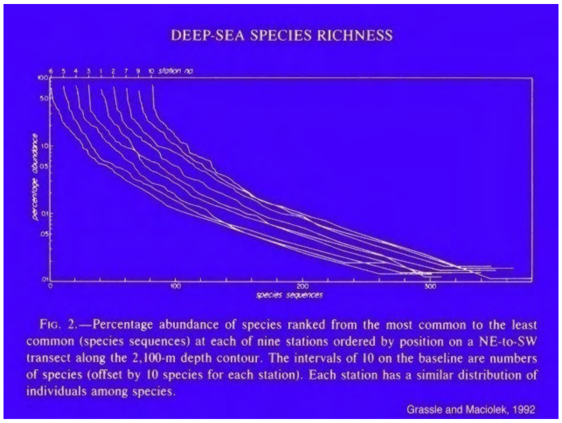
- Mostly sediment covered (~90%)
- Vast, largely continuous habitat (often 1000's km)
- Low temperature (<4°C)
- High hydrostatic pressure
- Physically very stable (most structure biogenic)

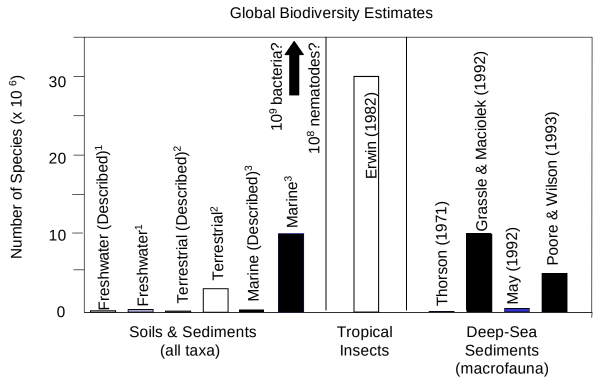
L. Levin



1240 m Northeast Pacific

4500 m Equatorial Pacific





Snelgrove & Smith

SUMMARY OF THE PRESENTATION

Dr. Smith said that he was going to speak about the ecological characteristics and current research activities related to biodiversity of the Abyssal Clarion-Clipperton Fracture Zone (CCFZ).

He said that he first wanted to give the general framework of the ecological characteristics of the CCFZ floor, that, what it was like, in terms of the biological systems. He said that it was unusual; that it was not included in most of the experiences that one had. He therefore believed it was important to put it in the ecological context. He then intended to tell participants about some of the University's studies on biodiversity and species ranges in the CCFZ, particularly on the Kaplan Project. Finally, Dr. Smith said he wanted to speak a little bit about what biology can do for the geological model and vice versa, what the model might do for our understanding of the biology.

In terms of some general ecological characteristics of the abyssal seafloor, Dr. Smith said that it was mostly – perhaps 90% - sediment covered. It was a vast largely continuous habitat; habitats typically ranged for thousands of kilometres; it was a very broad habitat. It was low in temperature, typically less than four degrees - around two degrees had been seen - and it had high hydrostatic pressure. He said that, incidentally, it was also physically very stable - one of the most stable ecosystems on earth, and much of the habitat structure was actually biogenic, formed by giant protozoans; one could describe those as shells of giant protozoans, tens of centimetres across.

Dr. Smith said that the abyssal seafloor of the CCFZ was thicker, with very low rates of productivity, biomass, population densities, growth rates, and recolonization rates. The reason all those biological rates and biomass parameters were, in general, very low, was that, because the ecosystem was what was called "food-limited." The food that was feeding the animals on the deep-sea floor was sinking from the euphotic zone; it decreased exponentially with depth. So by the time the sinking particle blocks of food arrived at the abyssal seafloor, it was very limited; perhaps a couple percent of euphotic zone productivity ultimately made it to the bottom of the ocean in the CCFZ. As a consequence, the abundance of life was very low. In terms of biomass, for example, macrofauna (the larger organisms); it was a biological desert.

In giving some examples of low rates that were of relevance to manganese nodule mining, Dr. Smith said that, if one looked at the CCFZ floor, there were biogenic mounds, things that were formed by animals living on the seafloor. A lot of faecal matter had been found in one spot. Those could grow at rates of a few centimetres per several days in some parts of the deep sea. And even though that kind of burial disturbance was common on scales of one of every hundred metres or so, it might still take the community years to recover from that burial disturbance, from being inundated by naturally deposited sediment. That was in some ways a physical analogy of what might happen for mining.

According to Dr. Smith, other evidence of slow rates came from some of the environmental impact studies of manganese nodule mining; simulations of what mining might do. For example, the Japanese had done a study - the JET experiment - in which they had redeposited seven millimetres of sediment on the seafloor. After two years, in their system, which was the area that they studied and that had undergone deposition, the megafauna were much less abundant in the depositional area, than in the non-depositional area.

Dr. Smith said that there had been a lot of studies similar to that one conducted by the Russians and by the Germans, and in general, the pattern was that recovery rates were quite slow; modest deposition led to recovery rates on time scales of years. So it was a system with low recolonization rates.

In addition, because of low benthic biomass, and available food levels, generation times of deep-sea fish and other animals in the deep-sea were very long. Dr. Smith referred to the story about the 'Orange Roughy' which was a commercially exploited species that people all over the world ate; it actually had a generation time of decades, 20, 30 years, and might even live over a hundred years. This was not atypical. There were others, mostly fish, with low growth rates and potentially slow recovery rates in the face of disturbance.

Dr. Smith said that another characteristic of the deep-sea biota was that most of the animals that lived there were very tiny, a few millimetres long, and were what we called surface deposit feeders. They were animals with tentacles that they put out on the surface of the seafloor, and picked up the recently deposited organic particles.

Yet another characteristic of the deep sea, according to Dr. Smith, was that there was extremely high local species diversity. If one took one square metre of deep-sea floor, you would frequently get in the order of 50 species per one hundred animals collected; or one square meter might have a hundred different species of surface deposit feeders all apparently doing the same thing – living in a tiny area of seafloor. Now this continued the ecological enigma; most of the ecosystems that had high diversity also had a very high habitat complexity. For example, the diversity of the deep-sea sediments rivalled that of a tropical rain forest or a coral reef, but the habitat diversity was much, much lower. The most diverse ecosystems on earth, except for the deep-sea sediments, tended to have a lot of structures and form; they also tended to have high productivity and high food resources. This was not true for the seafloor.

Dr. Smith said that there were a number of processes that seemed to combine to produce, to promote that high species diversity, and some of them were dependent on very large pools of species potentially in the system. That was just a list of a variety of processes, all of which appeared to be operating at the deep-sea floor.

Dr. Smith asked what then could be concluded, in terms of the general ecological characteristics of the deep-sea floor, and the CCFZ in particular. He said that they were primarily soft-sediment deep-sea communities that were easily disturbed and potentially very slow to recover from a variety of human impacts, including manganese nodule mining. However, it was also very vast in size. The area being discussed was the Abyssal North Pacific, but that habitat size might lead to very broad species ranges, meaning that species extinction from nodule mining in one or two areas was very unlikely, but not yet known.

Dr. Smith then focused specifically on macrofaunal diversity on the CCFZ floor and on how broadly species ranged. He said there was some evidence that on very large scales, the deep sea was very species rich. It turned out that most of the evidence all came from one study in the North Atlantic, where Grassle and Maciolek box employed about 230 box cores. What they had found was that as they moved along the Northeastern to Northwestern Atlantic Coast, they accumulated species; over a distance of 176 km, they had accumulated species at a rate of 1 species per kilometre. They had taken that curve and extrapolated it to get roughly ten million species in the bottom of the ocean. That was a gross extrapolation, but nonetheless, it was one of the few extrapolations ever done. Dr. Smith said that if one believed that extrapolation on deep sea as a reservoir for a significant percentage of all the species on earth that was graduated extrapolation. There were numbers of species extrapolated from a variety of other habitats. Tropical insects were estimated at about 30 million species.

According to Dr. Smith, one of the problems with the Grassle extrapolation was that it did not include the largest part of the deep-sea floor, which was the abyssal Pacific. If one looked at a picture of the world, one could see that most of the world was deep-sea floor. It made up a large percentage of the ocean floor, and a large percentage of the earth's surface. If one was going to do an extrapolation to calculate how many species there were in there, one needed to consider the abyssal Pacific.

He said that the abyssal Pacific also happened to include the CCFZ and areas for nodule mining. To predict the risks of species extinctions from mining, it would be extremely useful to know a couple of things, such as:

1. How many species were living within a particular area potentially impacted by mining;
2. Species ranges and scales of gene flow within the nodule provinces within the CCFZ, in particular, if one were able to answer the question: "Are species ranges greater or smaller than the potential area of mining impact?" If species ranges were large, then mining in one area was not likely to cause species extinctions. On the other hand, if their distribution ranges were restricted, then the risk of extinction was substantially higher.

Dr. Smith said that very little was known about species ranges and gene flows, and even diversity levels in the CCFZ. This was so because, first of all, the abyssal Pacific was very poorly sampled; although it was a vast region, there were only eight sites from which people had collected box core samples and actually were sampling the sediment biota and actually distinguished all the different species in the samples. This was a subtotal of the world dataset, in which something was known about the diversity in the abyssal Pacific. That did not comprise very many data points for a region that was large. Thus, it was very poorly sampled.

In terms of numbers of sites, Dr. Smith said that it was often relatively poorly sampled at each site. In other words, each site was far from fully sampled. If one took the best sampled site, which was Dome site A, and looked at how species were accumulating as a function of area sampled, one would see that as areas sampled were added, species continued to be added. If that system were fully sampled¸ the curve would eventually flatten out; more and more species would be taken and there wouldn't be any more new species. But even in the best-studied area, the accumulation of species continued. The bottom line was that there were few points that had been sampled in the abyssal Pacific, and each site was still relatively poorly characterized. Dr. Smith indicated another curve showing essentially the same thing, that is, the number of species, versus the number of individuals collected, and again, the slopes continued upward and there was a lot of diversity in the system.

With regard to what could be said about species ranges from the dataset being discussed, Dr. Smith said that the diagram had come from two different datasets. The upper panel showed percent of species at each site that were ubiquitous (meaning they occurred at all three stations), widespread (they occurred at two stations) or unique (they occurred at only one of the three stations).

Dr. Smith said that if one looked at the percentage of species at each site, one would see that something like 30-40% appeared to be ubiquitous, and one would infer that they were widely distributed. That meant that about 60% did not occur at all the stations, and that kind of data would suggest that species distributions were, in fact, relatively narrow. They were not distributed across the whole CCFZ. Nevertheless, he said, one had to be careful, in terms of that, because the sites were still relatively poorly sampled. Probably only the most abundant species had been sampled very well. That was one interpretation. It could be that many of the species were widely distributed, but had been so poorly sampled that we had not collected them at all the sites where they occurred.

According to Dr. Smith, another reason that so little was known of species ranges and gene flows in the Pacific was because of poor description of the fauna. Approximately 90 per cent of all the animals that were brought back in samples from the Pacific were new to science. They had never been described by a taxonomist. So a lot of difficulty was experienced in comparing different samples.

Another problem was that there had been very little intercalibration. There had only been eight sites studied in which the species structure had been well documented in the macrofauna. But those had been studied by two different groups, namely the American scientists and the Natural History Museum of London. They had never been intercalibrated. Therefore, one could not compare the list of species from the transect with the data points, and this needed to be done in order to explore the total range of the species living within the region.

Dr. Smith said that a third problem with identifying species ranged in the abyssal Pacific was that most of the species description, the taxonomy, how you distinguish species, was based on morphological characteristics. in other words, the physical characteristics, the shapes of the species. One looked at them under a microscope, and counted how many setae they had, how many segments, etc. He said that morphologically-based taxonomy appeared to be very conservative. It was not possible to resolve or distinguish all the species. Recent DNA-based techniques, in which people extracted the DNA from animals and looked at the genetic sequence, suggested that there were many cryptic species, many species that looked the same, but were actually different. He gave an example of one of the most common species, the polychaete worm, based on morphology; it was called *Chaetozone setosa* and was one of the most abundant species in the CCFZ and the California Slope; it was also common in intertidal habitats in the Northeast of the United States of America and was originally described in Europe, Norway and the Mediterranean. It was probably not the same species living in all these habitats; it just looked very similar. Thus, it was really necessary to apply DNA techniques to the seafloor animals in order to really distinguish them.

In summary, Dr. Smith said that the major gaps in knowledge concerning macrofaunal diversity in CCFZ resulted from:

1. Undersampling: Substantially more samples needed to be collected across the region to resolve presence and absence of particularly rarer species;
2. Lack of intercalibration (and species descriptions): cross-referencing of taxonomic collections was needed in order to resolve species ranges and additional scientific descriptions of the fauna;
3. Lack of molecular (DNA-based) data: needed to resolve cryptic species and elucidate patterns of gene flow.

Dr. Smith then referred to the Kaplan Project, which he said everyone had been waiting to hear about. He said it was a study designed to begin to resolve a number of the issues in the Clarion-Clipperton Fracture Zone. In particular, it was designed to study biodiversity, species ranges, and gene flow in the abyssal Pacific nodule province, with specific reference to predicting and managing the impacts of deep seabed mining. It involved a broad cast of characters, investigators from a variety of different countries, including the Natural History Museum of London, Alex Rogers, British Antarctic Survey; Andy Gooday, the National Oceanography Centre in Southampton, Dr. Hiroshi Katazato, Japan, Myriam Sibuet, France, and Karsten Zengler, San Diego.

The problem

Dr. Smith stressed that deep-sea sediments might be major reservoirs of biodiversity, but regional species richness and species ranges were very poorly known.

With regard to nodule mining, he said that seven contractors were currently licensed by the International Seabed Authority to explore nodule resources and to test mining techniques in claim areas, each covering 75,000 square kilometres (an area half the size of Florida). When mining began, each operation was projected to directly disrupt quite a large area, approximately 300 - 800 square kilometres of seafloor per year, and to disturb seafloor biota over an area two to five times greater, due to sediment redeposition. He said that some relatively reasonable calculations had found that two over a 15-year period, two to three nodule mining operations might severely damage the abyssal seafloor area up to half the size of Germany. He said he had picked Germany because it was an area where everyone could identify the scale; so potentially large areas would be impacted by mining.

Dr. Smith said that it was very difficult to evaluate the threat of nodule mining to biodiversity (in particular, the likelihood of species extinctions) without estimates of the following:

1. The number of species residing within areas potentially perturbed by single mining operations, and
2. The typical geographic ranges of species (and rates of gene flow) within the general nodule province.

So, the Kaplan Project, with funding from other sources, including the International Seabed Authority, aimed to:

1. Estimate, using, molecular methods and rigorous statistical techniques, the number of polychaete, nematode and foraminiferal species at three stations spaced at 1,500-km intervals across the Pacific nodule province;
2. Evaluate, using state-of-the-art molecular and morphological techniques, species overlap and rates of gene flow across this whole zone;
3. Broadly communicate the findings to the scientific and mining-management communities, particularly the International Seabed Authority, and make specific recommendations to it on minimizing the risks to biodiversity resulting from mining.

Dr. Smith said that, in addition to sampling the three main groups that he mentioned, the University would also be exploring patterns of diversity within sediment microbial assemblages across the nodule province, using DNA sequencing approaches.

In brief, they would sample with box cores and multiple cores using “DNA-friendly” techniques. Those had not been applied in the deep sea and abyssal Pacific before. The plan was to sample at three different sites, 1,500 kilometres apart, on the eastern, central and western parts of the CCFZ; the goal was to sample across the whole width of the CCZ and to look at species turnover upon moving from each of the stations. It was hoped on the order of 14 to 20 box cores would be collected from macrofauna, and 6 to 10 multiple cores for meiofauna and microflora; some other techniques, such as like epibenthic sleds, dredging, crawling, and even submersibles, might be used for more mobile macrofauna.

With regard to how samples were collected, Dr. Smith said that DNA was very sensitive to warmth. Thus, once brought up, samples were immediately placed in cold water and washed with chilled seawater to avoid damage to the DNA. Parallel samples of macrofauna and meiofauna were also being collected from each station and fixed in formaldehyde to allow for comparisons of morphological techniques versus DNA-based techniques.

Dr. Smith informed the participants that the first cruise had just been completed aboard *RV New Horizon (*4 Feb–7 Mar 2003). Eastern stations had been sampled and 8 multiple cores and 14 box cores had been collected. The samples were being processed and sorted to see what can be made of DNA analyses. Additional sampling of central and western stations was planned for February and the summer. Furthermore, Dr. Smith said that there would hopefully be additional sampling in collaboration with the Korean and Chinese programmes in the CCFZ.

Although he did not go into detail, Dr. Smith mentioned that there were laboratory analyses and traineeships involved in the project, including working with the samples at the University of Hawaii. He said the taxonomy would be done at the Natural History Museum; there would be foraminiferan studies conducted at the National Oceanography Centre in Southampton; and finally, molecular genetic analyses done at the British Antarctic Survey, and in San Diego. He added that there were possibilities of traineeships on molecular techniques and field and sorting techniques at a variety of those institutions. In terms of communication, Dr. Smith said that the results would be released to the general scientific community and to the Authority. The plan was to produce a webpage and to present the findings at international scientific meetings. The intention was also to provide direct input advice to the International Seabed Authority on the relevance of the area to the management of mining.

Dr. Smith said there were additional potential collaborations with the Kaplan Project, namely with the Megafauna component which he said he believed was getting under way with Gerd Schriever from Germany. He said that one of his goals was not dissimilar to those proposed for the geological modeling project. He said that he wanted to use the vast collection from pioneer investors and others that had been working in the CCFZ to evaluate the distribution and diversity of megafauna, because megafauna were relatively difficult to sample and were observable in photographs, so that would be very useful. Dr. Smith said there were other major faunal groups that were not being addressed in the Kaplan Project that it would be interesting to address, and said that collaboration was being pursued. Finally, there would be a workshop held in Oregon in August to discuss what kinds of international collaboration would be useful for understanding biodiversity patterns in the deep sea. The workshop would be sponsored by the CoML and Dr. Smith would be present to talk about the Kaplan Project.

Dr. Smith said he had been asked to speak about water column research, and although he was not going to say much about it, he wanted to point out that there were a number of projects under way in which different groups were studying water column processes. Some of them, including COMRA, he said were collaborating with the University of Hawaii on the Kaplan Project. The COMRA "Natural Variability of Baseline" or NaVaBa programme was working in the Chinese claim area and the University hoped to coordinate with them in their cruise plans from 2003 to 2007, possibly as soon as 2002. In addition, KORDI was conducting a variety of baseline studies from the surface to the bottom of the ocean, and they had cruises planned throughout the next six or seven years, and the University hoped to coordinate with them as well. Their study area was in the Central portion.

Noting that participants had attended the workshop for the purpose of discussing geological models, Dr. Smith said he would speak a little bit about the geological model from a biological perspective.

Commenting that the first thing that might be asked was what benthic biologists could do for the geological modeling effort, Dr. Smith said they might be able to do a few things and that maybe he would have more ideas as the discussion groups progressed. He said that one thought that had occurred to him was that he believed there was some thinking that primary production from ocean colour data might be a useful proxy for nodule abundance or quality. He said that he would suggest that what one really wanted was export production. He explained that what was really affecting the nodules on the seafloor was the flux of carbon from the photic zone to the seafloor; so one really wanted to know the export production, or how much organic carbon was sinking to the seafloor. And because deep-sea benthos were food-limited, as he had pointed out in the beginning of the talk, the biomass and abundance of benthos was often a very good indicator of how much export production was reaching the bottom of the ocean. Animals living on a specific part of the seafloor actually integrated the export flux from an area of the surface ocean of thousands of kilometres, on time scales of months to years, depending on the life span of the animal. Dr. Smith said that recent data existed to bear out what he was saying. If one looked at, for example, the mean abundance of macrofauna on the seafloor, versus POC flux export production, one would see an excellent correlation of 0.94. [2] A number of other data points had actually been put in; the correlation was equally good; more than 90% of the variance in export flux could be explained by the abundance of animals at the sea floor.

Asked how this might help with the geological modeling efforts, Dr. Smith said that, although biomass data from all over the bottom of the Pacific was not available, the benthic standing crop could help to ground truth the productivity (i.e., export flux) versus nodule abundance and quality relationship in the CCFZ geological model. He said that based on the earlier presentations and discussions for example, one might think that there was some functionality between the flux of carbon from the surface ocean and the abundance and quality of nodules. He continued that the animal abundance might actually allow this to be tested, because it was actually a sensitive measure of how much flux was reaching the seafloor. In this regard he said that if one measured the abundance of animals at a given location, and then looked at the quality of nodules at that site, it might provide insights into the relationship between productivity and nodule quality/abundance.

[2] POC – Particulate organic carbon

On the question of what the geological model could do for seafloor biologists, Dr. Smith said that there were a variety of "key habitat variables" that controlled or at least were correlated with the distributions of species and the community structure at the abyssal seafloor. Some of them might be predicted from the geological model, and would be useful for interpreting the biogeography of the CCFZ, from the animals' perspective.

Dr. Smith said that important parameters included:

- Substratum type: presence and abundance of nodules and other hard substrata. In the CCFZ, different animals lived on hard substrates, particularly nodules, and lived on the seafloor, and by knowing how many nodules there were on the site, their abundance, could reveal something about the community that lived there. It was also useful from an ecological perspective to know the sediment type, particularly grain size, percent organic carbon. If those were to come out of the geological model, that would be useful;
- Flow regime: mean and maximum near-bottom current velocities and also the frequency of sediment transport events; how often the sediments were picked up off the bottom and transported. That would also be relevant to the amount of nodules on the seafloor;
- Bottom topography: how much vertical relief there was - slopes - at the bottom, were relevant to current intensification on the seafloor. In addition, the frequency of slumping events, for example, deep-sea landslides, that may affect the biology;
- Bottom-water O_2: oxygen penetration into sediments and the nature of the community on the sediments;
- Sinking POC flux: very important in controlling the abundance and species structure on the EZ floor; and annual rate and variability.

Dr. Smith said that he believed that the top three variables might come out of the model and were the ones that he thought would be useful to interpretive biology.

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CHAPTER 17 POLYMETALLIC NODULES RESOURCE EVALUATION IN THE CENTRAL INDIAN BASIN

Vijay Kodagali, National Institute of Oceanography, Dona Paula, Goa, India

Introduction

India ventured into its deep-sea minerals exploration programme in 1981 when the first batch of nodules was collected from the abyssal depths in the Indian Ocean. A massive programme was chalked out as a follow-up to this maiden attempt, identifying the Central Indian Ocean Basin (CIB) as the target basin for the exploration for polymetallic nodules. The National Institute of Oceanography in Goa was entrusted with the responsibility as lead agency for executing the survey and exploration work. Having selected the Central Indian Ocean Basin, an area of about 4.2 million km^2 was surveyed in detail for all the parameters that lead to delineation of areas of potential economic interest. A systematic grid wise sampling, along with single beam echo sounding, was the first task under this programme. The data collected in the first phase thus became the basis for two areas of potential nodule deposits on which India formulated its application to the Preparatory Commission (PrepCom) for the International Seabed Authority (ISA) and International Tribunal for the Law of the Sea for the granting of the pioneer area. The application consisted of two areas of 150,000 km^2 each with comparable polymetallic nodule grade and abundances and topography. As per the stipulations laid down in resolution II of Part III of the United Nations Convention on the Law of the Sea on 17 August 1987 a historic decision was taken by the PrepCom of the International Tribunal for the Law of Sea to allocate to India exclusive rights to carry out pioneer activities, including exploration of polymetallic nodules in an area of 150,000 km^2 in the Indian Ocean. India thus became the first country to receive such an honour. The application area allotted to India is shown in *Figure 1*.

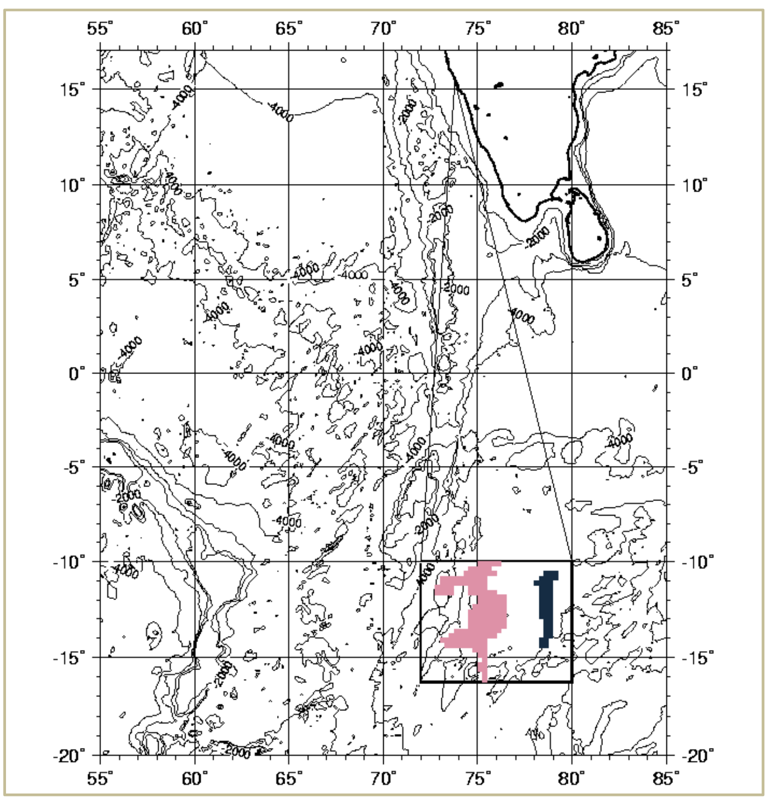


Figure-1: Pioneer Area allocated to India in the Central Indian Basin.

During the period from 1981 to 2003, huge amounts of data have been collected in the Central Indian Basin. The polymetallic nodule sampling was mainly carried out using free fall grabs. Initially, the entire basin was sampled at a grid spacing of 1°. The grid spacing was gradually reduced to 0.5°, then to 0.25° and finally to 0.125°. At each station, five to seven free fall grabs were operated in a square or hexagonal pattern and one or two of the grabs carried the camera (photo-free fall grabs). The photo abundance data has been used to compare with the ground truth. In addition, deep-tow photography/video photography was carried out in parts of the pioneer area, collecting over 52,000 shots. For the first phase of the surveys, the dual satellite navigator was used for the position fixing and for the 0.125° spaced sampling, the Global Positioning System was employed. The resource evaluation was carried out initially at 0.25° (total 201 blocks) block size, but after the entire area was sampled at 0.125°, the block size for estimation of resources was also reduced to 0.125°. There are 804 blocks of 0.125° size in the pioneer area. Recently, 40 blocks have been sampled at 0.0625° spacing using the Okean grab sampler. It is observed that, the nodule abundance from the Okean grab sampler is generally higher than that obtained from the free fall grabs. There is an increase of about 140% generally of the abundances. This is because of the different nature of the Okean grab sampler, which collects both nodules and sediments from the station, in contrast to the free fall grab, which collects only the nodules. The area of occupation of Okean grabs is larger than that of the free fall grabs. The mechanical failure rate of Okean grabs is less compared to the free fall grabs. Fortunately, the latter's abundance is under estimation.

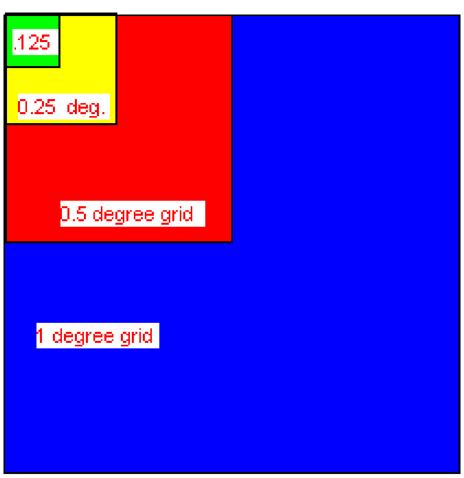
Sampling strategy

Stage A:	sampled the entire area at 1 degree interval (~111km)
Stage B:	sampled the area at 0.5 degree interval (~55.5km)
	This data was used for identifying pioneer area-application to ISA
Stage C:	sampled the pioneer area at 0.25 degree interval
	(~27.75 km) 201 blocks
	Relinquishment- first phase 20%
Stage D:	sampled the pioneer area at 0.125 degree interval
	(~13.875 km) 804 blocks
	Relinquishment-second phase 10%
Stage E:	detailed sampling in 40 selected blocks at 0.0625
	Degree interval- (~6.9375 km)

Figure 2: Sampling strategy.

Abundance data

The station data was reduced to station wise values, by the arithmetic average method. All the samplers deployed at each station were averaged for their abundance and coordinates to arrive at values of station abundance and station location, respectively.



Chemical data

The chemical data was reduced to sample-wise chemical parameters, based on their replicate analyses. The sample-wise values were further scaled to station-wise chemical values, based on the available sample-wise chemical data at a station. Such computations were based on the arithmetic average method. The raw chemical data was also subjected to weighted average methods and the resultant data used for variographic modelling and block-wise kriged estimations of metal values.

Bathymetric and nodule distribution

The entire pioneer area has been mapped using the Multibeam swath bathymetry system, Hydrosweep. As seafloor topography is one important factor in delineating a mine site, all morphological factors were considered while reducing the multibeam data to block-wise data. The original dataset included over 31 million data points in an area of 300,000 km^2. The resultant depth grid from this dataset was used to generate depth contour maps and also, a program was developed to convert the depth data into slope angle (gradient) grids. The number of contours occurring in the north-south and east-west directions and areas of seamounts average slope angles for the area, were all calculated for each block. The pioneer area mapped using the multibeam swath bathymetry system has brought to light over 150 seamounts and hills hitherto not reported from the regions.

Bathymetry is one important factor in controlling the nodule distribution. Both the local and the regional topography control the distribution of polymetallic nodules. Topographic domains such as hills, slopes and valleys, have higher abundance and the plain areas have distinctly less abundance. The higher the relief, the higher the abundance will be. However, it is observed that the distribution is more regular in the case of plain regions; whereas distribution is sporadic in the areas with high nodule abundance, nodule abundance varies over short distances in the high relief regions and distribution is uniform in the lower relief regions. The high abundance areas generally report higher cobalt values, compared to the low abundance areas. However, there is an inverse relationship between the nodule abundance and grade.

Block-wise estimations

The pioneer area was divided into various blocks for estimating the variables. A unit size of 7.5' x 7.5' (0.125° blocks) was selected. That block size selection was entirely based on the exploration grid sampling available in the area, and the database supports such a unit block selection. Only a small part of the area has been sampled at 3.75^{o} spacing.

The total pioneer area occurs in two split segments named P1 and P2. There are a total of 804 blocks of 0.125^{o} X 0.125^{o} unit size. Two basic models have been used for the present study, namely, block-wise kriged estimates and block-wise arithmetic mean estimates.

Before proceedings with the block-wise estimation, using the available station-wise mean values on abundance, experimental variograms were computed in different directions.

Unlike abundance, the station-wise metal values were not considered directly, as they are linked with respective abundance values for the block. Total metal values were treated by weighted averaging scheme. Metal accumulations for Mn, Ni, Co, Cu and for grade were calculated for each block using the formula

Metal Accumulation= abundance X % of the metal.

Block-wise kriged estimates

Experimental semi-variograms for abundance as well as grade accumulations were computed. An optimal estimation technique called "kriging" was used to estimate block-wise abundance, grade and individual metal percentages. The kriged estimator was defined as:

$Z_k = \Sigma a_i Z(x_i)$; where,

$Z(x_i) =$ experimental value at location x_i

$a_i =$ weights given to $Z(x_i)$

The weights a_i were computed such that the kriged estimator Zk (i) is unbiased, and (ii) has minimum error of variance. These block-wise values were further categorized at various cut-off levels and the distribution of these categorized blocks in the pioneer area.

Block-wise arithmetic estimates

Before generating the block-wise arithmetic estimates of various parameters, some basic statistical information was obtained by closely scrutinizing the station-wise mean values. The initial scrutiny included frequency distributions, regression and correlation analysis. The estimation accuracy of a given parameter (e.g. abundance or grade) mostly depends on the number of sampling points or the quantum of sampling carried out in each block. Based on the station-wise mean values of various parameters, block-wise arithmetic estimates were generated. Arithmetic estimates for each of the 804 blocks of the pioneer area were recalculated for the present exercise, averaging the station values within the block and also 1.5 km surrounding the block boundaries. This was done to accommodate station data, which fell just outside the block boundaries, and still influenced the average values for the block. The block-wise arithmetic values were also categorized at various cut-off levels and the distribution of these categorized blocks in the pioneer area for each variable has been compared with block-wise kriged estimates.

The following points were observed from block-wise kriged estimates:

- Areas where high abundances and lower grades often ascribe higher weightage
- Strong negative relationship between abundance and grade
- The metal accumulations exhibit no difference for both high abundance-low grade nodules and low abundance and high-grade nodules.
- Metal variables remain homogenous over large distances in spatial distribution, compared to abundance, which exhibits wide variations over small distances.

Comparison of block-wise estimates

The results of these two techniques - kriged and arithmetic estimates reflect the difference, and these two sets of values are expected to represent a two-boundary scenario for any selection of blocks based on present information. However, the kriged values are relatively lower when compared to the arithmetic values, which may be largely attributed to the smoothening process involved in kriging.

The block-wise kriged values show some distinct differences, as compared either to block-wise arithmetic means or contour values. In particular, it was observed that

- The blocks showing very high arithmetic means have lower kriged values
- The blocks showing very low arithmetic means have higher kriged values.

However, globally, that is, over the entire pioneer area, the mean picture for block-wise kriged values and block-wise arithmetic values matches closely. That mean picture emerged because of the broad categorization/cut-off classification adopted in the computation process. That observation once again suggests that the entire pioneer area is statistically homogenous with respect to all the variables studied. The above-mentioned observations are of high practical importance if the selection has to be based on small blocks. Further, the results obtained mostly depended on the methodology used. The arithmetic estimation depends entirely on local values. In the kriging procedure, in contrast, the weights of the local values are assigned depending on the variographic structure. It is due to the optimizing conditions, that block-wise kriged values have greater reliability than the classical arithmetic estimators or any other similar estimators.

Resources

A resource evaluation was carried out for the pioneer area and for individual segments P1 and P2. The larger segment P1 is found to be superior in terms of available in situ resources. The nodule tonnage calculations were based on wet nodule recovery and dry nodule computations (20% average water content has been assumed), whereas the metal tonnages were computed on a percent dry weight basis. The resource calculations were based on the average abundance and metal percentages for the individual segments. The FORTRAN program was written to calculate resources (dry tons of available nodules, total metal, and individual metal tonnages) in individual blocks and was not based on average abundance for the segment.

Model for relative ranking of blocks

Each of these 804 blocks was estimated for nodule abundance (quantity) and nodule grade (quality), as described in previous sections. Besides, detailed bathymetry of the seafloor was generated using the multibeam echosounder and thus, each of the blocks also contained information on the nature of topography derived from the seabed contours.

For the purpose of economic evaluations and determination of mineable blocks, it is necessary to rank the blocks in terms of relative superiority in respect of mineability as well as commercial potential. It was therefore attempted to develop a model considering the assemblage of all relevant factors that will provide the desired decision tool for relative ranking of blocks. This model was useful in selecting inferior blocks for the relinquishment area

Factors influencing ranking

The commercial potential or value of a given block is influenced by nodule abundance, nodule quality and seabed topography.

In order to develop a suitable model, it was felt necessary to assign relative weights to the three major influencing factors. Seabed topography was considered the most important factor since it determine technical feasibility of mining. Further, the block-wise topography was much more accurately derived from swath mapping systems than other parameters.

Elements of the model

The following criteria was used for selecting areas/blocks for ranking purposes:

Topography
Abundance
Grade (Co+Ni+Cu)

The variable "topography" was further split into following parameters:

Number of contours in 0.125^{o} square blocks excluding seamounts
Area of seamount(s)
Average block gradients

Thus, each block of 0.125^{o} size was evaluated against the above five parameters (three relating to topography and one each to abundance and grade). Each block was rated with respect to each of the above five parameters. Each parameter in a block was rated from -2 to +2 through zero, depending on the distribution of parameter values. Further, the following weights were assigned to each of the five parameters. The split of weightage for each parameter is as under.

Parameter	Weightage
No. of contours	100 for NS and 100 for EW contours in each block.
Area of seamount(s)	100
Local gradients	100
Abundance	300
Grade	300
Total Weightage	1 000

With the above weighing scheme and block-wise ratings for the five parameters, the Nett Score for each block was computed as,

$$\text{Net Score} = \sum_{i=1}^{5} W_i r_i$$

W_i, the weight assigned to the parameter r_i.

Based on the nett scores computed as described above, all the blocks were listed in the descending order of nett scores. This data can be used for identifying the first generation mine sites and also for identifying worse blocks in terms of mineabliity.

Conclusions

- Block wise parameter estimations were done using arithmetic mean and kriging.
- On a regional scale, the methods are comparable.
- A method for relative ranking of the blocks has been developed.
- Sampling methods must be chosen carefully; there are different methods for different geological settings.
- Abundance varies over short distances, whereas grade is constant over long stretches.
- Topography plays an important role in nodule distribution, at both regional and local scales. The higher the relief, the higher the nodule abundance.
- Plains have lower but more evenly distributed nodule abundances.
- Photo data and the ground truth show no good correlation.

Acknowledgements

This report is based on the work carried out under the project for the past 20 years. The contribution of all scientists, technicians working on the project is acknowledged. The significant contribution from Dr. M Sudhakar of the National Centre of Antarctic and Ocean Research, Vasco-da-gama, and from Mr. S. K. Das, Adviser, Department of Ocean Development, New Delhi, is heartily acknowledged. Dr. E. Desa, director, NIO is thanked for the encouragement and guidance. This work was funded by the Department of Ocean Development, Government of India.

SUMARY OF THE PRESENTATION

Dr. Kodagali said he had listened to the last six presentations and had heard several comparisons. There were several things that did not compare well with what had been tested, but the method that his project had used for resource evaluation could be common to the Central Indian Basin and to the Clarion-Clipperton Zone.

He showed the generalized bathymetry of the Indian Ocean and the pioneer area allocated to India in the Central Indian Basin, which was about 10^{o} South latitude. He said the pioneer area was 2,700 miles from Goa and was the best port for observations. He indicated the two blocks that had been the focus of concentration, explaining that one was about 150,000 km and had been allotted to India and that, after relinquishing 50% of the area, they had been left with 75,000 sq km. He pointed out a red block, which was the reserved area, and a black block, which was the one allotted to India.

In showing participants the quantum of data collected in the Indian Ocean, Dr. Kodagali said that a total of 4 million sq. km. had been surveyed. Several grabs had been used: the free fall grab, the Okean grab and the Van Veen grab. Some 2,500 stations had been sampled with 5 to 7 free fall grabs in each station; for each station there were two photographs. In addition, there was deep-tow photography, totalling nodule samples in a 12.5 km grid, covering over 10,000 operations. Sediment cores had also been collected from over 250 locations.

Dr. Kodagali said he had divided the data for his presentation into three portions. The first was on the source evaluation; the second on the ranking of the blocks, because that exercise would be used to identify the blocks that were not good, and from that a system would have to be devised to identify the blocks that were not going to be economical. That had some relevance to the source evaluation, so would be the second part. The third part, he said, would touch on the effect of using two different samplers in the area and how that had affected their calibrations.

Dr. Kodagali said that ten thousand operations had been carried out using free fall grab and about seven ships had been used with over 60 cruises undertaken, resulting in over 2,400 ship days spent in the area.

The equipment was owned by the Department of Ocean Development and was used almost exclusively for the program. In showing the sampling stations, indicating the two areas that had been entirely sampled at 12.5 km grid; Dr. Kodagali said that some blocks had also been sampled at 6.25 km grid; and pointed to where continuous photography had been done with over 2,500 samples taken in that area.

Dr. Kodagali recalled that, with all the other sampling stations, there was enough photographic data in the entire region. The sampling strategy had been to start with 1^{o} grid and go down to half a degree. Finally after completion of the .125^{o} grid interval, the entire region had been divided into the grid size being indicated because that was the minimal sampling size that was available in that region. In the other region that he indicated, Dr. Kodagali said that 40 sampling stations had been selected at 6 km intervals. So for some blocks, sampling was at 6 km intervals.

Indicating the two main sites, Dr. Kodagali said that the five to seven free fall grabs had been averaged arithmetically, including their coordinates, so that there had been one value for each station. Similarly for the chemical data, in order to avoid problems with the second system used, samples had been sent to three different labs, and the average of the respective analyses used.

In terms of the bathymetric data, Dr. Kodagali said that initially they had used the survey, which had been completed in 1985 and 1987, and then the new Multibeam system had been installed and used to map the entire region. The original dataset included over 31 million data points in an area of 300,000 sq km. The resultant depth grid from that dataset had been used to generate depth contour maps and a program had been developed to convert the depth data into slope angle (gradient) grids. The numbers of contours occurring in the north-south, east-west directions, areas of seamounts, and also the slope angles for the area, had all been calculated for each block.

In posing the question on how to quantify that measurement, Dr. Kodagali said it was a reflection of the roughness of the seafloor; the higher the number of the contours, the higher the seafloor. He said it had been found that the nodule abundance was higher in the areas of high relief and less in the plains. The nodule distribution was patchy in high relief areas and regular in plains. The topography was a key factor in whether the area was going to be mineable or not.

Dr. Kodagali said that for resource evaluation nodule abundance, there was the arithmetic mean of all free fall grabs abundance data and the block-wise estimation of nodule abundance, because each block had four to six stations. For all parameters there were arithmetic average estimates, which were then kriged for each block.

Dr. Kodagali said that the “Kriging” method had been used as one statistical method. It may have some reservations, but he believed it to be the best method to use.

The following points had been found:

- The areas with higher abundances and lower grade often ascribed higher weightage;
- There was a strong negative relationship between abundance and grade, which was also true in several areas.

Dr. Kodagali said that the metal accumulations exhibited no difference for both high abundance-low grade nodules and high–grade nodules, and metal variables remained homogenous over large distances in spatial distribution, compared to abundance, which exhibited wide variations over small distances.

He said that for the resource calculation for each block, the total areas of the block had been calculated; the area of the seamounts, hills etc. had been subtracted. It was not going to be mineable. The 20% moisture content had also been removed. The dry nodule abundance and the resources for nodules had been calculated, as well as each metal, total metal and metal accumulation.

Dr. Kodagali displayed a map showing the contours of abundance and said that it was from the total metal content of nickel, copper and cobalt. He then displayed a depth contour map, which had been generated from single beam echo-sounding data and produced in 1985. He said he would use the data from the Hydrosweep system installed on Sagarkanya in 1990, which in two years had mapped the entire region.

Next, Dr. Kodagali displayed a tectonic map of the Central Indian Basin which showed the 79-degree fracture zone. He said it had first been reported in 1992 and that, using the Multibeam data, it was possible to report over 250 seamounts in the area. He said that it was also known that the seamounts were clustered in the central region

He said that the data had been used to identify the areas of lesser importance, because it had been necessary to relinquish an area of 50%.

Dr. Kodagali said that for the relative ranking of the blocks, minable blocks had been used and the blocks ranked in terms of relative superiority in respect of mineability, as well as commercial potential.

He explained that the commercial potential of a given block was influenced by nodule abundance, nodule quality and seabed topography all of which were really important factors. Topography was further divided into parameters: the number of contours in the east-west and north-south directions, the area of seamounts and the average gradient of the block.

Dr. Kodagali said there were five parameters, three of which were for topography, followed by abundance and grade. Each block had been rated with respect to each of the five parameters and each parameter in a block had been rated from –2 to +2 through zero, depending on the distribution of parameter values.

The number of contours had been given a rating of 100 for north-south and 100 for east-west contours in each block. The area of seamounts had been given a rating of 100, local gradients given 100, 300 for abundance and 300 for grade.

Dr. Kodagali said that, for the nett score for abundance for each block, the values had been assigned in ascending order, so that the best blocks were selected, and the worst blocks relinquished.

Dr. Kodagali then spoke about what would happen if different samplers were used. He said that most of the previous speakers had talked about free fall grabs and the majority of samples had been taken using that type of grab. For 40 blocks, a different sampler had been used. Marginal blocks with kriged abundance in the 3 to 5 range had been selected. Blocks spread from north to south to avoid latitudinal clustering and there were four blocks that had some seamounts in them.

Those were the blocks proposed for Okean sampling (the sampling process using the Okean grab). As opposed to the free fall grab, that system could also provide the sediment along with the nodules. Dr. Kodagali said that when the Okean grab had been used in 40 blocks, and the abundance had risen 17 kg/square miles. For 19 blocks, the average abundance had been reduced, but in 20 blocks, the abundance had increased from 100 to 930%, and the average increase had been 132%.

Dr. Kodagali said that the results meant that there had been an increase in abundance. Lower abundance values had also been observed but the abundance had not increased much. However, when the abundance was high, when a different sampler had been used, the abundance had increased too much. When the abundance was 5 using free fall grabs, it had increased to 17 in some cases in those 20 blocks. The relation had been less in 19 blocks, but most of the change had been in the range of 90 to 98% only, compared to the free fall grabs. In the 20 blocks, the abundance had increased drastically. Therefore, if one took under 40 blocks, there would be an increase in abundance of over 130%. Fortunately, all the calculations of resources had been based on the free fall grabs.

Dr. Kodagali said that, based on the data that had been gotten from the Okean grabs, it could be concluded that their estimates were on the lower side, so there may be more nodules; however, they were reporting that there were less nodules, because of the samplers used. He believed that there were several ways to explain why the nodule abundance from the Okean grabs were much higher than with the free fall grabs. It also happened that when the Okean grabs did not pick up any nodules that had been recorded as no data, whereas with the free fall grabs, it was not known, because the free fall grab got all the nodules. Dr. Kodagali explained further that it was not known whether the grab had closed before or after reaching the bottom, so it was taken as data and ascribed a zero, whereas with the Okean grab, one knew that if it touched the bottom it would have had to at least been in the sediment. This was not the case for free fall grabs.

Dr. Kodagali said that the values of the free fall grabs were much lower than that of the Okean grabs but that obviously, it was not possible to go and sample the entire region again with another sampler. He added that it had been seen that the Okean grab also provided photographic information before taking the shot of the region. It had been seen that there was not much correlation between the data seen in the photographs and the actual samples which was also the case for free fall data. The correlation was not so striking. The photographic data could be used independently and actual sampling data gotten. The photographic data had certain limitations, as did the samplers. This had to be borne in mind when doing the calculations.

With regard to total metal, Dr. Kodagali said there was not much variation with free fall or Okean grabs. In fact, there was not much variation at all, which was quite expected. It could be said that the chemical analysis was the same.

Indicating a figure, Dr. Kodagali said that the *in situ* resources of the pioneer area were listed therein and that that was the data that they had started with. They now had half of that area, and the resources that they now had were more than half of what was shown in the figure. He said there were now about 9 million metric tonnes of metals in the 50,000 sq km, which was about 75% of what was available.

Conclusions

Dr. Kodagali ended his presentation with the following conclusions:

- Block-wise parameter estimations had been done using arithmetic mean and kriging. On a regional scale, the methods were comparable.
- Sampling methods must be chosen carefully, with different methods in different geological settings.
- Abundance varied over short distances, whereas grade was constant over long stretches.
- Topography played an important role in nodule distribution regionally and locally.
- Plains had lower, but more evenly distributed, nodule abundances.
- Photo data and ground truth showed no good correlation.

SUMMARY OF THE DISCUSSION

A participant asked Dr. Kodagali whether the last resource assessment was for all the 75,000 sq. km pioneer area before relinquishment. Dr. Kodagali clarified that 150,000 sq km was the original area of which 75,000 square kilometers was the area left after relinquishment.

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CHAPTER 18 THE CHINA OCEAN MINERAL RESOURCES RESEARCH AND DEVELOPMENT ASSOCIATION'S RESOURCE ASSESSMENT OF THE POLYMETALLIC NODULE DEPOSITS IN THE CHINESE AREA OF THE CLARION-CLIPPERTON ZONE (WESTERN PART)

*Jiancai Jin, Deputy Permanent Representative of the People's Republic of China to the International Seabed Authority, Kingston, Jamaica**

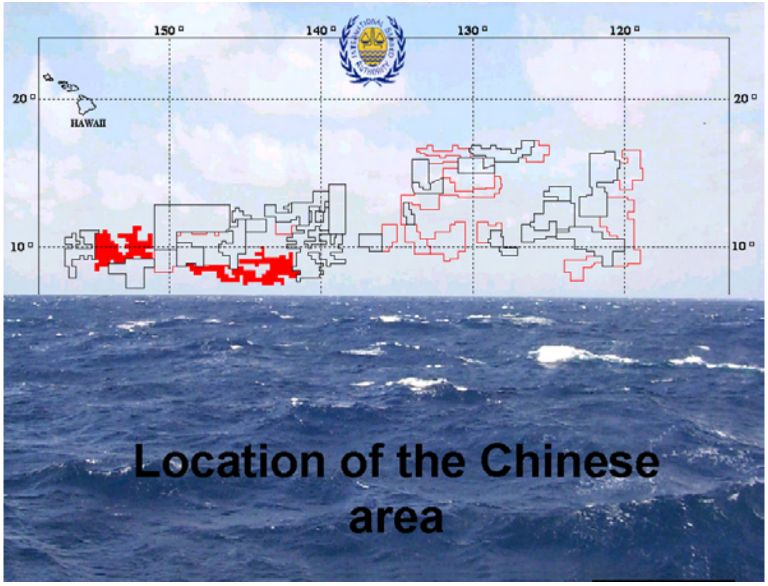
Introduction

The objective of the survey and resource assessment of polymetallic nodules during the exploration stage was to delineate an area that could support a future mining operation under the existing technical and economic conditions. The regulations on prospecting and exploration for polymetallic nodules in the Area therefore defined exploration as not only searching for deposits with exclusive rights, but also as the activities, including the studies of environment, technical, economic and other appropriate factors. Because of the uncertainty of the time for commercial mining of deep seabed nodules and the limited degree for the research and development and feasibility study, it is difficult at the current stage to predict the requirement for the indexes of the technical efficiency, quantity and quality of the mineral deposit and environmental limitation when the commercial mining starts. An economic model is therefore necessary to assume these indexes. The model was helpful in solving a problem such as how large the application and the exploration area should be during the process of the Area regime deliberation. This model and its indexes would also be useful for the resource assessment in the exploration area and the establishment of the geological model in a larger area.

The China Ocean Mineral Resource Research and Development Association (COMRA) was registered as a pioneer investor and allocated an area for exploration located in the western part of the Clarion and Clipperton Fracture Zones (CCZ) of the North Pacific Ocean in 1991. From a long-term point of view, the main objective of exploration was to delineate the mine site in this area that could meet the requirements for the geological, economic and technical indicators. Within a certain period, China is required to relinquish 50% of its allocated area, a total area size of 75,000 square kilometres. However, because the Chinese entities surveyed the CCZ later than the others, it was difficult to select an application area with relatively high quality. The application area was located in the western margin of the CCZ, which consisted of two main areas that were 200 kilometres apart from each other and that had a 1,500 kilometre-long spread from east to west. This scattered area has variable grade and abundance of nodules and an uneven topography. These factors make it more difficult to undertake resource assessment and relinquishment. For these reasons, resource assessment and the related research has been the priority in the COMRA programme, with a view to guiding the relinquishment and promoting the efficiency of exploration at sea.

Under the COMRA plan of work for exploration, the exploration of the allocated area is identified so as to collect data and information for the purpose of assessing resources and environmental impact on the site, designing the test mining and processing systems, while assessing the nodule resources for evaluating the quality, quantities, distribution and economic value of the allocated area, with a view to identifying the reserves and delineating the site suitable for commercial mining. Therefore, the resource assessment combined with exploration at sea is a step-by-step process of upgrading the nodule resources and a process of delineating a mine site.

* *The author wishes to thank COMRA for its permission to use some of its data and information. The views expressed herein are not necessarily those of COMRA.*



Strategy

Assuming an economic profitable model

COMRA accepted a prevailing assumption for an economically profitable mining operation, that is, a mine site that can yield 3 million dry metric tons of nodules per year for a period of 20 years. Although this figure is open to discussion, depending on the reserve and quality identified by exploration, the technology development and the economic variation at the commercial time, we simplify the formula to calculate the size of the mine site with this figure. Supposing the total recovery rate is 20% from the product of overall technical efficiency and the ratios of mineable areas in the mine site, the quantity of the mining operation needs 300 million dry metric tons in situ, roughly 420 million wet metric tons. Further, supposing that the grade of extracted metals is the fixed figure in nodules, the size of the mine site needs 60,000 square kilometres, giving the average abundance of the nodules as 7 kilograms per square metre.

Such an area could be delineated within the contract area during the first phase of exploration by sampling and using other means in a small selective area, together with the establishment of a model for further knowledge of nodule distribution. This knowledge will be applied to the delineation of the mine site in the contract area. The subsequent phase of exploration will then focus on identifying the mineable areas within the mine site to minimize the unmineable areas, such as the obstacles, erosion depression, cliffs, holes, etc. The technical efficiency will be reflected in mineable areas. However the indicators for assessment may be readjusted, depending on the prevailing economic and technical conditions at that time.

Factors for resource assessment

Factors relating to the character of the target areas (application area, contract area) have been considered as follows:

Geological factors

Target area: tectonic features, topography, regional strata, types and features of the surface sediment, regional rift structure;

Deposit: distribution and coverage features of the polymetallic nodule;
Ore: types and mineral features of the nodule.

Economic factors

Nodule grade and Ni-equivalent grade. Nodule grade is a leading economic index in evaluating quality of nodule ore. We treated Copper (Cu), Cobalt (Co), Nickel (Ni) and Manganese (Mn) as useful metals in the nodule. As these four metals are different in price, Ni-equivalent value is converted from the contents of the metal elements weighted by Ni price ratio (the ratio: Ni 1, Mn 0.07, Cu 0.3, Co 3) and is the sum of the products of the four metals contents multiplied by their price ratio to Ni.

Nodule abundance and Ni-equivalent abundance. Nodule abundance is the leading economic index to evaluate the target areas. Because the content of useful metals (Mn, Cu, Co, Ni) in the nodule and the economic price is different, the abundance can only reflect the quantity, not the quality of the nodule. We thus use the Ni-equivalent abundance as an economic index integrating the five parameters of abundance, Mn, Cu, Co and Ni. This value refers to Ni-equivalent concentration of Mn, Cu, Co and Ni (g/m^2) in dry nodules of unit area seafloor and reflects the quality of the resources in the target areas.

*Amount of resources***.** The amount of resources include the amount of nodule resources and the amount of the metal (Mn, Cu, Co, Ni) resources, which is directly related to the economic efficiency and time limit of mining.

Environmental factors

These factors are related to the future operation environment and technical efficiency of the mining system, including:

- Hydrological and meteorological factor;
- Shape and integrity of ore-fields and size of ore-field blocks;
- Topography of seafloor, variation of slope and the obstacle;
- Feature of the deposit and ore, including the hardness, size and porosity of nodules;
- Geotechnical properties of sediments, including the solidness, shear strength and grain size;
- Ecosystem and its sensitivity to the operation system.

Other factors

Except for the factors relating to the target area *in situ*, commercial factors, such as the investment and the operation cost related to the collecting, recovery, transportation and processing of the nodules, price variation for the metals possibly recovered from the nodules, and the rate of return, should be considered. Owing to the uncertainty of the commercial mining time, it is difficult to define the indices of the profitability without the data and information from the pilot testing for the mining and processing.

Main economic and technical indices to delimit the target area

Average boundary abundance $\geq 5.0 kg/m^2$
Average boundary grade (Cu+Co+Ni)≥1.80 per cent
Sea-floor topographic slope $<5^o$
Solid bottom sediments

Methods and parameters for calculating resource amount

Parameters

The main parameters for calculating the amount of nodule resources are as follows:

Parameters in calculating the size of area

The Klasovsky formula to calculate the surface area of the earth's ellipsoid is used to calculate the size of areas:

$$S = a^2(1-e^2)(\lambda_2-\lambda_1)\left[\frac{\sin\varphi}{2(1-e^2\sin^2\varphi)}+\frac{1}{4e}\ln\frac{1+e\sin\varphi}{1-e\sin\varphi}\right]_{\varphi_1}^{\varphi_2}$$

S = size of the target areas and relinquished areas; *a*: radius of earth equator (6378.137km); *e* = 0.081813334, the earth's first eccentricity; λ_1,λ_2, longitude value expressed in radian;Φ_1,Φ_2, latitude value expressed in angle.

Average abundance of the nodules

Average abundance of the nodules is the mean value of the abundance resulted from the sampled nodule at each station. If there are several abundance values from several samplers, their arithmetic mean is used. The average abundance of an ore-field is the arithmetic mean of the abundance values of every station in the ore-field.

$$A = \sum_{i=1}^{n} Ai/n$$

A is the average abundance; *Ai* the abundance of each station; *n* the station number.

Average grade of the nodules

The contents of Cu, Co and Ni are determined in the laboratory and the resulted data are used as their grade. The average grade of an ore-field was calculated by the method of arithmetic mean on the grade values of all the stations in the field.

$$G = \sum_{i=1}^{n} Gi/n$$

G is the average grade; *Gi* the grade of each station; *n* the station number.

Ni–equivalent grade

The Ni-equivalent grade (NEG) is the sum of the products from Mn, Cu, Co and Ni contents multiplied by the ratio of their international market price, with the Ni price as 1 (Mn 0.07, Cu 0.3 and Co 3).

NEG () = Ni%+0.07 x Mn%+0.3 x Cu%+3 x Co%

Ni-equivalent abundance

The Ni-equivalent abundance (NEA) is the sum of Ni-equivalent values of Mn, Cu, Co and Ni in the dry nodules from one square metre seafloor.

NEA (kg/m^2) = Abundance (kg/m^2) x (0.07 x Mn per cent +0.3 x Cu per cent +3 x Co per cent +Ni per cent)

Average water content of the nodule

The generally accepted 30 per cent water content is used.

Calculation method

Pioneer/relinquished areas

Both the arithmetic mean and Kriging methods were used in the evaluation of resources in the pioneer/relinquished areas. The results indicated that the relative error between the two was 0.09 per cent in the east part and 2.59 per cent in the west of the pioneer area. The difference of the resource amount calculated by the two methods was originally about 7 per cent before relinquishment and decreased below 3 per cent after relinquishment, indicating the results from more sample stations.

Reserved area

The Arithmetic mean method is used to calculate the amount of nodule resources, the amount of metal resources and Ni-equivalent amount of metals.

P (amount of nodule resources) = S (area) x A (average abundance)
Q (amount of dry nodule resources) = P x (1-w), where w is water content (%)

M*i* (amount of metal resources) = Q x G*i* (Grade), where *i* is Mn, Cu, Co, Ni content
NEM (Ni-equivalent amount of metals) = MNi+0.07MMn+0.3MCu+3MCo.

Strategy for survey at sea: size and layout of survey station and line

Survey before the application

Stage I: A 400,000-square kilometre area in the CCZ was selected after sampling at 1^{o} interval (~111km) in ~1 million square kilometre area in both mid-Pacific and the CCZ.

Stage II: 300,000 square kilometres in the CCZ was selected as the pioneer investor application area after sampling in 15’ (0.25^{o}, ~28km) interval with ~590 stations in the above area.

Survey in the pioneer area

Stage III: A survey was carried out mainly with geological sampling and bottom photo in 7.5’ interval (0.125^{o}, ~14 km), line survey for bathymetric, multi-frequency and geophysical measurement in 3.75’ interval (0.0625^{o}, ~7km) and full coverage measurement for seabed topography with multi-beam system. The result was the relinquishment of the 30 per cent, total 45,000-square kilometre part of the pioneer area.

Stage IV: A survey was carried out in a 105,000-square kilometre area mainly with the deep-tow system for optical observation of the camera and video. A geological sampling station was inserted in the middle of each 7.5' x 7.5' (14 x 14km) grid, making the interval as 5.3' (0.088^o, ~9.9km). The result of this stage was the relinquishment of another 20 per cent, a total 30,000-square kilometre part of the pioneer area.

Survey planned in the contract area

Stage V: A **s**urvey is planned and is being carried out in a 2,000-square kilometre selected area with sampling in an interval of 1.875' (~3.45km), full coverage measurement of micro-topography, acoustic and optical profile observation with the deep tow system in an interval of 2 kilometres.

Research relating to the resource assessment and geological model

For the purpose of resource evaluation and guidance of relinquishment and exploration at sea, research relating to the characteristics and the controlling factor of the deposit have been carried out as follows:

Characteristics of polymetallic nodules and the technique methods of exploration in the Chinese pioneer area and CCZ

- Pattern of local distribution of ore deposit of polymetallic nodules,
- Classification and characteristics of ore deposit of polymetallic nodules,
- Model for controlling factors of mineralization of polymetallic nodules,
- Tectonic characteristics in seismic stratigraphy and conditions of mineralization,
- Atlas and study of the characteristics of topography and geomorphology of the pioneer area.

Assessment system of geological, technical and economic factors of mineral area

- Dynamic assessment of resource and study of delineation of mineral areas in the pioneer area,
- Multi-variables geostatistics on the resource assessment of nodules,
- Study of the K-variable of polymetallic nodules.

Geological condition concerning mining engineering

- Sediment classification and acoustic feature of seabed based on data of profiler,
- Geological engineering condition in the mineral area of nodules.

Study of basic geology of mineral area

- Composition and tracer of isotopes Sr, Nd, Ce of sediment, nodule and crust in pioneer area,
- Application of isotopes Sr, N, Si in the prospecting of nodule and crust rich in metals,
- Study of bio-mineralization of nodules,
- Relationship between micro bio-ecology and growth of nodules,
- Preserved and enriched condition of nodules in the Pacific,
- Chemic evolution and paleo oceanography of nodules.

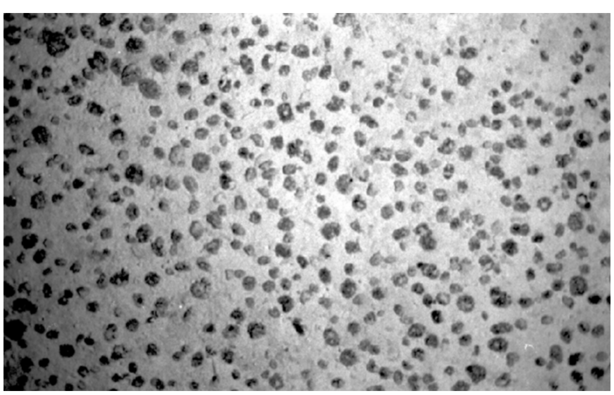
Result

Based on the data and information from the cruises and the research results; resource assessment is characterized in the comparison of the western and eastern parts of the Chinese area, systematically describing the environment of mineralization, characters of the deposit, distribution and variation of resources in the area, and analysing the resource amount, its trend of distribution and the difference of the two parts. While the focus on the assessment is on the knowledge of the leading factors for controlling deposit in the pioneer area, some basic work has been done for the reserve area and the parts relinquished in the pioneer area.

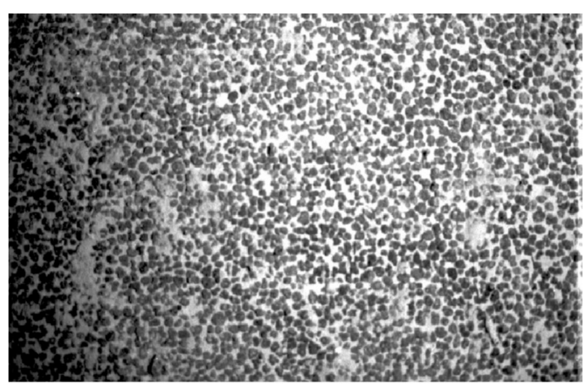
General remarks on the Chinese area

The Chinese area is located in the southwest between the Clarion and Clipperton Fracture Zones. The whole mineral belt is distributed between and evidently controlled by these two fracture zones. The topography resulted from the smaller scale rifts developed roughly south-north between the two fractures and have obvious influence on the regional distribution and scale of the ore-fields and ore-body and types of the nodule. The rift near 149^{o} W roughly from south to north divides the Chinese area into the west and east parts, in which the geophysical and geological features and features of mineral deposit are evidently different from one another. In the west part, nodules are predominantly of a smooth type and comparatively small in size, with high abundance, slightly low grade, and with mainly a detritus and polylobate/intergrown shape. Those in the east are of a rough or intermediate type, relatively big in size, with low abundance and high grade, and with mainly cauliflower and ellipsoidal shapes.

The formation and distribution of the polymetallic nodule varies in time and space. The formation time is early Miocene, Pliocene and late and middle Pleistocene, especially at the sediment gap, which is the main period for the generation of the nodules. This coincides with the prevailing time of the Antarctic Bottom Current, indicating that the formation, development and change of the current hasgreat influence on the formation and development of the nodule. Spatially, polymetallic nodules are closely related to topography. In seamount areas, there are fewer nodules, which are of a smooth type, small in size and of lower grade, and always with a detritus and polylobate/intergrown shape. At the lower part of abrupt slopes and transitional area to smooth terrain, the nodules are enriched, in big sizes and of high grade and usually have a cauliflower and ellipsoid shape. There are also fewer nodules at the central part of the wide plain, while in the hilly areas, the nodules are relatively enriched. Nodules are also predominantly distributed below the CCD boundary. In areas 100-300m below the CCD, in particular, the nodules are most concentrated, indicating that this is the most favourable water depth for their formation. In areas shallower than the CCD, nodules decreased evidently, especially in areas above the carbonate strong solution belt, where very few nodules were found. This shows that water depth plays an obvious controlling part of the nodule.

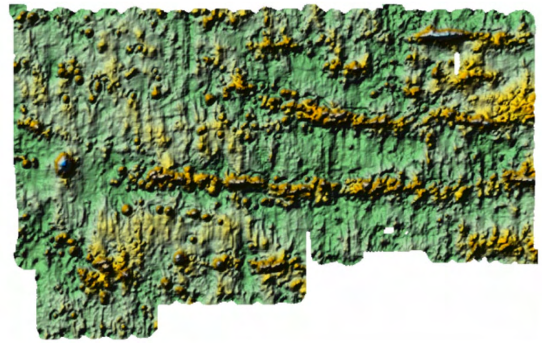


Nodules in the eastern area

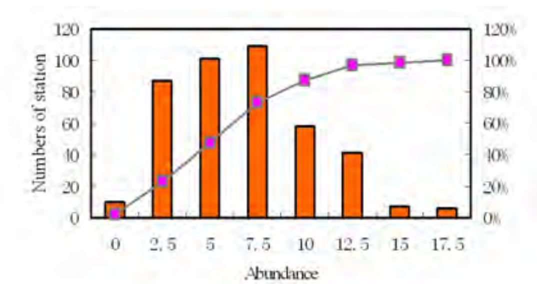


Nodules in the western area

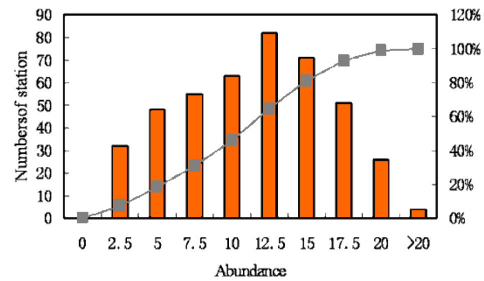
Topography of the eastern part of the pioneer area



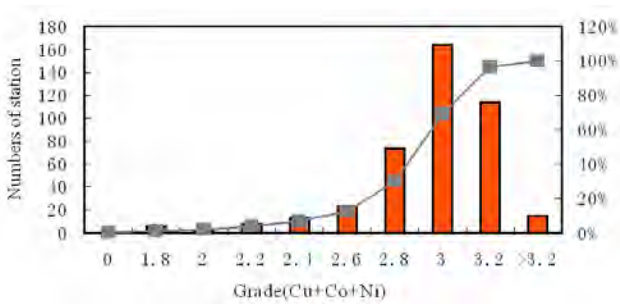
Topography of the western part of the pioneer area



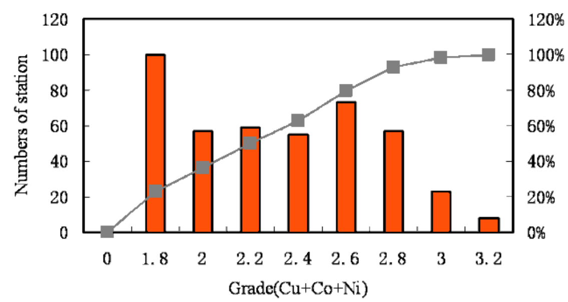
Distribution frequency of abundance in the eastern area



Distribution frequency of abundance in the western area



Distribution frequency of grade in the eastern area



Distribution frequency of grade in the western area

The reserved area

The resource assessment of the reserved area was carried out to determine the representativeness of data and to compare it with the data and information in the Chinese area, together with the possible contribution to the Authority of data. Since the reliability of the assessment is mainly related to the degree of survey, it should be pointed that the assessment was based on the data and information obtained before application, but referred to the methods and standard used for the pioneer area. The following tables show some of the results.

Table 1: Tonnage and tonnage per unit area of each block

Block	Area (km^2)	Abundance (kg/m^2 dry weight)	Tonnage ($\times 10^4 t$ dry weight)	Metal amount of unit area (g/m^2)				NEA (g/m^2)	Tonnage of Ni equivalent metal ($\times 10^4 t$)	Ratio to mean NEA of the whole area
				Mn	Cu	Co	Ni			
CA_1	43266	6.38	27603.71	1565.84	51.19	15.21	63.74	238.64	1013.89	1.40
CA_2	7591	3.72	2823.85	933.01	35.48	8.70	40.50	144.82	108.25	0.85
CA_3	2370	4.28	1014.36	1102.70	46.05	8.35	55.69	178.12	40.71	1.05
CA_4	20231	3.65	7384.15	934.02	36.69	7.51	45.18	144.44	291.53	0.85
CA_5	76542	3.58	27402.04	921.72	39.90	7.50	43.29	139.31	1079.84	0.82
Whole	150000	4.43	66450.00	1112.60	40.56	9.80	49.50	170.34	2534.23	1.00

Table 2: Size, abundance, grade and tonnage of the possible ore blocks

Block	Possible ore block	Average abundance (kg/m^2)	Average grade (%)	Station Nos	Size (km^2)	Tonnage (wet) ($\times 10^4 t$)	Tonnage (dry) ($\times 10^4 t$)
CA_1	1	9.25	2.18	2	1518.4	1404.5	983.2
	2	10.52	1.96	2	1518.4	1597.4	1118.1
	3	8.50	2.29	2	1518.4	1290.6	903.4
	4	11.84	2.20	2	1518.4	1797.8	1258.4
	5	9.59	2.30	4	3036.8	2912.3	2038.6
	6	11.84	2.20	2	1518.4	1797.8	1258.4
	Ave./ Total	10.26	2.19	14	10628.8	10800.4	7560.3
CA_2	1	8.10	2.20	7	5314.4	4304.7	3013.3
CA_3	1	10.31	2.73	3	2277.6	2348.2	1643.7
CA_4	1	7.25	2.37	4	1708.2	1238.4	866.9
	2	6.13	2.44	4	2657.2	1628.9	1140.2
	3	11.82	2.18	2	759.2	897.4	628.2
	4	12.68	2.67	2	1138.8	1444.0	1010.8
	Ave./ Total	9.47	2.42	12	6263.4	5208.7	3646.1
CA_5	1	8.77	2.34	4	3036.8	2663.3	1864.3
	2	8.09	2.54	13	9869.6	7984.5	5589.2
	3	6.19	2.54	2	1518.4	939.9	657.9
	4	6.50	2.41	7	5314.4	3454.4	2418.1
	Ave./ Total	7.39	2.46	26	19739.2	15042.0	10529.4
Ave./ Total	16	9.21	2.35	62	44223.4	37703.96	26392.8

Parts relinquished in the pioneer area

The parts relinquished in the pioneer area are the unmineable sectors, characterized mainly in the sea mountain chains spreading in the whole pioneer area, the low abundance sectors in the east part of the pioneer area and the low grade sectors in the west. The following tables contain some results for the resource assessment during the process of relinquishment and show the possibility to seek some additional data for model from this process.

Table 3: Average abundance, grade and the numbers of station in 20% relinquished areas

Sectors	Size (km^2)	Abundance (kg/m^2)	Mn (%)	Cu (%)	Co (%)	Ni (%)	Cu+Co +Ni (%)	Numbers of station
East	18631.43	3.49	28.88	1.13	0.21	1.41	2.75	222
West	11368.86	6.68	24.31	0.80	0.24	1.07	2.11	129

Table 4: Average abundance, grade in relinquished areas calculated by different methods

Relinquished area	Size (km^2)	Abundance (kg/m^2)	Mn (%)	Cu (%)	Co (%)	Ni (%)	Cu+Co+Ni (%)	NEG (%)	NEA (g/m^2)	Numbers of station /block	Method
East(mean)	44181.43		28.86	1.17	0.20	1.40	2.78	4.37	97		Geo-samples
West(mean)	30818.86		24.62	0.81	0.26	1.08	2.14	3.83	161		
(East+West)/2			27.08	1.02	0.22	1.27	2.06	4.14	126		
East(mean)	44181.43		28.98	1.18	0.20	1.41	2.79	4.40	107.11		Kriging
West(mean)	30818.86		24.42	0.80	0.26	1.07	2.12	3.78	170.41		
(East+West)/2			27.12	1.03	0.22	1.27	2.52	4.15	132.91		

Table 5: Average abundance, grade and size of block in the east 20% relinquished area

Block	Mn (%)	Cu (%)	Co (%)	Ni (%)	Grade (%)	Abundance (kg/m^2)	Size (km^2)	Number of stations	Main reasons for relinquishment
CE1	29.51	1.22	0.19	1.44	2.85	2.44	1069.38		Low abundance
CE2	29.33	1.21	0.2	1.42	2.83	3.32	3178.93		Low abundance
CE3	29.58	1.22	0.19	1.45	2.86	2.75	1814.47		Low abundance
CE4	31.17	1.34	0.18	1.48	3.00	2.32	747.52		Low abundance
CE5	28.42	1.22	0.19	1.44	2.85	3.36	1328.36		Low abundance & sea mountain
CE6	30.51	1.11	0.19	1.42	2.73	2.61	664.03		Low abundance
CE7	28.15	1.04	0.22	1.38	2.64	4.16	9090.83		Low abundance & integrity
CE8	30.38	1.18	0.22	1.44	2.84	1.38	145.08		Low abundance
CE9	28.35	1.07	0.21	1.35	2.64	2.99	592.83		Low abundance

Table 6
Resource amount in blocks of the east 20% relinquished area (x10^{4}t)

Block	*Weight (wet)*	*Weight (dry)*	*Mn*	*Cu*	*Co*	*Ni*	*Cu+Co+ Ni*	*Ni equivalent metal*
CE1	2609.3	1826.5	539.0	22.3	3.5	26.3	52.1	81.1
CE2	10554.0	7387.8	2166.9	89.4	14.8	104.9	209.1	327.7
CE3	4989.8	3492.9	1033.2	42.6	6.6	50.6	99.8	155.7
CE4	1734.2	1214.0	378.4	16.3	2.2	18.0	36.5	55.9
CE5	4463.3	3124.3	887.9	38.1	5.9	45.0	89.0	136.4
CE6	1733.1	1213.2	370.1	13.5	2.3	17.2	33.0	54.1
CE7	37817.9	26472.5	7452.0	275.3	58.2	365.3	698.8	1144.3
CE8	200.2	140.1	42.6	1.7	0.3	2.0	4.0	6.4
CE9	1772.6	1240.8	351.8	13.3	2.6	16.8	32.7	53.2
Total	65874.4	46112.1	13221.9	512.4	96.5	646.1	1255.0	2014.8

Suggestion

The establishment of the geological model represents an effort on the part of the Authority to evaluate the resources and delineate the potential mine sites in the reserve area under the current circumstances, where no further survey will be seen in this area, since the time for commercial mining is still unpredictable. Given the fact that the data and information submitted by various entities during their applications for registration as pioneer investors are limited, it would be hard to establish the model without knowledge of the whole area of the CCZ. Therefore, the initial suggestion to establish the geological model of the reserved area, as put forward during the meeting of the representatives of pioneer investors in March 2001, has now been developed into the current initiative of establishing the model for the whole area of the CCZ.

Objectives

The most substantial function of the Authority is the administration of the resources in the Area. It is a crucial time for the contractor to seek a cost-effective way in which to continue the assessment for its area after many years of work at sea, as required for the relinquishment, while the time for commercial mining is still in the air. This background, together with the initiative to establish a geological model has given an opportunity to the Authority to promote cooperation in resource assessment at a time when cooperation in the environmental assessment has been successful. Therefore, the purpose for the establishment of the model is beyond the model itself. For the Authority, the model should encourage the collaboration for scientific research, particularly in the field of the various resources in the seabed, which will be one of its most substantial work. The contractors, on the other hand, may derive benefit from the model as a guide for their resource assessment and the delineation of mine sites in the contract areas with a reduced exploration at sea.

The direct objective of this initiative is certainly to establish a mathematical model for nodule assessment. However, if the significance of the initiative is recognized, we can see the more important objective which exists in the process, namely, the efficiency and the standardization of the resource assessment. This objective is not only for the nodules, but also for other resources, such as sulphide and cobalt-rich crusts. Rules relating to prospecting and exploration of these resources are under consideration. Should these rules be based on the recognized standardization and indicators, they would be more effective and authoritative. The model may also be helpful for the rules to reflect a relationship between the density of data and the grade of the assessment, which will guide the activities at sea.

Quantity and quality of data and information

As the structure of the model depends on the quantities and quality of data and information, it is important to become acquainted with the existing data and the way to improve their quality. The former is the precondition for the acquisition of the data and the latter is the guarantee for the model, when established, to work efficiently.

Existing data and information

The existing data and information are either public or proprietary. The scope of data and information in the CCZ includes: the reserved areas; the contract areas for exploration; the relinquished areas from original pioneer areas; the potential application areas; and the areas surveyed before application. The data belongs to public research bodies, the Authority, the contractors and potential applicators. While the data on the reserve areas and some other areas in CCZ from public source and contractors are available for the model, the Authority and the partners may make the joint effort to allocate and make the best use of the data available, so that the model will be representative and may apply to the assessment for other resources.

Standardization

Once sufficient data and information is available for the model, it may be more important and difficult to judge the confidence and reliability of the data. Because of the various sources of data and information, standardization is necessary for the quality of the model. This process may include: the comparison of the methods and techniques to obtain the data and information at sea; to analyse and process the obtained data and information in the laboratory by various actors; to select the factors and indexes for the resource assessment, and to select the parameters for the model.

Role of the Authority

The Authority is the organ responsible for organizing and controlling the activities in the Area, particularly in the administering of the resources in the Area on behalf of manind. This gives the Authority an important role to play in the promotion of the collaboration among the different entities. For the model, it may cover the following:

- Explanation of its function and power, and of the regulations, especially those dealing with data and information;
- Utilization of the existing data and information;
- Enlargement of the source of data and information;
- Development of the standards for the resource assessment and the parameters for the model;
- Application of the standardization to the resources other than the nodules;
- Creation of the environment for cooperation without the obstacles caused by different cultures and languages.

If the above occurs, we can expect to see a model not only for geology, but also for the future activities in the Area.

SUMMARY OF THE PRESENTATION

Features of the COMRA application area

Mr. Jin began by explaining that the application area was located on the western margin of the Clarion-Clipperton Zone (CCZ) and that it consisted of two main parts that were 200 km apart and with a spread ofabout 1,500 km from east to west. The area had a variable grade and abundance of nodules and uneven topography.

Compared with other areas in the CCZ, the area had deeper water depth, a lower grade in the west and lower abundance in the east.

Mr. Jin said that perhaps because of the relatively late time the Chinese entities entered the CCZ, he thought the area might have a lower quality compared to the others and the degree of information might be lower as well.

He said that as was known, an objective of resource assessment during the exploration phase was to delineate areas that could support a huge mining operation and thus have an economically viable and technical purpose. There was thus a perspective on prospecting and exploration. Exploration was not only defined as searching, but also as activities, including the study of economical, technical purpose.

Therefore, said Mr. Jin, exploration of a particular area was carried out in order to collect data and information for the purpose of assessing resources and the environmental impact on the site, and the design of the test mining and processing systems.

Assessment of nodule resources involved evaluating the quality, quantities, distribution and economic value of the allocated area, with a view to identifying the reserves in the allocated area and delineating the site suitable for commercial mining in future. Hence, said Mr. Jin, resource assessment combined with exploration at sea was a process of upgrading the nodule resources and delineating a mine site.

However, because of the uncertainty of the time for actual mining; the exploration area has been delineated for research and study. At this time, Mr Jin said that it was very difficult to predict the requirements for the technical and environmental aspects for commercial mining.

Mr. Jin said that there should be an index models which was helpful in solving such problems as to how large application areas and exploration areas should be under the United Nations Convention on the Law of the Sea. This would be important to assess factors for the geological models and include the possible size of mine sites and the various economical, technical and geological factors.

For the Chinese assessment therefore, those factors had been considered as follows: geological factors included target areas, deposits and ores, as well as different features that were considered important factors. With regard to economic factors, Mr. Jin said that nodule grade was very important, but that nodule abundance and Ni-equivalent abundance and the amount of resources would also be considered.

Mr. Jin said that the third factor was that of the environment, which related to the operations environment and the efficiency of the mining systems. Mr. Jin said special mention should be made of the last one, namely, "ecosystem and its sensitivity to the operation system" because the system might be working efficiently technically, but not environmentally.

Mr. Jin said that other commercial, factors which also needed to be considered were as follows:

- Investment and the operation cost related to the collecting, recovery, transportation and processing of the nodules
- Price variation for the metals possibly recovered from the nodules, and also the rate of return

He said these were the main economic indices to delimit the target area. He said that parameters to calculate the resources amount had been considered: the pioneer/relinquished area, using both the arithmetic mean and Kriging methods; and the part of the reserved area for which the arithmetic mean method would be used.

Strategy for survey at sea

Mr. Jin said that a survey had been done before the first application, pointing out that there had been stages 1 and 2. A sampling had been done at 1^{o} intervals. In stages 3 and 4, all 50 per cent of the pioneer area was relinquished; this was required by the Law of the Sea Convention.

He said that for the next stage, some activities were being carried out in the contractor area, to survey about 2,000 sq. km and to do some geological sampling.

Mr. Jin said that the second thing was the assessment system of mineral areas; geological conditions concerning mining engineering; and lastly, the study of the basic geology of mineral areas. After some years of studies, the Chinese scientists had obtained results, and had also published several volumes of that research. He said that he would try to show the summary.

In showing the summary of the research, Mr. Jin indicated nodules in the eastern and western areas; pointing out the topography and distribution frequency of abundance in the eastern area. He said that efforts had been made to calculate some parameters, to try and show which areas to relinquish. Those were additional data and information; because those were international areas and not contractor areas that had been relinquished. He said there was a lot of information there - for instance, there were over 200 stations for which information was available.

Mr. Jin said that the objective of this initiative was to establish a mathematical model for nodule assessment, according to the programme. For the long term, however, and for the effectiveness of the functioning of the Authority, he believed that it needed to be given importance. It was important in itself, and not just to the model.

He said that this was really in the future. If this model were done successfully, it would be useful for the future work of the Authority and down the line, it would benefit not just the Authority, but all the contractors as well. Mr. Jin said that for the Chinese – who spent a lot of money, if the time for commercial mining was unpredictable, it would be foolish for them to still spend a lot of money, but they would continue their work. It should be more efficient to continue our work in the contractor areas.

Mr. Jin stressed that the quality and quantity of data and information was important. Some of the topics not mentioned here were the type: public or proprietary; the scope: reserved areas and contract areas for exploration; parts relinquished from pioneer areas; potential application areas; and also areas surveyed before application. Of course there were the owners - different entities.

According to Mr. Jin, when it comes to data, the most important thing was standardization as the Authority had mentioned. Comparison of the methods and techniques to obtain the data and information at sea; to analyse and process the obtained data and information in the laboratory by various actors, selection of factors and indexes for the resource assessment and selection of parameters for the model.

He said the role of Authority was very important, not only for the model, but also for the work, in terms of:

- Explanation of its function and power, and the regulation dealing with data and information;
- Utilization of the acquired data and information;
- Enlargement of the source of data and information;
- Development of the standards for the resource assessment and the parameters for the model;
- Application of the standardization to the resources other than the nodules; and
- Creation of the environment for cooperation without the obstacles caused by the different culture and language.

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CHAPTER 19 POLYMETALLIC NODULE RESOURCE ASSESSMENT IN THE EQUATORIAL SOUTH PACIFIC: CONSIDERATIONS IN RESPECT OF AN INTERPOLATIVE GEOLOGICAL MODEL*

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Introduction

The considerations in respect of an interpretative geological model presented in this paper are based primarily on basic data provided by the South Pacific Applied Geoscience Commission (SOPAC) and the Metal Mining Agency of Japan (MMAJ) and represents the results of 11 cruises, conducted between 1974 and 1994 by Japanese, French, United States, German and New Zealand research teams. The data utilized included seismic reflection profiles, bathymetry, 3.5 kHz profiles, various samples and chemical analyses of water bottom and manganese nodule samples. *Figure 1* provides an overview of ship-track lines cruised in each individual survey within or directly adjacent to the Cook Island exclusive economic zone (EEZ). Acoustic sounding bathymetry and sea bottom sound pressure survey methods which apply precision depth recorder or narrow beam echo sounder and multiple frequency exploration systems were used to obtain the geological data in survey areas. In addition, sea bottom observations using free-fall camera and continuous deep-sea camera methods were conducted on the MMAJ cruises.

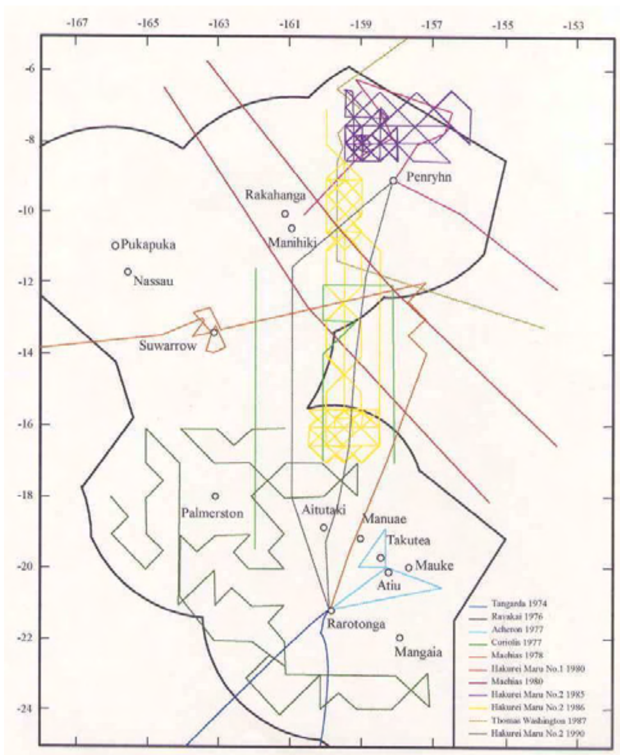

Figure 1: Survey tracks in the Cook Island EEZ

All available information previously compiled by SOPAC, and subsequent compilations and analyses undertaken by the East-West Centre, were utilised to construct a comprehensive database for assessing the occurrence, distribution and composition of manganese nodules in the Cook Islands exclusive economic zone.

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* The interpretations presented in this paper are largely based on the results of a study by the East-West Centre at the request of the South Pacific Applied Geoscience Commission (SOPAC), of the manganese nodules within the EEZ of the Cook Islands. The author gratefully acknowledges the contributions of his co-researchers, Mr. Jackson Lum, Dr. Chang Li, Dr. Charles Morgan, Dr. Yoshiaki Igarashi and Mr. Wifredo Icay, in the research presented herein.

The primary objectives of the present study are (a) to present a comprehensive overview of the characteristics, occurrence; distribution and resource potential of manganese nodules in the Cook Islands EEZ and (b) to compare these factors with similar characteristics of manganese nodules in the Clarion-Clipperton Zone (CCZ).

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Geography of the Cook Islands' exclusive economic zone

The Cook Islands territory occupies approximately 2.5 x 10 km² in the South Pacific Ocean and comprises two groups: the southern group, including the islands of Roratonga, Mangaia, Atiu, Mitiaro, Aitutaki, Manuae, Takutea; and Palmerston and the northern group, including the islands of Penrhyn, Manihiki, Pukapuka, Pakahanaga, Suwarrow, and Nassau (*Figure 2*)

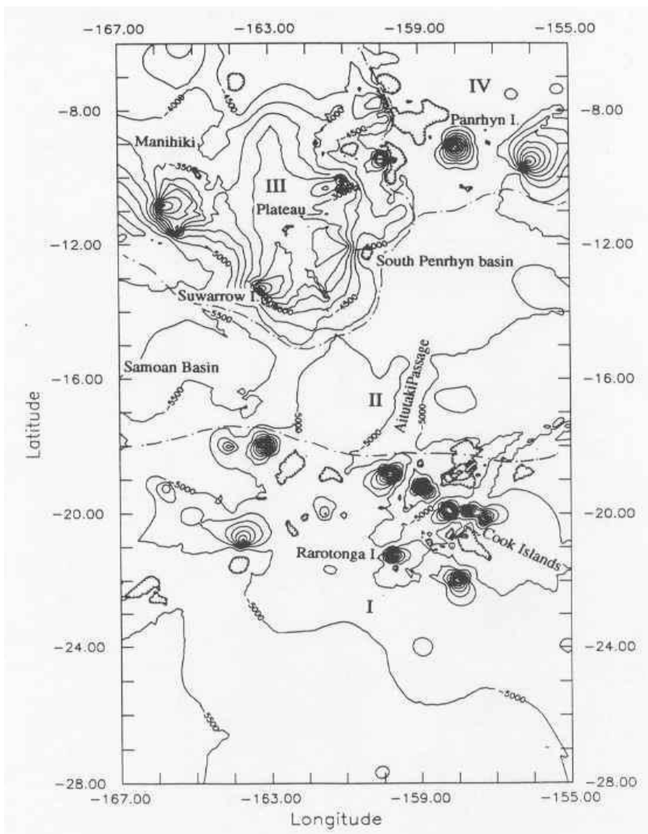


Figure 2: Submarine geomorphologic regions of the Cook Islands EEZ

The Cook Islands region includes four district topographic provinces (*Figure 2*):

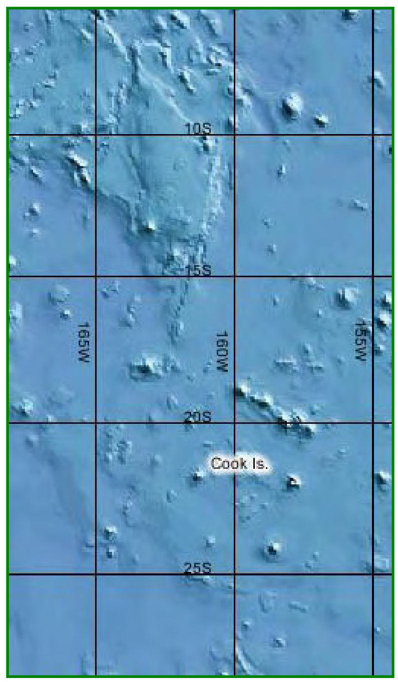
1. The area occupied by the southern Cook Islands group featuring several northwest trending chains of submarine and volcanoes (Wood *et al*., 1970);
2. The area between Aitutaki and Penrhyn, characterized by low topographic relief or a deep current passage and two abyssal basins, the south Penrhyn Basin and the eastern Samoan Basin, with water depths greater than 4,500 m;

3. The Manihiki Plateau, in the northwest, outlined approximately by the 4,000m bathymetric contour;
4. The southern part of the north Penrhyn Basin, where water depths are greater than 5,000 m predominate.

These provinces not only appear to be distinct in morphological characteristics, but also seem to reflect different tectonic histories during various stages in the development of Pacific Ocean Basin crust.

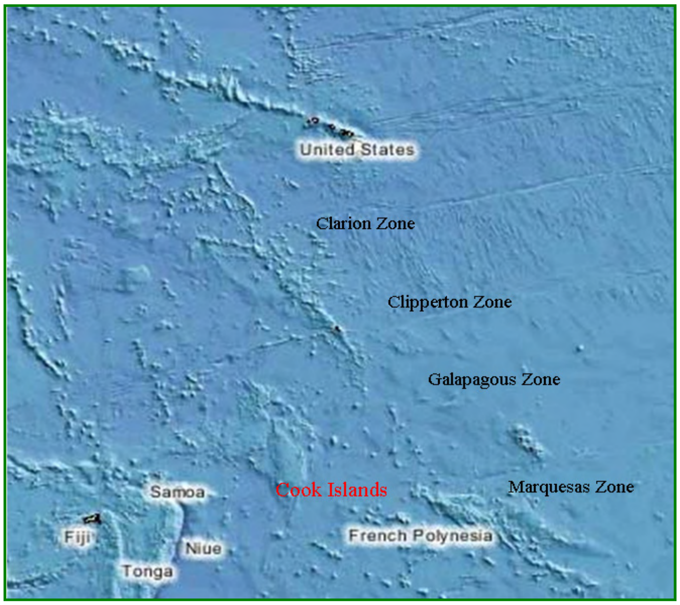
Geology and topography of the Cook Islands exclusive economic zone

The geology and topography (*Figure 2*) of the Cook Islands EEZ can be divided into (a) the Cook Islands seamount line region in the south; (b) the Manihiki Plateau in the northwest; (c) the Aitukai Passage in the centre; and (d) the southern North Penrhyn Basin in the northeast. Each region is characterized by its ocean floor topography, subsurface geologic structure and ocean current activity. The difference in geologic and topographic environments may determine the regional ocean circulation and sedimentation which in turn affect the concentration and metal content of the manganese nodules in the Cook Islands EEZ.



Seafloor topography of the Cook Islands exclusive economic zone

Generally, in the northern region, the broad ocean plain, knolls and hills are the major topographic features. In contrast, in the middle region, the Manihiki Plateau is the prominent feature which has played an important role in the ocean circulation throughout the history of the region; the Aitutaki Passage is dominated by the relatively narrow flat bottom or semi-flat from a macroscopic point of view and the seafloor features in southern region are mainly seamount chains, hills. The zone of high abundance of manganese nodules in the middle region is characterized as being topographically flat or semi-flat with knolls several hundreds of metres high.



Cook Islands exclusive economic zone

The subsurface geological structure of the Cook Islands EEZ consists essentially of basalt basement with overlying consolidated and unconsolidated sediments. The basalts are lavas and hyaloclastites, while the sediments are Quaternary brown clay, calcareous clay and calsiliceous clay. The surface sediments of the seafloor can be classified into two types, unconsolidated and consolidated sediments. The unconsolidated sediments, identified by the SBF profiles as transparent layers in the uppermost layer of the sediments, are mainly distributed on flats and sea knolls with thickness ranging from 0-40 m. In contrast, the consolidated sediments, recognised by SBF profiles as opaque layers in the uppermost layer, are mainly distributed on seamounts and sea knolls; most opaque layers are considered to be exposed basement rocks.

The thickness of the unconsolidated sediments seem to be affected by the Antarctic Bottom Water current, which flows northeastward through the Cook Islands EEZ. Compared with the southern and northern regions, the central region has a relatively low sedimentation rate. This is because of a stronger Antarctic Bottom Water current caused by the narrow Aitutaki Passage. A NNE elongated zone of high concentration of manganese nodules occurrences in the central region imply that the higher abundance of manganese nodules may be caused by the stronger Antarctic Bottom Water current which erodes/or dissolves the sediments and creates an environment suitable for continuous nodule growth.

The Antarctic Bottom Water current not only influences the concentration of manganese nodules, but also affects the distribution of major metal content of the nodules in the Cook Islands EEZ. Generally, the cobalt content is higher in the southern and central regions where nodule abundance is also higher. Conversely, copper and nickel contents are higher in the northern region where nodule abundance is generally lower as a result of a relatively strong oxidized ocean floor environment in the central and southern higher nodule abundant regions to the effect of stronger Antarctic Bottom Water current, such as relatively strong oxidized environment in turn favours the deposition of iron and cobalt. On the contrary, weakly oxidizing ocean floor environment would be formed in the northern region due to the weakening of the Antarctic Bottom Water current after it passed the Aitutaki passage and reached to a broad ocean plain region. The weakly oxidizing ocean floor environment would be favourable for manganese, nickel and copper to deposit.

Manganese nodule abundance

A major factor in any assessment of potentially economic occurrences of manganese nodules is that of abundance (concentration of nodules per unit area) which is determined primarily by the geologic and topographic environments and their impact on ocean circulation patterns and sedimentation. These complex interactions of factors determine the overall abundance of nodules. In the Cook Islands EEZ, for instance, all of these factors favourably coincided in the Aitutaki Passage region, in the central portion of the area, where the greatest abundance of nodules is to be found and will be discussed in detail later. In the following, these factors and the overall abundance of manganese nodules, and therefore the nodule resources of the Cook Islands EEZ, are discussed.

An effective way to assess overall abundance, based on sample data, is to construct an isoline (lines of equal abundance) map of the Cook Islands EEZ based on the abundance of nodules (expressed in kgs) per unit area (expressed in m²). *Figure 3* shows the manganese nodule abundance isoline map based on the sample stations for the Cook Islands EEZ. Overall, *Figure 3* shows that the Cook Islands EEZ has a uniformly high abundance distribution, densities over 10 kg/m², over broad zones (ranging from 100 km to 300 km in width and extending NNE) throughout the central areas of the zone (*Figure 4*).

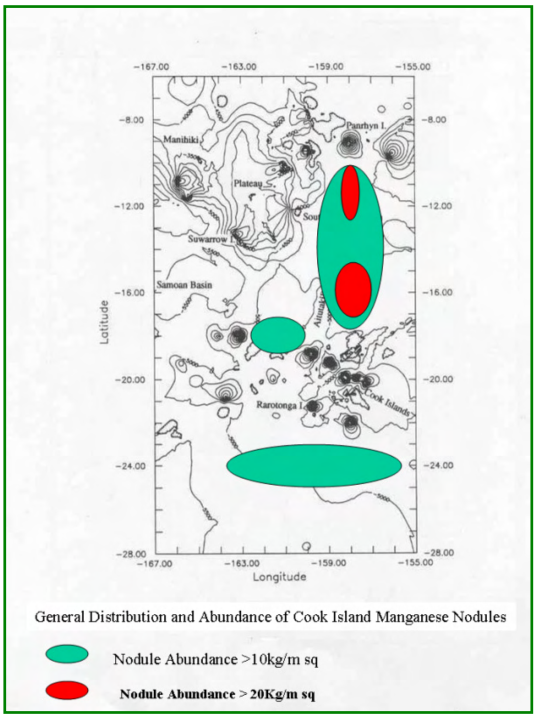


Figure 3: General distribution and Abundance of Cook Island Manganese Nodules

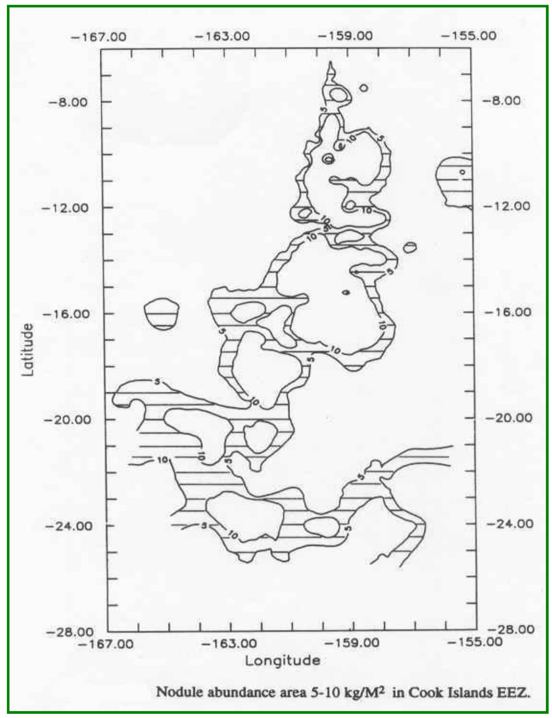
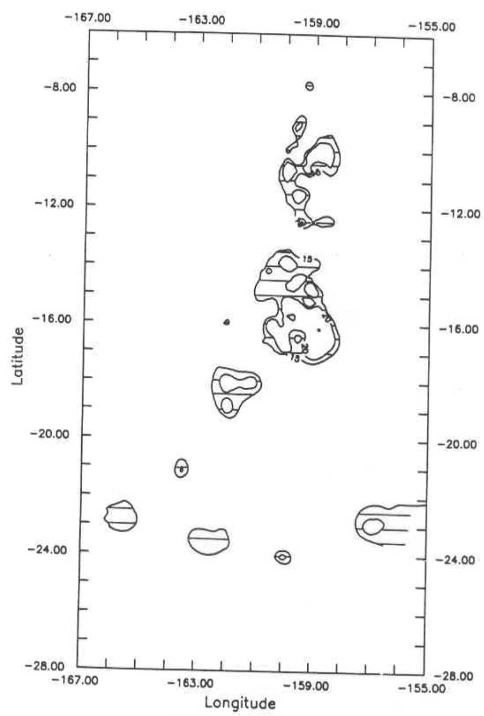


Figure 4: Nodule abundance area 5-10kg/m² in Cook Islands EEZ

Analysis of *Figure 3* further shows that the highest abundance of nodules (over 30 kg/m²) occurs in the area of 15°S-16°S and 159°W-160°W which is an area where the narrow Aitutaki Passage joins the broad ocean floor of the south Penrhyn Basin (*Figure 3*). Surrounding this area is a broad zone of high abundance which correlates with the northward extension of the Aitutaki Passage. The spatial relationship of the highest abundance with the Aitutaki Passage area is related to both the presence of a strong Antarctic Bottom Water current and the surrounding topographic elements of the Aitutaki Passage and the south Penrhyn Basin. Specifically, it is believed that the Antarctic Bottom Water current carrying a concentration of chemical elements (Cu, Ni, Co, Mn) may reduce its speed and drop most of chemical elements as the current passed the Aitutaki Passage and met a relatively broad ocean floor environment. In contrast, the north Penrhyn Basin located east of the Manihiki Plateau shows a low abundance of manganese nodules, probably due to the relatively weak Antarctic Bottom Water current and higher sedimentation rate in the area. The east Samoan Basin also presents a low abundance of manganese nodules.

Distribution of the manganese nodule composition

Metal concentration in the manganese nodules seems to also relate to the circulation of the Antarctic Bottom Water currents. Generally, cobalt content in the manganese nodules is higher in the southern and central regions, where the nodule abundance is also higher than in the northern region. Conversely, copper and nickel contents are higher in the northern region where nodule abundance is lower. The studied major compositions in the manganese nodules are manganese, cobalt, nickel and copper (*Figure 5*).



Nodule abundance area 15-20 kg/M² in Cook Islands EEZ.

Figure 5: Nodule abundance area 15-20 kg/M² in Cook Islands EEZ

Manganese concentrations in nodules are higher in the northern area of the Cook Islands EEZ as a whole, and increase from south to north. Maximum values of between 20-25 per cent occur in the areas between 6^{o}S and 10^{o}S in the centre of Penrhyn Basin, and eastward to the Manihiki Plateau (*Figure 6*). Minimum values of between 10-15 per cent Mn occur primarily south of 12^{o}S, the exception being nodules in the southern Cook Islands area near 22^{o}S, 160^{o}W where values rise to 20-25 per cent Mn. The manganese distribution is best explained by the existence of a relatively weakly oxidized ocean floor environment caused by a weak Antarctic Bottom Water current in the central Penrhyn Basin. Such a relatively weak oxidized environment would be favourable for the accumulation of manganese.

Cobalt is present in nodules in concentration of less than 0.3% north of 8^{o} S, and increases to between 0.3 and 0.5% from 8^{o} to 21^{o} S, then decreases again to 0.3% or less for most of area south of 19^{o} S. The cobalt concentration tends to correlate with nodule abundance, i.e., the higher the nodule abundance the higher the Co content. A zone containing maximum values of between 0.5 and 0.8% Co extends the NNE discontinuously along the zone of maximum nodule abundance between 21^{o} and 10^{o} S. As noted previously, the zonation of the cobalt distribution is influenced by a combination of ocean currents, particularly the Antarctic Bottom Water, and ocean floor topography. A relatively strong Antarctic Bottom Water current longitudinally passing though the centre of the Cook Islands EEZ resulted in the formation of a relatively strong oxidized ocean floor environment which was favourable for the development of cobalt-rich manganese nodules.

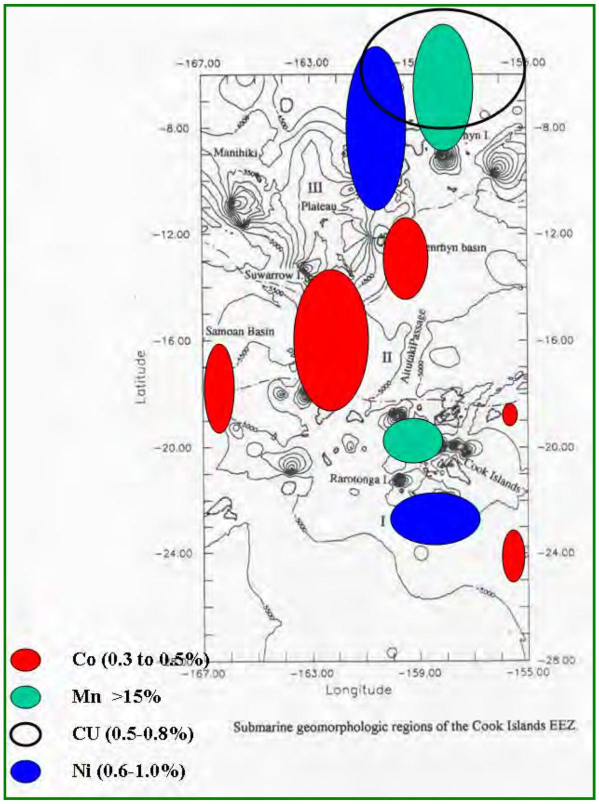


Figure 6: Submarine geomorphologic region of the Cook Islands EEZ

Regional nickel concentrations show a clear pattern of high nickel value distributed in the north eastern area of the Cook Islands EEZ. Maximum values of between 1.25 and 1.70 per cent occur in the central Penrhyn Basin at around 6° - 9° S, but there are also high values of 1-1.2 per cent around 13° -11° S. Low nickel values of between 0.1 and 0.5 per cent occur in most of the area south of 13 S, except in an area between 22° and 24° S where nickel concentration relates inversely with the abundance of manganese nodules in the Cook Islands EEZ.

Regional copper concentration patterns follow nickel fairly closely although there are some minor differences in their distribution. Like the nickel distribution, copper maximum values of between 0.8 and 1.25% occur north of 9°. Copper values decrease to 0.3-0.1 per cent in most of the area south of 9°. The concentration of the copper and nickel in the nodules of the Cook Islands EEZ are also related to the ocean circulation of the region. The relatively weak oxidized ocean floor environment, created by the weak Antarctic Bottom Water current favours the deposition of nickel and copper in the manganese nodules.

Manganese nodule resources estimate

To estimate the total amount of potentially mineable manganese nodules within the Cook Islands EEZ, the area of calculation of nodule abundance are divided into four categories: (a) areas where nodule abundance is >20 kg/m²; (b) areas where nodule abundance is 15-20 kg/m²; (c) areas where nodule abundance is 10-15 kg/m²; and (d) areas where nodule abundance is >5-10 kg/m² (>5 kg/m² is a commonly proposed cut-off abundance for mining purposes, according to Bastien-Thiery *et al*. (1977).

Estimates of the total metal and economic value presented in this paper are used based on the above four categories of nodule abundances. The grades (Wt. per cent) of the cobalt, nickel and copper used to calculate metal quantities and values are averaged by each corresponding area nodule abundance.

The resources of the Cook Islands EEZ are estimated to consist of a total weight of nodules, with a cut-off grade of greater than 5 kg/m² in an area of 652,223 km² of the zone, of 7,474 million tons containing 32,541,000 tons of cobalt; 24,422,000 tons of nickel, and 14,057,000 tons of copper. (These figures are, however, not recoverable reserves, which would be at least 60~70 per cent lower.)

Obviously, the great amount of metals contained within the manganese nodules in the Cook Islands EEZ is mainly a result of their great abundance and high cobalt grade. The high cobalt content in the manganese nodules, coupled with high nodule abundances, makes the total resource value of cobalt in the Cook Islands EEZ, where the nodule abundance is greater than 5 kg/m², reach $967.34 billion. The cobalt resource value alone accounts for 85 per cent of total metal resource values in the Cook Islands EEZ. However, it should be mentioned that the amount of in-place manganese nodules cannot be entirely recovered, due to geological, mining and processing recovery losses.

Comparison of the Clarion-Clipperton Zone with the Cook Islands exclusive economic zone

Depositional environment

The depositional environments for the manganese nodules of the CCZ and the Cook Islands EEZ are both tectonically and geochemically quite different and it is these differences which primarily account for the textural, abundance and chemical variations between the two areas.

The CCZ is located just north of the equator and contains the most studied nodule deposit in the world's oceans. The Clarion-Clipperton nodule area, known as the "Manganese Nodule Belt", is within the area bounded by 90°-160°W and 5°-15°N, an area delimited by the Clarion and Clipperton fracture zones on the north and south, respectively. The Clarion-Clipperton Zone is characterized by gently rolling abyssal hills (Meyer, 1973; Horn et al., 1972), high nodule densities and a seafloor composed predominantly of siliceous radiolarian oozes and clays (Horn, et al., 972; Hans, 1973; and Meyer, 1973).

The oceanic crust beneath the sediments was formed originally near the equator about 53-78 M.Y. (von Stackelberg and Beiersdorf, 1991) and has tectonically drifted northwestward to its present location. When the Tethyan Seaway closed in the early Middle Miocene (von Stackelberg and Beiersdorf, 1991) the Antarctic Bottom Water flowed northward, favouring the inception of nodule growth (von Stackelberg and Beiersdorf, 1991) and preventing the deposition of sediments during several periods of the Miocene (Riech and Von Grafenstein, 1987). During the time when the "Manganese Nodule Belt" was located near the biologically productive equatorial zone, there was an abundance of organic matter on the seafloor. High nodule concentrations are found in 4,900 to 5,300 m. (Hans, 1973) depths from the sea surface, which is below the carbonate compensation depth (CCD) of 4,600 m. (Horn et al., 1973). In this zone, the dissolution of the organic sediments is postulated as the primary source of the diagenetic metal ions (in particular Mn, Cu, Ni and Co) that have been adsorbed by the growing activity and the presence of bottom currents kept these nodules afloat on the sediment floor.

On the other hand, the Cook Islands nodule fields (which are within the islands' 200-mile EEZ and located south of the equator) are, expectedly, quite different when compared to the Clarion-Clipperton nodule fields. The age of formation of these volcanic edifices, according to Wood and Hey (1970), was Eocene and Oligocene. The oceanic crust on which these islands are resting was formed some time during the Cretaceous, as compared to the Late Cretaceous to Early Tertiary age of formation of oceanic crust on which the Clarion-Clipperton prime nodules are resting.

In a very general sense, the sea bottom topography of the Cook Islands EEZ is somewhat similar to the Clarion-Clipperton area; the predominant sediment types on which abundant nodules were sampled are quite different, being reddish to grayish-brown abyssal clay and siliceous or calcareous oozes and clays (Landmesser and Kroenke, 1976; Landmesser *et al*., 1976; Monzier and Misseugue, 1977; Glasby, 1978; Exon, 1981; French Delegation, 1981; Glasby *et al*., 1983, 1986).

The Cook Islands nodules and those of the Clarion-Clipperton Zone also started forming about the same time (Glasby, 1983); however, the proposed nodule growth method of hydrogenetic adsorption (Glasby, 1978) of metal oxides from the enriched bottom currents is different from that of the CCZ. Also different is that the source of the metal ions is postulated to be associated with the tectonic activities that formed the Cook Islands and from activities with the 100 m.y. B.P. triple junction in the south of Penrhyn Basin (Winterer et al., 1974). It is mainly the presence of the intensified Antarctic Bottom Water flow (Landmesser et al., 1976) that keeps the nodules afloat on the seafloor. In the Cook Islands EEZ, high nodule concentrations were found in the 5,000 to 5,400 m (Usui and Moritani, 1988) depth range, which is below the carbonate compensation depth of 4,800 m (Glasby *et al*., 1983; Cronan *et al*., 1989).

Nodules

Having been formed differently, it is to be expected that the nodules from the Clarion-Clipperton Zone and the Cook Islands will differ in form, structure and chemical composition. The Cook Islands EEZ nodules are generally smaller and more symmetrically spheroidal (various authors) than the Clarion-Clipperton nodules, which are often characterized by a flatter bottom side and/or "a knobby band in the equator zone" (Meyer, 1973) of the nodule. The surfaces of the Cook Islands nodules are smoother when compared to CCZ nodules, since the former formed hydrogenetically (Usui and Moritani, 1988). When sliced, nodules from both zones have concentric layers. However, according to Glasby (1978), the innermost layers in most nodules of the Cook Islands EEZ formed by "interpenetration and replacement of a pre-existing volcanic core by manganese oxides" with only the outer layers precipitated directly from seawater.

Mineralogically, the Cook Islands EEZ nodules resemble the mineralogical structure of ferromanganese crusts. The dominant ferromanganese mineral of those nodules is vernadite (δ-MnO_2) (various authors), as compared to todorokite in the CCZ (Meylan, 1974). The formation of vernadite is favoured by the presence of highly oxygenated bottom waters, the Antarctic Bottom Water, which at this location may be considered to be highly oxygenated, having been formed as part of the Circum Antarctic Water Current in the Ross and Weddel Seas (Nishimura, 1987). This difference in the dominant ferromanganese mineral reflects the variances in the metal enrichments of the nodules between the two regions. For this study, the strategic metallic elements considered were cobalt (Co), copper (Cu) and nickel (Ni). The CCZ nodules favoured the adsorption of more Cu and Ni in their ferromanganese structures, while the Cook Islands EEZ nodules favoured the adsorption of more Co. The nodule metal averages in the CCZ are Cu 1%, Ni 1.3% and Co 0.22% (Cronan, *et al*. 1991), as compared to those in the Cook Islands EEZ, which are Cu, 0.5%, Ni <0.5% and Co 0.5% (Usui and Moritani, 1988).

Based on survey reports, areas within the EEZ of the Cook Islands that have the highest probability of high nodule abundances are to the north, southwest and south of Rarotonga. Using the East West Centre (EWC) Minerals Policy Programme Data Bank, 2^o x 2^o areas within the Cook Islands EEZ were studied to evaluate their metallic content of copper, nickel and cobalt. The results and locations of these areas are shown in the following pages. In addition, areas recommended in some reports were evaluated using the same data bank.

The enrichment of cobalt in the Cook Islands nodule areas is very obvious when compared to the enrichment of Cu and Ni in the Clarion-Clipperton nodules. Furthermore, average nodule densities calculated in all the areas considered show that the Cook Islands areas are generally higher compared to the Clarion-Clipperton areas by almost a factor of two. However, this may just be an artefact, since not all the sampled areas have reported sample densities. Considering only the available data used in these calculations, the generally higher nodule densities reported from the sample areas of the Cook Islands are due to the combined effects of: (a) a good supply of nucleus materials from terrestrial as well as submarine volcanic activities; (b) low biological activity near the sea surface giving rise to low sedimentation rates; and (c) intensified bottom current velocities. It should be noted, however, that high nodule densities often do not guarantee high metallic contents (Exon, 1980; Exon, 1981; French Delegation, 1981). But the hydrogenetic origin of the nodules leads to slower nodule growth rates and, thus, smaller nodules than diagenetically formed nodules.

Apparently, due to the different tectonic setting and ocean circulation environment, the geological and geochemical characteristics of the Cook Islands EEZ nodules are distinct from those of the CCZ nodules. A comparison of nodule geology and geochemistry of the nodules from both zones is shown in *Table 1*.

Cook Islands manganese nodule model components

Based on the analyses provided earlier, it is proposed that a geologic/exploration model for manganese nodules in the Cook Islands EEZ would be the "Concentrator Basin Model (CBM)". As defined by the author in 1990, the CBM basically postulated that the formation of manganese nodules, as well as manganese crusts, is dependent on the occurrence of various levels of concentrating basins, ranging from megabasins (such as the Peru Basin and the Clarion-Clipperton Zone, within which there are a number of smaller basins (such as the Penrhyn and Samoa basins in the Cook Islands EEZ), all of which serve to create the necessary environment for the development of manganese models. Particularly important in the CBM is the role of the Antarctic Bottom Water current. It is believed that the individual concentrator basins provide for successive channeling of the ADB, resulting in areas of laminar and turbulent flow of the Antarctic Bottom Water within the basin, the largest concentration of nodules being formed, based on other geological parameters (given below) in the areas of turbulent flow.

The critical and ancillary geological parameters of the concentrator basins are as follows:

Critical components of the model

- Requires combination of macro and micro basins {Scale varies by region (Cook Islands EEC vs. CCZ)
- Antarctic bottom water
- Distribution proximal to main current
- Water depth in excess of 4,000m
- Carbonate compensation zone depth
- Sediment transparent layer
- Type determines nodule and characteristics

Ancillary components

- Volcanic activity (Pyroclastic)
- Nucleating material
- Turbulent versus laminar flow
- Slope

The evaluation of these components in the context of "Concentrator Basins" provide a useful exploration and evaluation model for manganese nodules within the Cook Islands EEZ and is believed to be generically applicable to developing similar exploration models for manganese nodules in the CCZ. Central to this effort would be the creation of detailed bathymetric and tectonic maps in order to define more clearly mega and small concentration basin areas.

Summary and conclusions

The major conclusions of the present study are as follows:

Based on the geology and topography, the Cook Islands exclusive economic zone (EEZ) can be latitudinally divided into northern (6^{o}-10^{o} S), central (10^{o}-17^{o} S) and southern (17^{o}-25^{o} S) regions. Each region has unique geological and topographic environments which have determined the ocean circulation and sedimentation which in turn has affected the concentration of metals and abundance of the manganese nodules.

Table 1
Comparison of the Cook Islands exclusive economic zone and the Clarion-Clipperton Zone nodules and depositional environments

	Cook Islands exclusive economic zone		
Nodule and deposit characteristics	*Area NW-S of Rarotonga*	*Area N-SE of Rarotonga*	*Clarion-Clipperton Zone*
		Nodules	
Size	Range from 1-6 cm in diameter – mostly 2-6 cm up to 8 cm	Normally range from 1-7.5 cm in diameter (4-7.4 scarce).	Normally range from 1-2.5 cm (small) in diameter to large (5-6 cm) with an average of 3-4 cm
Shape	Spheroidal (most common) to ellipsoidal and pebble. Also present are plates (thin and massive)	Spheroidal, ellipsoidal, discoidal with some poly-nucleate often irregularly deformed or flattened. 20-60 mm nodules are normally faceted.	Discoidal, ellipsoidal and widespread poly-nodules (pancake to hamburger size on siliceous ooze)
Surface texture	Smooth micro-botryoidal (black surface colour) to rough botryodial (brown surface colour)	Smooth micro-botryoidal (black surface colour) to micro-botryoidal and (brown surface colour) – normally granular surface texture on one side and micro-botryoidal on the other	Rough, botryoidal to smooth with the presence of large equatorial collars suggesting that nodules grow half submerged in sediments.
Internal structure		Outer 1-4mm of Mn Oxide (direct deposition from sea water) and a hard inner layer of hard lustrous Mn oxide w/variable amounts of clay minerals (interpenetration and replacement of pre-existing volcanic core by Mn oxides).	Concentric banding that may be asymmetric depending on the shape of the nodule.
Depths	4,800 to 5,400 metres - highest Cu+Ni+Co at 4,820 metres	Highest nodule concentration @ 4,900 to 5,300 metres; highest Ni+Cu+Co content at 5,400 to 5,400 metres; high nodule abundance at 5,000-5,400 metres. Ni and Cu enrichment at 5,000-5,300 metres regionally.	Highest nodule concentrations at 4,900-5,300 metres but range in depth from 4,000 to 5,600 metres. Ni maximum at 4,900 m on siliceous sediments.
Density	NW (Sm) – 8.4kg/m² SW locally 20.4kg/m²	Ranges from 22.5 to 2.58kg/m² (9-11ºS and 155-157º W) – Approx 1 kg/m² (11-20ºS and 158-161ºW)	Approx 10 kg/m² on average and ranges from 10-15 kg/m²
Surface	53%	90% in densest areas; and	Max of .50% with 20-50cm %

coverage		25-50% (Aitikai)	common in many areas. At 7-13ºN and 118-155ºW in easternmost and westernmost areas 50-100%; Central Area 0-25% with some 25-50%
Growth rate	10 mm/m.y	1.1 mm/m.y. in Penrhyn Basin	
Nucleus type	Often small piece of altered volcanic material w/evidence of Mn oxide replacement.	Often small piece of altered material w/evidence of Mn oxide replacement	Often one and sometimes two or more aggregates normally weathered basalt and nodule fragments. Small nodules (1-4 cm) yellow grains of palagonite – large nodules (5-10 cm) ferromanganese fragments.
Nucleus core	Terrestrial, biological	Terrestrial, biological	Terrestrial (fracture zones and seamounts)
		Sediment type	
Type	Brown silty clay (eastern part of Samoan basin); chocolate brown clays (suggesting increased oxidation); pelagic clay; brown clay is common, but in areas <4800 m calcsiliceous clay is common	Reddish brown abyssal clay; stiff reddish-brown abyssal clay SPB; burnt sienna clayey mud; stiff grayish brown abyssal clay; (Aitutaki passage) homogeneous dark-brown to dark-reddish brown pelagic silty clays; in NPB varies from calcareous ooze to calcareous clay, in SPB calcerous ooze above 4500 m and pelagic clay below 4800m high productivity areas zeolitic clay is common	(south of 10ºN and between 90º-160ºW) radiolarian ooze, (north of 10ºN) red deep sea clay' brownish colour radiolarian clay and ooze.
Deposition Rate		(Aitutaki passage) 2 mm/thousand years	(radiolarian ooze) 3 mm/thousand years, (red clay) 1 mm/thousand years
Thickness/Age		(Aitutaki passage) thickets 50-1000 msec in deep parts and terraces, mostly less than 10m., age ≈ 70,000 yrs B.P.	Tertiary Age
Source	Low biological productivity at sea	Metalliferous elements from once-active tectonic features-postulated triple junction in SPB, AABW, NPB very low plankton productivity; types (smooth) nodules elements are hydrogenic; AABW; biological and organic carbon	High biological productivity at the sea surface, type r (rough) nodule elements are diagenetic (in mildly reducing environment associated with siliceous sediments) type s (smooth) mainly hydrogenetic
Benthic Life		(Aititaki) mounds, stick	Benthic life, evidenced by high

		structure and large spiral loops	organic carbon content of sediments, are responsible for keeping the nodules on the sediment surface
Hiatus Ages		(Aitutaki passage) 70,000 years B.P.	Major erosional event 70,000 yrs B.P.; early Miocene-late Pliocene also the period for initiation of nodule growth
Cu Average	<0.5 wt%(EEZ of CI); 0.25 wt%	>0.75 wt% just south of equator and 7^o-8^{o}S max at 1.25-1.41 wt%; south of 10^{o}S <0.5 wt% and 0.25 wt%	Ave. 1 wt%
Ni Average	Max. at 25^{o}S at <0.5 wt% (EEZ of CI); 0.5 wt%	>0.85 wt% - max 1.25-1.7 wt% (3^o-4^{o}S & 7^o-8^{o}S), at equator & south of 10^{o}S <0.5 wt%	Ave 1.0-1.2 wt%; ave 1.3 wt%
Co Average	13^o-17^o and 19^o-23^{o}S max 0.5-0.58 wt% (EEZ of CI); increasing towards Rarotonga from the South and Southwest	In NPB north of 5^{o}S<0.25 wt%, south of 10^{o}S 0.5 wt%, 13^o-17^{o}S and 19^o-23^{o}S max of 0.5-0.6 wt%	Ave 0.25% wt%; ave 0.22 wt%
Ni + Cu + Co	Max is 2.02 wt%; at 3^{o}S max at 2.5 wt% highest near Rarotongo	1.0 wt% or less; >2.5 wt% (east of Manihiki, 3^{o}S and 7^o-8^{o}S); max 2.02-2.1 wt%	Ave is 2 wt%
	Mineralogy		
Major	δ- MnO^2; some 10 angstrom Manganite	δ- MnO^2; (Aitutaki) δ - MnO^2	todorokite
Minor	Quartz, feldspar are always present; sometimes montmorillonite & goethite	Montmorillonite-phillipsite of montmorillonite-feldspar; (Aitutaki) zeolite, magnetite quartz, illite (?) and plagioclase	Constant amounts of quartz and feldspar
	Sea bottom features		
Topography		SPB characterized by gently rolling plains, abyssal hiss, by steep, narrow scour channels, w/up to 40 m relief.	Gently rolling abyssal hills
Current	Deep water masses: Pacific Deep Water overlying Antarctic Bottom Water separated by benthic Front at about 3500 m	Deep water masses: Pacific Deep Water Overlying Antractic Bottom Water separated by Benthic Front at about 3500 m; (1.3º C) AABW	AABW winnows sediment and uncovers nodules
CCD Depth	4800 m	In NPB 5100 m, in SPB 4900 m.; 5000 m. at 17^{o}S to 5300 m. at equator	4600 m.

The Aitukaki Passage area shows the most abundant manganese nodule concentration in the Cook Islands EEZ.

Metal concentration in the manganese nodules in particular cobalt, copper and nickel is inferred to be related to the circulation of the Antarctic Bottom Water currents within the Cook Islands EEZ. This physio-chemical control results in the cobalt content in the nodules being highest (0.5-0.8%) in the southern and central regions; in addition, in the southern region, the nodule abundance is higher than in the northern region. Conversely, copper and nickel contents are highest in the northern region, where nodule abundance is lower.

The geology, microtopography, and ocean environment of the Cook Islands EEZ is quite different than that of the Clarion-Clipperton Zone (CCZ). As a result, the manganese nodules of the Cook Islands EEZ and the CCZ differ in form, structure and chemical composition. The nodules of the Cook Islands EEZ are generally smaller, smoother in surface and more symmetrical (approaching spherical) than the CCZ nodules, which are characterized by a flatter bottom side of the nodules. The CCZ nodules contain an average metal content of Cu 1%, Ni 1.3% and Co 0.23%, as compared to those of the Cook Islands EEZ, which contain Cu 0.19%, Ni 0.32%, and Co 0.45%. The 2.5 times enrichment of cobalt in the Cook Islands EEZ nodules is obvious, as is the enrichment of the copper and nickel in the CCZ nodules. Average nodule densities in the Cook Islands EEZ areas are generally higher compared to the CCZ areas by almost a factor of two.

Variogram analyses of nodule abundance and composition from the Cook Islands EEZ and the CCZ show that the nodule abundance and compositions of the former zone are significantly more spatially correlated, that is,, more uniform in abundance and composition than in the CCZ. The variogram analyses of the cobalt abundance in the central region of the Cook Islands EEZ show particularly high values of 80-105 g/m^2 in an area that is between 14^o-18^oS lat and 157^o-161^oW long.

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SUMMARY OF THE PRESENTATION

(The Chairman informed participants that the speaker, Dr. Allen Clark, had been an early employee of one of the very first groups that explored the deep ocean in the Clarion-Clipperton Zone. He said that Dr. Clark had kept track of the developments in that discipline over the many years, and that he was going to talk about the Equatorial South Pacific, and any lessons that he could give that could be applied to the Clarion-Clipperton Zone).

Dr. Clark said that the results that he was going to speak about were actually probable projects that had been sponsored by the South Pacific Applied Geoscience Commission (SOPAC), by the Government of the Cook Islands and by the East-West Centre, of which he happened to be an employee. He said that his presentation was a combination of a large amount of the various studies that had been done in the Cook Islands' exclusive economic zone (EEZ) from the mid-1970s into the 1990s. The studies shown were much broader than what he was going to talk about. He clarified that presenters at the workshop had provided a range of papers including resource assessments, economics, policies and politics, markets and other things pertaining to manganese nodules. He said he was going to give participants a brief summary of the geological work done on nodules around the Cook Islands.

With regard to the orientation and size of the study area versus the Cook Islands, Dr. Clark said that it ran more or less from about 6^{o} south down to about 28^{o}, and more or less from 155 to about 168 west. He said that the major topographic feature of the study area was the Manihiki Plateau, which he described as outstanding. He said he would be talking about several other outstanding features during his presentation.

Dr. Clark showed participants a topographic map of the submarine morphology in the region, and said that he would be talking about its major geomorphic subdivisions. He told his audience to keep in mind that in addition to the Manihiki plateau, there was a very large basin called the Penrhyn Basin, the Aitutaki Passage, the Cook Islands chain; and the southern portion of the Cook Islands. He said that each of these areas had different geomorphic provinces along with different relationships with manganese nodules. Dr. Clark said that knowledge of the topography in the Cook Islands region was fairly general and that there was probably more information on the Plateau Area than what they had on the other parts of the study area. He however suggested that basically in the region of the basin and Passage Area the topography was relatively flat.

Presenting a summary of the cruises undertaken, Dr. Clark said that it was to give an idea of where samples had been taken. He said that the belt, the passage and the Penrhyn Basin were to be kept in mind. He indicated some areas that he said he had always focused on, including where David Cronan had gone, which was basically the transect, right through the heart of the region.

Dr. Clark said that in the paper that would be distributed there was additional information on the actual distribution of nodules, and also maps of the distribution of the metals, so he would not go into great detail on that matter. Dr. Clark said that if that paper did not satisfy the appetite of participants, there was a 250-page report, which had been prepared for the Cook Islands Government, containing the geochemistry of the nodules and the statistical analyses that were performed.

According to Dr. Clark, the distribution of the nodules was concentrated in three areas with two very distinct hot spots, in which nodule abundance was greater than 20 kilograms per square metre, and in some of those areas, it went up into 30/32 kilograms per square metre. He said that the distribution pattern was a little more detailed. He pointed out a fairly broad area with nodule abundance of 5 to 10 kilograms per square metre, and other areas with abundance of 15 to 20 kilograms per metre. He suggested an area that he described as having the greatest potential, based on the grade data.

Dr. Clark pointed out the area where copper and nickel primarily occurred, and a cobalt rich area. He said that as one went beyond that, once again a fairly substantial nickel anomaly could be picked up in that area. Speaking about cobalt, Dr. Clark said its presence in nodules was less than three-tenths, but scaled off in areas down to 0.5. He also said that cobalt concentration tended to correlate very well with nodule abundance - the higher the nodule abundance, the higher the cobalt content. So, that was one of the positive correlations that existed in the area. He noted that in talking about that, one talked a lot about the Antarctic bottom water current, about which he would say a few words later.

With regard to nickel, Dr. Clark said that concentrations were in the North-East area of the Cook Islands, and that the maximum values were between 1.25 and 1.7 per cent, which he described as very high grade, and that they occurred in the northern portion of the central Penrhyn Basin. Beyond that, Dr Clarke said that nickel values were quite low, except for one small area in the South.

According to Dr. Clark, copper concentration followed nickel very closely; in the Cook Islands, copper tended to be very much concentrated in the South.

Dr. Clark said that for those who were interested in resource estimates in the area, it was very small compared to the Clarion-Clipperton Zone. Comparing the two regions, he described the Clarion-Clipperton Zone as a copper/nickel mine, and the nodules in the Cook Islands region as a cobalt mine.

He said the cobalt results were associated with other small areas throughout the region. There was actually one that had not quite made the cut-off. He said that it was his belief that a major portion of the control of the development of the nodules was because of the Antarctic bottom water coming up through the passageway into the Penrhyn Basin. He said that one could think of the Antarctic bottom water as a river, because it was very dense, stayed on the bottom, moved up, and looked very much like a river. He said that it looked so much like a river that where there was some information on it, it was known that it was basically characterized by laminar flow in the central portion of it, and fairly turbulent flow in some areas, in the marginal areas; it was the same as the river. He also said that it was conceivable that when they started to look at the deposition of nodules, it was certainly known that the carbonate compensation zone played an important role in that. It was necessary that it be there, but, there were also a number of other things that needed to be there at the same time.

Dr. Clark said that with regard to the distribution of nodules in the Cook Islands, it was largely controlled by what he termed a series of large and small basins. He said that if one envisioned the Antarctic bottom water coming on up towards the Cook Islands into the Aitutaki Passageway, as a river coming in, two things happened. First, when it came to the passageway, a great deal of turbulence occurred at its edges. He suggested that the turbulence was required, along with the proper sedimentological basis, along with a proper slope, and all the other physical characteristics. He said that these factors were responsible for the very high concentrations of nodules before and after the Aitutaki Passageway. Dr. Clark described the process as akin to the Venturi effect, saying that if one took a flow, choked it down, and then let it come out the other side, one would get turbulence going in and coming out; those were the sorts of things that were not that dynamic but they meant that there was a certain amount of agitation, a certain amount of transfer, and if one carried the right kinds of materials as one came, one would be depositing them and forming nodule type deposits. He emphasized that it was necessary to have the right sedimentation - the transparent layer.

Dr. Clark said that the transparent layer existed in these areas, which was why large concentrations of nodules were found. He also said that the carbonate compensation zone, a roughly 4,800-metre zone, (below what Professor Cronan had pointed out earlier) where cobalt and other metals would be dropped off was very important. Basically, copper and nickel would be dropped out in a simple way. He said that when all these things were put together and one started looking at their distribution in the Cook Islands, one came up with sort of a model, that indicated that those individual basins that were formed adjacent to the Manihiki Plateau, including the Penrhyn Basin, which was the largest of them had a very important role in nodule deposit formation.

Dr. Clark said that wherever the little basins were found, there tended to be a concentration of nodules because they had the right slopes, the right sedimentation, and the right environments for developing nodule fields. He said that to some extent in the Cook Islands, what had been observed was the formation of nodules and nodule fields that were associated with a series of macro-to-micro basins. He described a macro basin as about 150 to 200 square miles and a micro basin as about 50 to 60 square miles. He said that if one looked at the topography of the seabed surrounding the Cook Islands in detail, one could identify the macro and micro basins. Dr. Clark said that if one viewed the Clarion-Clipperton Zone as a basin, which it most certainly was, or acted like one, there was a massive concentration of nodules in the Clarion-Clipperton Zone, which, in his mind, was what he termed a simple basin. There were about five different sizes of these basins.

Dr. Clark said that he was interested in basins because a large proportion of mineral deposits either occurred in or adjacent to them; there was no reason why nodules would be any different. He said that if one looked at it in that context, and began to think about it in terms of the Clarion-Clipperton Zone, and if one looked at some of the maps, which showed high concentrations of nickel and copper, one began to see from the maps that they were actually, fairly large macro basins; and it was in these areas that things like the Antarctic bottom water got turned around, and manganese nodules began to be formed in the kinds and amounts that were seen; otherwise, one just got nodules out in the Clarion-Clipperton Zone and there was a whole variety of variables that controlled that.

Dr. Clark said that if he had to develop an exploration model, from which he would go looking for manganese nodules, he would do it on a basin analysis, and that would be the fundamental thesis that he would start working on. All of the other characteristics had to be there just as with any other kind of mineral deposit.

In conclusion, Dr. Clark stressed that there had to be some fundamental, structural physiological feature that was primarily responsible for most mineral deposits that were known of in the world. He said that he did not know that manganese nodules were any different. Thus, he believed that the idea of having concentrator basins showed up fairly well in the Cook Islands and was one level of looking at it. Another level was to look at the Clarion-Clipperton Zone in the same general kind of a concept. Dr. Clark said that he did not know that it could ever be proven, but one could perhaps look at the data to see whether it gave rise to any ideas and led to some broader areas that could be concentrated on in the Clarion-Clipperton Zone.

SUMMARY OF THE DISCUSSION

A participant wanted to know to what Dr. Clark ascribed nickel enrichment in the southern coast.

Dr. Clark said that those were areas that tectonically were very, very active and with an extreme amount of volcanism, and he believed that some of those anomalies were actually associated either with volcanism itself, or that they might be associated with some sort of hydrothermal activity that was going on. Dr. Clark said that he was guessing that the nickel was coming out of the faults somewhere, and that that was why it was seen there as some sort of broad regional anomaly, but he really did not know.

The participant said that he was trying to get an answer because, in that particular basin, there was this strange site, and he had seen nickel-enriched nodules in places where one would not expect it on the basis of a biological area for the productivity model.

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CHAPTER 20 WORKING GROUP DELIBERATIONS

The Workshop's recommendations emerged largely from three working groups that considered what sorts of data should enter into a geological model of the Clarion-Clipperton Zone (CCZ) and what further work would be needed to assemble existing data: Group A dealt with tectonics and volcanism; Group B, with bathymetry and stratigraphy; and Group C, with sediment and water column characteristics. In all cases, the focus was on how natural processes affected the abundance and metal grade of nodules, and how information on those relationships could be derived by analysing earlier research.

Tectonics and Volcanism

Group A looked at the "basement" underlying nodule deposits – specifically, the shifting patterns of the earth's crust (tectonics) and the contribution of volcanoes and magma flows in realigning undersea topography (volcanism). The CCZ might be divided into three physiographic zones in which the crust varied in age from 10 to 74 million years. Nodule formation was seen to be related to motion of the crustal plates defining those zones, notably the Pacific plate that abuts the western edge of the North American continent. In the group's view, that relationship deserved further study.

The group saw tectonic activity, including faulting and fracturing of the crust, as a major component of the geological model. Fissures in the seafloor provided channels through which deep currents might supply extra oxygen conducive to nodule formation. An unnamed, east-west fracture through the centre of the CCZ deserved study, along with similar but smaller features traversing the zone from north to south, as locales for above-average accumulations of nodules. The group recommended the compilation of maps defining such features in greater detail.

The group noted that volcanic activity had played a major role in reworking the seabed in the CCZ, creating mountain ridges, plateaus and seamounts. While that fact was well recognized, it was thought that a comparison was needed of the age and nature of such activity in different parts of the zone, beginning with studies of the age of different structures.

Finally, the group urged that a closer look be taken at information presented to the Workshop about traces of recent hydrothermal activity in the CCZ. Nodule composition and structure might have been affected by past stages of intense hydrothermal activity.

Group A was chaired by Yuri Kazmin, a consultant with the Russian Ministry of Natural Resources and the Interoceanmetal Joint Organization.

Bathymetry and Stratigraphy

Group B dealt with the mapping of the seabed (bathymetry) and the sediment layers underlying it (stratigraphy). Noting that past analyses had dealt mainly with the CCZ as a whole, the group suggested that greater emphasis be placed on models specific to sites and areas of the zone. It also favoured the creation of two exploration models – one in narrative form and the other predictive, with a mathematical base.

With regard to the narrative version, the group observed that, as general factors affecting the origin, distribution and metal content of nodules were well understood, the emphasis should now be on how those factors interacted in specific instances. Most of the group's recommendations concerned the predictive model, for instance, what chemical and physical characteristics in the nodule environment could be used as indicators of the likely presence of high-grade deposits.

The group viewed the carbonate compensation depth (CCD) as a critical factor in the abundance and metal content of nodules. When the seabed lay too far above or below that depth – which varied in different parts of the ocean – nodule formation was inhibited.

The "grain" of the seafloor – its gross local and regional structure – was identified as another factor in determining the abundance of nodules and, to a lesser degree, their content. Alongside this factor was topography, including slope and surface texture.

Present and past sedimentation was cited as critical to almost every aspect of nodule abundance and content. The highest nodule concentrations lay in beds of siliceous ooze and zeolitic clays. At the same time, none were found outside zones of high biological productivity near the equator. The group believed that sedimentation rates, erosion and currents must be in balance; too little or too much of any of these factors had a deleterious impact on nodule formation.

While the group found that a great deal of data on these factors already existed, much of it had not been given to the Authority. It was therefore of the view that the Authority should identify and access such data from seabed contractors and public sources.

The group offered seven recommendations for action by the International Seabed Authority. They included the development of databases on seafloor nodule photography, and seafloor morphology and sedimentation; a definition of the geological evolution of the CCZ over the past 20 million years; the creation of sediment maps; the collection of information on heat flow; the development of exploration models for specific areas; and the undertaking of additional work to acquire and study data and develop a system of open data access.

Group B was chaired by Allen L. Clark, Senior Fellow at the East-West Centre, Honolulu, Hawaii.

Sediments and seawater

Group C concentrated on the interface between sediments and the overlying water. It cited as the main element in that regard biological productivity, and specifically export productivity – the part of the chemical soup that reached the bottom. That was regarded as a much more important source of metals than the surrounding seabed. Since abundance and mineral grade were not generally related, the group felt that separate models were needed for those two factors.

The group observed that the relationship between productivity and nodule formation was not linear. While abundance rose with greater productivity up to a certain level, it diminished beyond that point, eventually dropping to zero. Thus, it was critical to determine the turnaround point. The depth of the oxygen minimum zone was another important element, but more work was needed to establish how that factor operated differently from productivity.

Like Group B, Group C saw a need for further studies of the carbonate compensation depth (CCD), including its variations from east to west. Copper, manganese and nickel concentrations increased near the CCD, while cobalt and iron grades decreased. Given that relationship, the task was to plot areas likely to be richest in particular metals. While no convincing relationship existed between nodule grade and the surrounding water, nodules were more likely to be found in particular types of organic sediments, with the richest and most abundant occurring in siliceous radiolarian ooze, rather than diatomaceous ooze or red clay. Rate of sedimentation was probably more important than sediment type in predicting abundance.

Organic carbon in the sediment also increased towards the CCD but little data was available on this factor in the CCZ. Other factors included the calcium carbonate and silicate content of sediments, and the content and composition of pore water -- the seawater within nodules that bore additional metals. The group cited productivity, calcium carbonate dissolution, biologically-generated silicates and organic carbon as topics that required further work. The group cited evidence that nodules were most abundant in areas of greatest bioturbation – burrowing and other animal activity that rearranged sediments.

Finally, the group suggested that any differences between the CCZ and the South Pacific be examined. If there were no substantial differences, a model for one could be applied to the other. Otherwise, the reasons for any difference should be investigated.

Group C was chaired by David Cronan of the Department of Earth Science and Engineering, Imperial College, London.

Presentations by working group chairmen

A. Working Group on Tectonics and Volcanics

(Yuri Kazmin)

Tectonic and volcanic processes, as well as plate motion, are related to nodule formation in the CCZ.

The group identified suitable proxy factors and data from which the tectonic and volcanic processes could be determined. The group also discussed appropriate actions that should be undertaken in the process of developing the geological model. The inferred relationship of tectonic and volcanic activity with nodule abundance and grade, especially with the distribution of nodule in the CCZ, was established. The point was made that tectonics and volcanic activity might have a direct relationship with nodule grades, being a source of nodule supply. Tectonic processes on the global scale might also have played a role indirectly by creating favourable conditions for nodule creation in the CCZ. It was also pointed out that the actions to be taken during the development of the geological model, in connection with the tectonics and volcanics, would deal with the collection and processing of raw data, as well as with interpretation of regional data.

1. Plate motion

Plate motion and seafloor subsidence were considered to be important factors in these processes, as they alternate the influence of the bathymetry and the depth of the ocean floor. This entire relationship was the result of chemical composition in water columns, such as the CCD. How might the increase of the depth of the CCD be a result of its subsequent fall in history. It was noted that the rest of the CCD dated from 65 million to 10, 20 million years in the eastern part and that its formation was related to the spreading processes in the East Pacific Rise. One could consider the CCZ as comprising of three geographic zones, defined by the bathymetric character, and separated at 140^{o} west and 125^{o} west. The western part belonged to the transitional zone from the old oceanic plate to the young oceanic plate, with the crust dating back to more than 60 million years, up to 74 million years.

The nickel blocks of the CCZ were created on the young oceanic plate 36 million years ago, and that part was confined to its transitional zone from the young oceanic plate through 10 to 30 million years.

This side of the region was based on the location and the results of the Deep Sea Drilling Project. It was the common view of the group that the plate motion might have been closely related, although indirectly, to the nodule formation in the CCZ by creating favourable conditions in the bioproductivity zones. It was noted that some related nodule composition grade to the age of the crust itself.

The view was expressed that, with respect to special trends that caused the reverse correlation in metal grades and abundance of nodules, the phenomenon could also be related to the age and tectonic structure of oceanic crust as a result of plate motion; it needed to be addressed within the geological model.

It was agreed that the age, composition and structure of the adjoining crust in the CCZ might constitute a suitable proxy for a review of plate motion and subsidence. That could be derived through the synthesis, interpretation and analysis of the available data on anomalies, and other relevant geophysical information could be derived from published and unpublished sources, including data from various data centres and published maps.

From the position of the history of the CCZ, tectonics could also be quantified by a review and interpretation of the geological results of the Deep Sea Drilling Project. The collection and review of Deep Sea Drilling Project data should be undertaken simultaneously, as well as other available information on the age of the basement and the overlying sediments. A digital map series of the basic tectonic structure of the CCZ, substratum and age might be compiled. It would be useful and helpful to develop a model of the tectonic evolution of the Clarion-Clipperton Zone during the past 20 million years, in order to better understand the possible relationship of nodule genesis and formation processes in the zone, in relation to the geological history.

2. Tectonic activity

The process of tectonic activity, including crustal structure, folding and fracturing, was one of the major components of a geological model on a regional and local scale. Some scientists believed it to be a primary source of metals, which potentially exploited weaknesses, such as major fault systems, shells or metals supplied to the ocean floor.

Another view was that fracture and pull zones might provide a supply of free oxygen, thereby creating a favourable environment for nodule formation.

Besides the Clarion Clipperton transform faults themselves, the oceanic basement of the zone was characterized by a normal variant of folding sub-parallel to the East Pacific Rise and generated during normal processes of seafloor spread. The spreading course was calibrated using a magnetic anomaly at the age of basement. The composition of volcanic regions as seamount changes parallel to the Clarion-Clipperton course strongly suggested tectonic control of volcanic activity.

The south longitudinal fault system was responsible for the predominant regional and local morphological landscape of the zone, which was defined by a classic *horst and graben* structure of the basaltic basement. Understanding the significance of the primary seafloor spread and the subsequent reactivation during the tectonic evolution of the zone would be essential for determining the effects on sedimentation and the re-sedimentation processes. During consideration of a mixture of possible relationships between nodule abundance and tectonic processes in the zone, it was recalled that a presentation had been made highlighting the special relationship between high nodule abundance and the postulated Unnamed Fracture Zone. It was thought that particular attention should be focused on the issue and should foster the development of the geological model. The existing location of such a fracture zone showed realistic readings from the probe and analysis of bathymetry and other geophysical and geological datasets. The appropriate analysis would be in respect to nodule abundance and grade within profiles across the fracture zone, showing period level wherever possible.

The same view was expressed with regard to the assumption of a possible correlation of manganese concentration in the Clarion-Clipperton Zone on a global and regional scale, with fractures of horsts in a north-north-west direction which were confined to the east-south-east extension of the volcanic ridge system.

Concerning possible proxy data, which might be used to constrain the tectonic framework of the CCZ, the general view was that the Seabed Authority should express tectonics on a general and local level. The relief in general reflected the basalt structure at various stages of all mineral activities. The analysis and interpretation of the bathymetry and ocean floor topography and the calibration of that data with other geophysical parameters might facilitate indication and lineation of fresh resources. In short, the linear volcanic regions and the volcanic seamount changes strongly suggest sub-latitudinal pull systems on both a regional and local scale.

Attention was drawn to some presentations which had indicated that nodule abundance and metal grade anomalies were spatially related in the CCZ to soil and lineaments on a regional scale. The view was expressed that, in addition to bathymetry and seabed morphology, with the appropriate analysis of the spatial distribution and configuration of nodule fields, the fold and fracture system might identify with various abundance and grade within the Clarion-Clipperton Zone. Other important local and regional indicators might be gravity/magnetic anomalies, as well as crustal age, composition and tectonic structure of the basement and underlying sediments. Location of registered size for ridge and volcanic activity and earthquake epicentres in the Eastern Pacific might also represent important evidence of tectonic activity in the past. With regard to the direction that may be undertaken for the development of the geological model, the group would commence with the analysis and interpretation of the bathymetry and topography maps of the CCZ to be compiled on the scale of one to five million, one to million, as well as a review of all data and information on bathymetry and topography.

The workshop was being undertaken with the aim of delineating fractures, faults, and other lineaments, at various levels, to develop the tectonic framework for the model. The same procedure would also be applied with respect to available information on the spatial distribution and configuration of such nodule parameters as abundance and metal content. Priority would be given to the appropriate analysis and interpretation of relevant geophysical maps and data for the CCZ and to analysis of recent seismic activity in the CCZ based on information registered by earthquake epicentres in the Eastern Pacific. As an outcome, the geological model development showed the preparation of schematic maps at various scales reflecting tectonic features – fractures, faults and lineaments, registered earthquakes, etc.

3. Volcanic activity

General structure and composition of the Clarion-Clipperton ocean floor had been influenced by several stages of volcanic activity. First, it was observed that the volcanic origin had been formed as a result of seafloor spreading courses at the East Pacific Rise. It was suggested at various scales that volcanic structures had been superimposed on the primary seafloor fabric; plateaux, all volcanic seamounts would change the mountain ridges. Volcanic plateaux outside the normal volcanic areas had been met with results in extreme relief in some parts. In some areas the relief had been complicated by latitudinal change in volcanics, culminating in eight hundred (800) to three thousand (3000) metres above seawater, and volcanic mountain ranges. Those ranges were being controlled tectonically and might reflect primary crustal weakness along flow lines, perhaps generated as existent key ridges or fracture zones.

The general view was expressed that, although the important role of volcanism in the Clarion-Clipperton Zone was well known, no proper attention had been given to the comparative analysis of the age and nature of volcanic activity in various parts of the CCZ. It was only the more intensive volcanic activity registered on the north-east of the zone, within the western flank of East Pacific Rise spreading zone, with rather young basement, where organic changes and ridges might represent volcanic structures typical for extinct spreading centres. It was also more than the volcanic activities reported in the north-west, near the Line Island volcanic chain. That part of the zone was confined to the transitional zone from the old to the young, with the crust dating back to more than 60 million years.

It was felt that the regional volcanism, in that part, may be different from volcanic activity in the east and belonged to the processes of formation of volcanic ridges over a hotspot. It was considered that, in many respects, proxy data for reflector would come in during various phases in the CCZ; maybe it would be similar in many respects to those mentioned above in tectonic activity. Therefore, possibilities for development of the geological model in that area might also be similar. However, the steps were going to be taken in relation to the various regional volcanic structures in different parts of the CCZ. This also included certain analytical research including age determination.

4. Hydrothermal activity

Attention was drawn to the presentation with respect to values of traces of risen hydrothermal activity in the CCZ. It was considered to be an important factor which deserved much attention during the development of the geological model. In particular, verification of the original observations was needed. The research would thus be carried out to obtain additional information to legislate. The group considered whether that factor was of significance, and thought that it was possible to suggest a proxy dataset on this stipulation. It was still unlikely that, aside from basement sampling information, it would be possible to follow up with this research.

A view was expressed with regard to the possible interrelationship of nodule composition and the structure with certain stages of a basic hydrothermal activity in the Clarion-Clipperton Zone, resulting in sufficient import of metals in seawater and sediments, resulting in the formation of minerals and nodules intercalated with nodules in the nodule phase, and which also contained the same elements. However, the group felt that factors of such importance were not of value to the working groups dealing with the nodules' genesis.

B. Working Group on Bathymetry and Stratigraphy

(Allen Clarke)

I don't actually have a complete list of all the people who were in the working group. It was a highly-dynamic group of people that kept changing. At any given time, there were inputs from up to 14 persons, and down to about 6. So all those inputs of benefit that we were discussing today came from the participants; the things which are in error, came from me. So you now know who to blame.

We sort of took a slightly different approach which came out about the same way as the previous group. We started from the results of the initial meeting held in January. The general model that was put together for manganese nodules consisted of these general characteristics, and there was very little specificity with respect to these. I think you heard a lot more specificity so far today, and in the meetings that have taken place earlier, so that we're beginning to sort of close in on providing some sort of better definition of these areas.

Our basic approach was to get the x-version model, largely based on a broad view of statistical and structural tectonic analysis of the CCZ, therefore what we're trying to do is to reduce this model development a smaller scale, so that it actually becomes an exploration model. I would say that what we've developed so far could be called a reconnaissance model, in the exploration trade which is one step away from being an exploration model.

The real issue is to begin to refine the model to the extent possible, into specific areas and then within those areas, look at those in terms of their real exploration value one way or the other. Now, the basic data that has been used so far, has been that information which has been compiled and is basically information that has been provided by the pioneer investors, both in the initial application and subsequent to their contributions. The only reason I reiterate this is to make the point that the data presently available to the Authority in their database only represents a relatively small proportion of the total amount of data available in the region, and does not even represent the complete totality of data for the reserved areas. There is, however, a great deal of information that needs to be acquired in the CCZ, particularly in these areas. Exactly how one goes about doing that became the heart and soul of our discussions.

Now, there is also a very large amount of publicly available information from national and international institutions and their databases, to the extent that these have been integrated into some of the overviews presented here. That information is sort of textually available, but a lot of it is very detailed, and is in very well-formed databases, available from other institutions, so we'll be talking about this in terms of fortifying the traditional data which will be acquired as we go forward.

The model that we've been working with, or discussing, in our group used primarily this list of issues, as being those most relevant to refining the exploration model. When we talk about seafloor tectonics and volcanics, there's obviously very little that one is going to add to the discussion that Yuri has presented. We may have, however, two small issues as we go forward. The other matter that we will discuss is the water column and there's not much we need to say about that, because I think David Cronan will be covering that part pretty well.

We'll skip over those fairly quickly, and we'll spend most of our time looking at seafloor morphology to the sediments, to the specific issues of hiatuses, and look at nodule facies and nodule morphologies, particularly in the context of how these attributes can be acquired and integrated into the development of an exploration model which is more area-specific than the existing model. That was really what we were attempting to do in our discussion. Now, Yuri has already covered in great detail what needs to be done with respect to the geophysical structural data relating to seafloor. Simply to reiterate, from our perspective, in addition to the broad association, there is a need to acquire, to the extent possible, information which will allow us to define specific areas or provinces, that are amenable to nodule development concentration, and it may have possible economic importance.

What it means is one has to come back from the regional information and try to break it down into more precise common areas that we can begin to develop more realistic models for evaluation, for exploration. Just to reiterate, from our interest, these are primarily related to basement depth, and to spreading centres and to heat flow. Those seem to be primary determinants that have lead, or may have lead to the individual provinces that we see within the data so far. We perhaps need to get a better handle on this. Now, I think there is a common recommendation that there needs to be an aerial reconstruction of the CCZ. Let's just say that that's one of the things that has to be done. In terms of the water column, what are most important to our model has already been discussed in great detail, obviously the carbonate compensation zone is absolutely critical to any kind of a model. Getting a good analysis of the carbonate compensation zone over time is particularly important, in this area. Getting some idea of the vertical dimensions of the zone, is also critical in looking at what nodule concentrations, metal concentrations are going to look like.

More recently, to the extent that its relevance has not been discussed, is the need to look at the potential impact of the Antarctic bottom water and other activities, and the effects that might have had on the ability of nodules to form in the region. Particularly looking at carbonate, which is potentially the all-time killer of manganese nodules. What we are suggesting is that there is a need to focus in on more local issues relating to zones of fracturing and to the structures that may form at basins. That is, we need to know a lot more about the form and distribution of seamounts in the region. We also need to know and gather more information on the major structural erosional features.

It's particularly interesting here because one of the issues is that there is a considerable amount of bathymetric information and seismic information in the Clarion-Clipperton Zone, not all of which, of course, is in the reserved areas, but some of it is, and in the adjacent areas belonging to the Pioneer Investors. One of the key issues defining the small zones is going to be gaining access to this bathymetric information. In the paper, we briefly discuss the problems with that bathymetric information; basically the comment was that although the information was available, a substantial amount of it may not be correlated to the point that would be particularly useful. Getting a better idea of the general morphology of the seafloor in more detail is therefore, a critical issue. One of the recommendations which we'll see later, is to take the available information and put it on the one-minute bathymetric map. The two-minute is supposedly being used, and supposedly refining the existing information.

As far as stratigraphy goes, the close association of nodules, and the composition of nodules with different sedimentary facies is well known, and we pretty much have an understanding of the relationship between these. It is not clear that we have the detailed understanding of the individual types of the individual distribution of these within the areas of greatest interest; so there is a need to get more precision with that. Another area in which there is very little information within the Authority is with respect to all of the individual bottom samples, cores and other types of sedimentological information. Gaining access to that kind of information is absolutely vital to refining the model from the broad sorts of classification down to what may be the real controls on nodule distribution and abundance. Now, the discussion on these topics was not particularly encouraging, and it has to do with the fact of the classification of sediments by the individual pioneer investors. Each of them has apparently used their own system of nomenclature, and there's not a lot of hope that this nomenclature can be rationalised into a common one. That would represent a fairly significant problem, so it may be something that the Authority does something about.

In terms of nodule data, let me just say that, I had a group of people who really loved nodules, and so I learned more about nodules; I thought I knew a little bit, but I learned I know very little. The major distributions of nodules is fairly well-known, but the important recommendation here and the important observation with this is that there is a very, very, large amount of information about nodules available, which is basically in bottom photos, both individual photos, transect photos, video transfers and transects. This information provides a great deal of very valuable information, to get at the fundamental issue of abundance. The other thing with nodules is that this nodule distribution and analysis of the types of nodules and the morphology, perhaps gives you one way of actually approximating the boundaries of what we would call potentially economic returns of nodules. So, there's a great deal to be learned and done from extracting a very detailed assessment of nodule occurrence and distribution based on photos and videos.

Basically, the characteristics of nodules are metal content with cores of matter. But using the nodules themselves as a surrogate, if you will, or proxy, for looking at the values of areas in terms of metal content, and perhaps in certain ways to define abundance, looks like a very promising area of research, and in the model itself.

As instructed by our leader, we went through each one of these areas and defined potential areas of data sources for additional information that could be put in to help substantiate the models. To a large extent, the list tends to be somewhat similar, that a large amount of the information is still in the hands of the pioneer investors, both within the reserved and adjacent areas. There have been a number of other projects going on that provide a lot of useful information with respect to sedimentation and the distribution on the seafloor in that part of the area. That's been done largely by the Ocean Drilling Program, headed by Texaco. So there's a great deal of additional information in the region that is available and in databases that would be accessible to the Authority.

In addition, a number of universities and ocean research groups have been working in the area and through a whole variety of things - Craig has talked about his biodiversity traverse, etc. – all these provide information on the sedimentation and the characteristics of the area. So there's a fairly large spectrum of information out there that provides useful data. There has also been a great deal of information that has been done by naval research programmes of virtually every country. A lot of this information is being made available. Data for the United States, for instance, is already in the geophysical data centre, and publicly available in Denver, Colorado. This information could be integrated into the databases to help refine issues that have been defined by this group. So I'm going to skip through these in terms of the data sources for the other areas, because they are essentially the same although there is a whole series of different ones.

I'll go straight to the recommendations, which I guess is a part of this. Basically, the group has six recommendations:

1. To develop a database of seafloor nodule topography.
2. To create a geophysical database on seafloor morphology and sedimentation; keeping in mind there's a caveat in the paper that everyone should constantly read. What it basically says is, that in the collection of this and any other data, there should not be an overall just grab collection of information; this is a collection of information that's specific to an area and specific to a problem that you wish to address. So it's going to require a very selective database; but if that information is well thought out, when the acquisition is done, it will answer many of the fundamental questions that have to do with nodule abundance and concentration in the Clarion-Clipperton Zone.
3. To undertake a programme aimed at defining the geological evolution of the CCZ, at least over the last twenty million years. That's something that Yuri has talked about, and I think that's something that Charles has talked about; so it's probably one of the things people need to do.
4. To get better maps in the reserved areas of sediment, and get better information from a variety of sources that we can extrapolate in there because of the close relation of nodule characteristics with the sediments. There is a need to look at heat flow information. A lot of that information has been compiled and is available.
5. To think about general model development, based on specific structural areas, because these are

going to be the fundamental controls on the nodules and their occurrence that people will have an economic interest in.

6. Once the data on the definition areas that Yuri has been talking about has been acquired, we can begin to construct more specific models for the occurrence, distribution and abundance of nodules in the area.

We also need to formally request additional information from national and international agencies and programmes and national data centres. I think there's also a need for the compilation of state special studies; various particular important issues that have to do with manganese nodule abundance or concentration, that may require special studies by international experts, pioneer experts, that the Authority will have to enter into negotiations with to get those kinds of studies done, so that they can begin to develop more effective models in the reserved areas. A wide range of people should have access to the information and continue to work on refining and developing the models that are needed.

So those are basically the recommendations, which include five further points to the proposed work plan:

1. Initially enter into discussions with pioneer investors and other institutions/consortia to gain access to the kinds of data that we have suggested here
2. Set up a framework for undertaking the paleoreconstruction of the CCZ for at least the last twenty years. And we'd lay out a programme of how to approach that.
3. As recommended, basic data should be initiated through a series of very special studies to characterise what we call nodule basins or areas of potential economic importance in the CCZ. And that is to bring these models down to where they actually have a quasi commercial counterpart to them.
4. There should be an evaluation of heat flow within the CCZ; and,
5. As soon as possible, develop different models for different tectonic areas.

This is the summary of the recommendations and activities of the working group on bathymetry and stratigraphy

C. <u>Working Group on Sediment and Water Columns</u>

(David Cronan)

The relationship between productivity and grade and abundance (particularly abundance but also grade) is not well known.

A task to help resolve this would be to check the relationships between nodule parameters between nodule grade and abundance, in terms of productivity for the Clarion-Clipperton Zone and over the entire Pacific. This work has been done in the South Pacific, and it's quite easy to do. I think it would be very useful to simply draw maps or to do correlations between grade and abundance, and productivity for the CCZ data set.

Then we come on to other water column parameters, firstly - the oxygen minimum zone. The oxygen minimum zone is not a parameter which has featured very much in nodule studies, mainly because it's a couple thousand metres above most of the nodule fields. Nevertheless, in recent years it's been shown to have an important effect on cobalt-rich or hydrogenous ferromanganese oxide crusts, which, if you like, are very close relations of the nodules. It is also possible that there may be some effect on the nodules. However, the oxygen minimum zone and the depth and intensity of the zone is dependent on productivity, so it's not an independent variable. Whether its directly related, in other words, as productivity goes up the o and z parameters change in a linear manner; is still not known but would be useful to find out.

We don't have this variable intensity through the Clarion-Clipperton Zone. It is possible that it might modify the signal supply from the surface, as concentrations of metals in the sinking organic material. For example, if it's very intense, and the waters are nearly anoxic, the amount of organic carbon decay in it will be less. If they are not anoxic, it could well be that organic metal in it will fall through, in some cases without significant modification or in other cases indicate some modification. We don't know the answer to this and need to check this out.

On the basis of work done on the oxygen minimum zone in relation to ferromanganese crusts elsewhere, it's likely that it's going to have a greater effect on cobalt, than on nickel and copper. This has certainly been the experience that we get from the South Pacific when we get hydrogenous ferromanganese oxide crusts.

A task that we could include therefore, would be to conduct analyses of variance, of oxygen minimum depth of intensity against nodule grade and abundance in the Clarion-Clipperton Zone or indeed in other areas, to see if it differs from the relations of these variables to productivity. In other words, does it simply mirror productivity in its behaviour or does it actually modify the signal supplied to the seafloor, by the authority. We simply don't know this also and, again need to check this out.

Let me, at this point, come down to the seabed, and to the calcium carbonate compensation depth; a critical parameter that everyone has emphasized. All I can do is reemphasize it. The calcium carbonate compensation depth intersects the seafloor, and is probably not horizontal going from east to west; but if you look at the literature, there are various estimates of what it does. I think one of the first things we need to do is actually check it out and find out at what depths it actually is. We know it varies from north to south, but what we don't know is how it varies from east to west.

We do know that the sediments in the east of the area tend to have a higher component of carbonate ooze than the sediments in the west of the area, which are predominantly siliceous oozes. So clearly, more of the seafloor must be above the calcium carbonate compensation depth (CCD) in the eastern zone than in the western zone.

So, what is the importance of the CCD, in terms of nodule abundance? We know by looking at photographs and measuring the abundance, and we also know that nodule abundance in many areas tend to increase in the vicinity of the CCD. There's a concentrated process here and its very logical because the rate of sedimentation on the seafloor decreases as you get towards the calcium compensation depth and calcium carbonate is removed. We also know that nodule abundance is inversely correlated with sedimentation rate and would expect an increase in abundance towards the CCD. Indeed that is what I found, and I have tried to represent that in these findings. If we go above the CCD, nodule abundance drops off, and as we go below the CCD nodule abundance drops off too, but, in the vicinity of the CCD, it's quite high.

I've been shown some diagrams based on work in the South Pacific, showing how it affects grade in the South Pacific. There was a diagram showing the two main minerals in the nodules: 10-angstrom manganite and delta-MnO_2 indicating the calcium carbonate compensation depth, the distance below and the distance above. When we look at the distribution of this ratio, we see a clear increase in the ratio between 10-angstrom manganite and delta-MnO_2 in the vicinity of the CCD. These minerals are essentially proxies for composition, because the 10-angstrom manganite is enriched in nickel and copper and delta-MnO_2 is enriched in cobalt. Now this was the general relationship for the whole of the Penrhyn Basin. If we look at specific sites that are shown, the findings are that as we come down to the CCD, we find that the concentrations of manganese, nickel and copper in the nodules increased overall; whereas iron decreased toward the CCD. If we look at this station, the seafloor was actually below the CCD, but in a group of stations, five degrees south, just south of the Clarion-Clipperton Zone; manganese, nickel and copper values in the nodules showed an increase and then a decrease. I think that in spite of the scatter, iron and cobalt may do the reverse.

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CHAPTER 21 WORKING GROUP REPORTS AND WORKSHOP RECOMMENDATIONS

Introduction

Background and Programme Objectives

One of the primary responsibilities of the International Seabed Authority (ISA) is to assess the quantities of metals to be found in polymetallic nodules. In this regard, the Authority undertook such an assessment for the reserved areas in the Clarion-Clipperton Zone (CCZ) using the data and information that were submitted to it by registered pioneer investors and that are maintained in its POLYDAT[1] database. The data and information submitted by the six registered pioneer investors, while adequate for some resource assessment, are not sufficient to allow an estimate of the quantities of metals to be found in these areas with a reasonable degree of confidence. Since the Authority does not have the financial resources to assess the resources via exploring the international seabed areas under its purview, geologic modelling is the most cost effective approach to overcome this problem.

Given the variability of nodule occurrences in the CCZ, modelling will not be an easy task. The Authority therefore, convened a meeting of a group of invited scientists in Kingston, Jamaica in January 2003 to consider various elements that should be included for such modelling.

The meeting in Kingston, subsequently called the Meeting of Scientists, examined several interrelated processes in oceans, lithosphere, and its sediment cover, as well as in the atmosphere and the biosphere, that are involved in the formation of nodule deposits. The scientists also discussed the results of scientific research correlating nodule grade and abundance with, inter alia, a surficial seismically transparent sediment layer to be found at potential nodule mine sites, seismic/volcanic activity in the CCZ, seabed topography, and certain properties of the sediment layer at potential deposits. Participants also discussed geostatistical methods and techniques that have the potential of being effective in geological modelling, and they produced a preliminary outline for a programme of work that formed the basis for subsequent programme development.

Based on the results of the Meeting of Scientists and subsequent discussions with its participants and others, ISA formulated the following general objectives for the proposed geological model development programme:

Develop a prospector's guide to include:

- Acquisition, examination and documentation of data that characterize the polymetallic nodule deposits of the CCZ and the natural environment in which they have formed Selection and preparation of specific data sets for use in the development of a quantitative geological model.

Develop a geological model to include:

- Improvement and extension of the polymetallic nodule resource assessments for the CCZ;
- Establishment of quantitative relationships between resource variables and environmental variables;

[1] POLYDAT is the International Seabed Authority's database on polymetallic nodules in the areas reserved for the Authority. The data and information currently contained in POLYDAT were provided by the registered pioneer investors in seabed exploration upon their registration by the United Nations Preparatory Commission that developed the International Seabed Authority organization.

- Complete documentation of methods to permit incremental improvement of the model;

The Meeting of Scientists concluded that data and information required for the proposed Geological Model of the CCZ should be as broad as possible and should be based on standards to be developed by the ISA. The participants recommended that the ISA convene a workshop to draft more detailed recommendations for the development of the model. They suggested that the workshop participants include experts from academic institutions, public and private enterprises, contractors, members of the ISA Legal and Technical Commission and representatives from ISA Member States.

In response to this recommendation, the ISA convened such a workshop from 13 to 20 May 2003 at the Fiji Sheraton Hotel in Nadi, Republic of the Fiji Islands. The remainder of this section describes the specific objectives addressed at the workshop and the methodology employed to address them.

Workshop Objectives

The workshop addressed the following objectives:

- Complete a review of the theoretical aspects of nodule formation;
- Discuss the basic geologic structure of the CCZ and the components of the geologic structure that will be required for resource assessments, identify the key nodule parameters for inclusion in the model;
- Encourage proposals for scientific research to assist in confirming apparent correlations between nodule grade and abundance with various events or environmental characteristics of the CCZ;
- Examine the application of geostatistical methods to resource estimation; and,
- Review the programme of work developed at the Meeting of Scientists and develop a more detailed programme for implementation by the ISA.

The workshop also included a summary by Professor Craig Smith of the University of Hawaii of the work being undertaken with regard to the biodiversity, species ranges, gene flow, and other research related to the protection of the marine environment from the impact of exploration and mining of deep-sea polymetallic nodules.

Workshop Methodology

Experts in the several relevant disciplines, including marine geology, geochemistry, biology, and geophysics, delivered technical presentations during the first three days of the workshop which identified the major tasks that the Authority should undertake to construct the geological model. The participants then broke into three working groups, each charged with developing specific recommendations for a programme to develop the model. The working groups developed their recommendations over the course of two days of informal meetings, and many individuals participated in more than one of the Working Group deliberations during this period.

The working group chairs presented their recommendations to the full assembly of participants, who discussed these recommendations at length in an open forum. The result of these discussions was a consensus on the priorities for tasks that the Authority should address in the programme. The resultant set of priorities was synthesized into a programme of work that was also discussed and modified until a final consensus was achieved.

The remainder of this report presents the key elements of this consensus including subject areas addressed by the working groups and their specific recommendations for programme tasks and general recommendations from the workshop, incorporating the specific working group recommendations into a general plan for implementation

Working Group Recommendations

After three days of presentations, the workshop participants formed three working groups to formulate specific recommendations for the development of the geological model. The objectives for the working groups were:

1. To identify specific, available data sets that can be used in the development of the model; and,
2. To specify the methods to be used for incorporation of the data into predictive models.

The chairpersons for the working groups were charged with assembling the final recommendations of each group. These are presented in the following sections.

Working Group on Tectonics and Volcanic Activity

Chair: Dr. Yuri Kazmin

The working group on tectonics and volcanism met and worked on Friday, 16 May 2003. It was composed of: Dr. Y. Kazmin (Chair), Mr. S.K. Das, Mr. B. Diene, Prof. Wenzheng Lu, Mr. K. Mafi, Dr. L. Parson, Ms. C. Pratt, Mr. R. Taake, and Dr. V. Yubko.

The discussions in the working group focused on the processes of tectonics and volcanism in relation to a Geological Model of the CCZ on a global (the entire CCZ), regional (large contiguous areas within the CCZ characterized by distinct tectonic or bathymetric features) and local (small areas usually where extensive survey activity has taken place) scales. The group decided to make the discussion as comprehensive as possible, by including processes of plate motion and subsidence, as well as hydrothermal activity.

Tectonic and volcanic processes (including plate motion and hydrothermal activity) potentially related to nodule formation and metal accumulation in the CCZ at a range of scales, were discussed. The group identified suitable proxy factors and data from which the tectonic and volcanic processes could be determined. The working group also discussed appropriate actions that should be undertaken in the process of developing a geological model to establish the interrelationship of tectonic and volcanic activity with nodule abundance and grade and spatial distribution of nodules deposits in the CCZ.

A point was made that tectonics and volcanic activity may have direct relationship with nodule grades being a source of metal supply. Tectonic processes on a global scale may also have played the important role indirectly by creating favourable conditions for the nodule formation in the CCZ.

It was also pointed out that the actions to be taken during the development of a geological model in connection with tectonics and volcanism shall deal with the collection and processing of raw data as well as with interpretation of such original data.

Plate Motion and Subsidence

Plate motion and seafloor subsidence were considered to be important factors since these processes ultimately influenced the bathymetry and the depth of the ocean floor and its interrelationship with key biochemical layers of the water column (such as the carbonate compensation depth, CCD) and how the increase of depth along the CCZ varies and might have been a result of the plate's spreading history. This was discussed for the East Pacific Rise and its subsequent cooling history.

It was noted that the oceanic crust of the CCZ dates from 65 (in western part) to 10-20 million years (in the eastern part) and that its formation was related to the spreading processes at the East Pacific Rise. The CCZ could be considered to comprise three physiographic zones, defined by bathymetric character, and separated at 140˚ W and 125˚ W. The western part belonged to a transitional zone from a relatively old oceanic plate to a relatively young oceanic plate, with the crust dating more than 60 million years (up to 74 million years). The middle block of the CCZ was located on a “young” oceanic plate (30-60 million years), and the eastern part was confined to a transitional zone from a young oceanic plate to a spreading centre at the East Pacific Rise (10-30 million years). This subdivision was based on a location of axes of magnetic anomalies and the results of the work of the Deep-Sea Drilling Project. It was a common view in the group that the plate motion might have been closely related, although indirectly, to the phenomenon of nodule formation in the CCZ by creating favourable environment for nodule accumulation in connection with the palaeo-position of the CCD layer and bio-productivity zones.

It was noted that some researchers were inclined to relate nodule composition and grade to the age of the crust substratum. A view was expressed that the phenomenon of the CCZ with respect to spatial trends in positive or inverse correlation between metal grade and abundance in nodules might be also related to the age and tectonic structure of oceanic crust as a result of plate motion and requires addressing within the geological model.

It was agreed that the age, composition and structure of the oceanic crust in the CCZ might constitute a suitable proxy for the review of plate motion and subsidence. This could be derived through the synthesis, interpretation and analysis of the available data on free-air gravity anomalies and magnetic anomalies and other relevant geophysical information derived from published and unpublished sources, including data from various data centres and published maps. The tectonic and depositional history of the CCZ could also be quantified by review and interpretation of geological results of the Deep Sea Drilling Project.

It was agreed that the actions that should be undertaken in the course of the geological model development would include collection, review and interpretation of gravity, magnetic and other relevant geophysical data and maps, which might be available in public domains and other sources. The collection and review of the Deep Sea Drilling Project data and information would be undertaken simultaneously, as well as of other available information on the age of the basement and overlying sediments.

A digital map series reflecting the basic tectonic structure of the CCZ substratum and its age might be compiled.

Another view was that it would be useful and helpful to develop a model of the tectonic evolution of the CCZ during the past 20 million years, in order to understand better a possible relationship of nodule genesis and formation processes in the CCZ in relation to the geological history of the Eastern Equatorial Pacific.

Tectonic Activity

The process of tectonic activity, including crustal structure faulting and fracturing, was one of the major components of a geological model on a regional and global scale. Some scientists advocated volcanic and hydrothermal activity as a primary source of metals, which potentially exploited crustal weaknesses, such as major fault systems as channels of metals supply to the ocean floor. Another view was that fracture and fault zones might provide access for the supply of free oxygen, therefore creating favourable environment for nodule formation.

The general structure of the CCZ crust consisted of several stages of faulting and fracturing of the basement. The primary structures were the Clarion and Clipperton transform faults. In addition, a normal fabric of pervasive faulting that was parallel or sub-parallel to the East Pacific Rise and was generated during the normal processes of seafloor spreading characterized the oceanic basement of the CCZ. That spreading process had been dated using magnetic-anomaly data and the ages of the basement rocks, obtained mostly through radiometric dating of core samples from the Deep Sea Drilling Project.

Well-documented sub-latitudinal volcanic ridges and seamount chains, parallel to the Clarion and Clipperton faults, strongly suggested tectonic control of volcanic activity – the ages of which might be diverse and needed to be validated where possible. The sub-longitudinal fault system (approximately parallel to the East Pacific Rise) was responsible for the predominant regional and local morphological landscape of the CCZ and was expressed by classic horst and graben structures of basaltic basement. An understanding of the significance of the primary seafloor fabric, and its relationships to the tectonic evolution of the CCZ was essential for understanding the consequent effects that those tectonic processes had on the sedimentation and re-sedimentation processes.

While considering the issue of possible relationships between nodule abundance and tectonic processes in the CCZ, the group recalled the presentation made at the workshop highlighting the spatial relationship between high nodule abundance and the postulated "Unnamed Fracture Zone." That poorly constrained structure was believed to extend along the central part of the CCZ, approximately parallel to the Clarion and Clipperton fractures. In view of the potential significance of that spatial relationship, it was felt that particular attention should focus on that issue in the course of the development of the geological model. The existence and location of such a fracture zone should be investigated through proper analysis of bathymetry and other geophysical and geological datasets. The appropriate analysis of available sampling data with respect to nodule abundance and grade within profiles across the fracture zone should be carried out wherever possible.

The same view was expressed with regard to an assumption of a possible correlation of manganese concentrations in the polymetallic nodules of the CCZ, on both global and regional scales, with fractures and faults of the NW and NW-W direction, which were confined to the E-SE extension of the Hawaiian volcanic ridge system.

With regard to possible proxy data, which may be used to constrain a tectonic framework of the CCZ, the general view was that the seafloor topography expressed tectonics on a regional and local level. The relief in general reflected the basement structure formed by various stages of faulting and volcanic activities. The analysis and interpretation of the ocean floor topography and the calibration of these data with other geophysical parameters might facilitate the identification and delineation of fracture and fault systems.

Sharply linear volcanic ridges and volcanic seamount chains strongly suggested sub-latitudinal fault systems on both regional and local scales. Attention was drawn to some presentations, which indicated that nodule abundance and metal grade anomalies were spatially related in the CCZ and to certain lineaments of various trend on a regional scale. A view was expressed that, in addition to bathymetry and seabed morphology, the fault and fracture systems might be identified through an appropriate analysis of the spatial distributions and configurations of nodule fields.

Other important indicators of global and regional deep fault and fracture systems might be gravity and magnetic anomalies, as well as crustal age, composition and tectonic structure of the basement and overlying sediments. The locations of recent volcanic activity and earthquake epicentres in the Eastern Pacific might also represent important evidence of tectonic activity in the past.

With regard to actions that might be undertaken for the development of the Geological Model the group recommended the analysis and interpretation of the bathymetry and topography maps of the CCZ (to be compiled at a scale 1:500,000 – 1:1,000,000) as well as a review of all data and information on bathymetry and topography. That work would be undertaken with an aim of delineating fractures, faults, and other lineaments at various scales to develop a tectonic framework for the model. The same procedure should also be applied with respect to available information on the spatial distribution and configuration of such nodule parameters as abundance and metal content, including relevant maps to be compiled.

Priority should also be given to an appropriate analysis and interpretation of relevant geophysical maps and data for the CCZ. Analysis of recent seismic activity in the CCZ, based on information on registered earthquake epicentres in the Eastern Pacific, should be also conducted. As an outcome, development of the geological model should include the preparation of schematic maps and schemes of the CCZ on various scales reflecting tectonic features (fractures, faults and lineaments, registered earthquakes, etc).

Volcanic Activity

The general structure and composition of the CCZ ocean floor had been influenced by several stages of volcanic activity. First, its substratum had a volcanic origin, formed as a result of seafloor spreading processes at the East Pacific Rise. It was suggested that at various scales, volcanic structures had been superimposed on the primary seafloor fabric as volcanic plateaus, old volcanic seamounts, volcanic chains, and mountain ridges. Volcanic plateaus and sub-latitudinal volcanic ridges had been mapped in the western reserved areas, which resulted in extreme relief in some parts. In many reserved blocks the relief was complicated by sub-latitudinal chains or ridges of volcanoes, which rose 800–3000 m above the seafloor. Those ridges appeared to be controlled tectonically and might reflect primary crustal weaknesses along the ridge lines, perhaps generated as ridge-axis discontinuities or fracture zones during seafloor spreading. Such volcanic chains had been mapped in almost all of the reserved blocks in the CCZ.

A general view was expressed that, although the important role of volcanism in the CCZ was well recognized, no proper attention had been paid to the comparative analysis of the age and of nature of volcanic activity in various parts of the CCZ. It was noted that more intensive volcanic activity was registered in the remote eastern part of the CCZ, which lay within the western flank of the East Pacific Rise and consisted of a rather young basement. Thus, the volcanic chains and ridges might represent volcanic structures typical for extinct spreading centres.

It was also noted that intensive volcanic activity was reported in the remote west near the Line Islands Volcanic Chain. That part of the CCZ was confined to a transitional zone from a relatively old oceanic plate to a relatively young oceanic plate. In that region, the type, age, and origin of volcanism might be different from the volcanic activity in the east and might belong to the processes of formation of volcanic ridges over a hot spot.

It was considered that, in many respects, proxy data for reflecting volcanism during various stages in the CCZ might be similar to those mentioned above for tectonic activity. Therefore, possible tasks for development of the geological model might be also similar. However, steps should be undertaken to determine the ages of various volcanic structures in different parts of the CCZ. That might also include a certain programme of sampling and analytic research (including age determination) undertaken by the contractors in the near future in conjunction with their exploration work.

Hydrothermal Activity

Attention was drawn to a presentation at the workshop with respect to findings of traces of recent hydrothermal activity in the CCZ. It was considered to be an important factor, which deserved much attention during the development of the geological model. In particular, verification of the original observations was needed. Certain research should be carried out to obtain additional on the subject. A view was expressed on the potential for palaeo-hydrothermal activity (contemporaneous with the formation of the basement crust at the East Pacific Rise) to have influenced basement composition. The group considered whether that factor was of significance, and, indeed if it were possible to suggest a proxy dataset to address that speculation.

A view was expressed with regard to possible interrelationships between nodule composition and hydrothermal activity in the CCZ. Hydrothermal activity might have caused the formation of hydrothermal layers in nodules interspersed with hydrogenous layers. However, the group felt that consideration of such a hypothesis was not within its competence and should be considered by the other working groups.

Working Group on Bathymetry and Stratigraphy

Chair: Dr. Allen Clark

Introduction

The working group on bathymetry and stratigraphy undertook its activities within the framework prescribed by the International Seabed Authority to:

Develop both a narrative and a predictive exploration model for manganese nodule exploration within the Clarion-Clipperton Zone (CCZ) with the narrative model being largely qualitative and the predictive model largely quantitative in structure. Both of the models should build upon the key parameters previously defined during the January meeting of the working group that included, but were not restricted to the following:

- Water depth
- Water column characteristics
- Seafloor topography
- Palaeo-environment and sedimentation
- Nodule origin and distribution

In the formulation of the exploration models, the working groups were asked to focus their deliberations and recommendations within the context that:

- Data must be currently available for a useful portion of the EEZ
- Workshop participants agreed that the data were clearly linked to nodule grade or abundance

With respect to specific data inputs the working group on bathymetry and stratigraphy was asked to:

- Identify sources of proxy data
- Identify potential sources of error in different datasets
- Define the quantitative link between the proxy data and nodule abundance and grade
- Produce a document on working group findings and recommendations
- Report on future work to be undertaken and establish quantitative links between the proxy data and nodule abundance and grade.

Model Formulation

In the formulation of both the narrative exploration model (NEM) and the predictive exploration model (PEM) the working group built largely on the discussions held at the January meeting of the group and on the presentations/discussions of the present workshop. Formulation of the NEM and the PEM of the working group was based on the following initial considerations:

Approach

Exploration model activities to date had been largely based on a broad geostatistical and structural/tectonic analysis of the CCZ, therefore, present efforts should attempt to develop more site/area specific exploration models.

Data Sources

Data sources to be included in the models would incorporate presently available data in GEODAT but, to the extent possible, include other data, such as:

- Data provided to the International Seabed Authority as part of the application process for pioneer status.
- Data presently held by registered pioneer investors on adjacent areas
- Publicly-available data in national and international institutions and databases.

Proposed Narrative Model

Manganese nodules in the Clarion-Clipperton Zone have been extensively studied and the parameters that influence their origin, occurrence, distribution, and metal content are, in general terms, relatively well understood. However, the specific impact and the interaction of the multiple parameters is less well know and in many cases problematic. Key parameters controlling the origin, distribution and manganese nodules in the CCZ that were considered in the working group on bathymetry and stratigraphy include, but are not limited to, the following:

- Water depth
- Characteristics of the water column (CCD – CDSiO2)
- Seafloor tectonics/volcanic activity (20 MY to present)
- Seafloor age/spreading history (20 MY to present)
- Seafloor morphology (regional- macro)
- Sediments (total distribution, thickness, facies and type)
- Hiatuses (Eocene and late Miocene)
- Nodule facies (east to west variation)
- Nodule morphology/size (qualitative and quantitative value)
- Primary productivity

Proposed Predictive Exploration Model

Specific data requirements and their related importance to the development of a proposed predictive exploration model were defined and briefly discussed, as follows:

Water Column

The most important factors were the distribution of the zone of high bio-productivity and the occurrence of the carbonate compensation depth (CCD).

CCD

- Depth from east to west (should deepen)
- Impact of bio-productivity on the CCD
- Distribution of carbonate within the CCD overall and the reserved areas in particular
- Palaeo-distribution of the CCD (assuming the bio-productivity zones stayed essentially the same over time).
- Impact of the Antarctic Bottom Water on more recent sedimentation and nodule development related to the CCD.

The CCD was a critical factor in the occurrence, distribution, abundance and metal content of Mn nodules throughout the CCD, now and in the past, and therefore its nature and distribution was of critical importance in the formulation of the PEM. Of particular importance was the inhibiting impact of carbonate sedimentation on manganese nodule development and the fact that nodules developed above the CCD were typically higher in cobalt and manganese whereas those below were higher in Ni and Cu.

Required geophysical/structural data: Grain of the seafloor

- Provinces
- Local structure
- Fracture zones
- Basement depth
- Plate motion
- Volcanic structures – seamounts/volcanoes
- Palaeo-tectonics, spreading centres
    - Each created different structures
    - CCZ spreading centres finished 10 MY ago

Heat flow

The gross structural features of the CCZ in large part determined the occurrence, distribution, abundance and, to a greater or lesser extent, the grade of manganese nodules. To further refine the predictive exploration model it would be necessary to further refine the macro and microstructure of the CCZ and the reserved areas of ISA, in particular.

Required morphological data: Major structural features reflected in the topography[2]

- Zones of fracturing
- Horst and graben structures
- Seamounts (volcanoes)
- Major structures (erosion features)
- Palaeomorphology of the manganese areas (with and without sediments) from Miocene onward (can be done by the French)

The major morphological structure largely determined the areas of accumulation of manganese nodules. The specific characteristics of those structures (size, slope, surface texture, cover) further refined the distribution, concentration and composition (related to CCD on seamounts) of the nodules.

- Required sedimentology/transparent layer (sedimentation, erosion, re-sedimentation) – surface and transparent-layer sediments
- Distribution of sediments (carbonates, silicious oozes, zeolitic clays[3]
- Presence or absence of Eocene and late Miocene hiatuses
    - Hiatus periods necessary for nucleation
    - In areas of 2 hiatuses second generation nodules are normally cored by manganese nodule fragments
- Thickness of the transparent layer[4]

2 It should be noted that a significant amount of bathymetric data of all types is poorly correlated with geographic position data (particularly in earlier cruises) and therefore may be of limited use, other than providing information on general morphology and stratigraphy.

3 Attempts to rationalize the nomenclature among the registered pioneer investors have proven unsuccessful, and this will be a major constraint on developing the sediment component of the Predictive Exploration Model.

4 Registered pioneer investors can give guidance to the interpretation of data the ISA acquires. This can be done both for flow directions/patterns and for the origin of transparent layers.

- Transparent-layer materials are poorly consolidated
- Basically the transparent layers were in the valleys between the ridges
- Sedimentation rates (particle flux rate)
  - Sedimentation rate should be less than 5mm/1Ky
  - Accumulation rate 2gm/1Ky
- Bioturbation
- Erosion and re-deposition

The role of present and past sedimentation within the CCZ was considered critical to virtually every aspect of nodule occurrence, distribution, abundance and metal content and was therefore extremely important to the development of the predictive exploration model, in the formulation of which, the following factors, related to sedimentation must be considered:

- Thickness was the important issue and drift (reworked) deposits were normally much thicker
- The most abundant areas of nodule concentration were associated with silicious oozes and zeolitic clays
- Sedimentary zones outside the high bio-productivity zone did not accrete nodules
- The presence or absence of the Eocene and late Miocene hiatus directly impacts the nature and abundance of manganese nodules
- The thinner the post-hiatus sediments, the fewer the nodules, whereas in areas of thick post-hiatus sediments, the nodules were more abundant (German area)
- In the eastern (Interoceanmetal) portion of the CCZ, only one hiatus was evident, whereas to the west, both hiatuses were evident, although post-hiatus deposits might be thin

Nodule development was strongly influenced by the rates of sedimentation, erosion and current flow (i.e. they must be balanced to foster growth) and too little or too much had a decidedly deleterious impact. The net rates of sedimentation, erosion and current were critical.

Required Nodule Data (occurrence, distribution, abundance)

Nodule morphology and distribution might be proxies for abundance in certain circumstances. The following considerations were important in this regard:

- Major concentrations of nodules were found in valleys and basins
- Slope nodules were normally smaller and more abundant whereas valley/basin floor nodules were larger and less abundant
- Nodule zonation (east to west)
  - Sample bias was a problem
- Nodules that enclosed fragments of older nodules required that there be two hiatuses
  - Might be related to winnowing and recycling in high current areas
- Limit of nodule fields was indicated by mixture of nodule types
  - Change in nodule types/distribution in short space
- Nodule associations
  - Largest and richest nodules were underlain by silicious oozes and zeolitic clay with a high content of Aeolian dust
  - Basin nodule abundance in rich areas was >10/kg/m2 and had a grade of 2.5% combined metal
  - More Co in the hydrogenetic and more Cu and Ni in diagenetic 10Å Mn
- Representative nodule morphologies
  - Polynucleate
  - Spheroidal
  - Discoidal
  - Tabular

A significant amount of information existed, particularly as a result of more recent cruises, on the occurrence, distribution, abundance and morphology of Mn nodules in the CCZ overall and within the reserved areas of the Authority. The members of the working group on bathymetry and stratigraphy noted that, to date, little analysis of those factors within the reserved areas had been undertaken, although considerable study and modelling of these parameters had been done by the registered pioneer investors within their areas. The sharing of those results would contribute substantially to the Authority's ability to interpret nodule data, particularly from bottom photos and video, for use in developing its predictive exploration model.

Data Sources

Although the Authority had acquired a significant amount of information from the registered pioneer investors on its reserved areas, a vast amount of additional valuable information on those areas had not yet been acquired and would be valuable for constructing and refining a predictive exploration model for the reserved areas of the Authority. Additionally, the registered pioneer investors had considerable information, at a much higher level of completeness, on areas adjacent to the reserved areas, and access to those data would materially assist the Authority in its present and future PEM activities.[5]

Similarly, it was recognized that considerable critical data for the construction of both the NEM and the PEM resided in the archives and/or active files of many national and international databases, organizations and agencies.

Therefore, a critical activity of the Authority was to identify and gain access to relevant data, both from the registered pioneer investors and other sources, to foster the development of its modelling effort. In the following, an overview of potential data sources considered essential for constructing the bathymetric and stratigraphic portions of the NEM and the PEM are listed:

Bathymetric Data

- NOAA bathymetric model data
- Registered pioneer investors
- Composite bathymetric maps
- Basic data files (multi-beam echosounders, SeaBeam and 3.5 kHz seismic profiles)
- Research programmes JOIDES/DSDP/ODP
- Universities/Institutes – Lamont-Dougherty, Scripps, Woods Hole – numerous universities
- Naval research programmes

Stratigraphy and Sedimentation

- Registered pioneer investors
  - Basic data (Multibeam echosounders, SeaBeam and 3.5 kHz seismic profiles)
  - Piston cores
  - Grab samples
  - Core samples
- International research programmes
  - JOIDES – DSDP
  - ODP (Texas)
  - Pacific Bio-productivity Traverse

5 Although considerable data exist, because of poor spatial location the value of the data, other than for general inputs to the PEM may be limited in many cases.

- Universities and Institutions - Lamont-Doherty, Scripps, Woods Hole – numerous universities

Tectonics/Geophysics

- Registered pioneer investors (multi-beam echosounders, Multibeam and 3.5 kHz seismic profiles)
- Universities and Institutes- Lamont-Dougherty, Scripps, Woods Hole – numerous universities
- Naval research programmes

Nodules

- Pioneer investors
  - Photos
  - Video
  - Box cores
  - Grab samples
- Bio-productivity (Pacific Bio-productivity Traverse)

Recommendations

Based on the discussions within the working group on bathymetry and stratigraphy and the critical components defined for the predictive exploration model, the following recommendations were made for consideration by the ISA:[6]

The International Seabed Authority should develop a database of seafloor nodule photography, for critical areas of the reserved areas of the Authority for purposes of establishing nodule continuity, distribution, abundance and morphology and for characterizing and assessing the resource potential of specific "Nodule Basins."

The Authority should undertake to create a geophysical database on seafloor morphology and sedimentation, for critical areas of the reserved areas of the Authority, based on Multibeam data and 3.5 kHz seismic and for the purposes of defining permissive areas of nodule accumulation, defining seafloor, slope, roughness characteristics and defining "transparent layer" characteristics.

The Authority should undertake a programme of activities aimed at defining the geologic evolution of the CCZ over the last 20 MY. That reconstruction should focus on:

- Palaeotectonics (including spreading rates)
- Palaeobathymetry
- Palaeomorphology
- Palaeostratigraphy (sedimentary facies and nodule distribution)
- Antarctic Bottom Water
- CCD

The Authority should undertake to develop detailed sediment maps within and adjacent to its reserved areas with special emphasis on defining areas of:

(a) Carbonate
  - Silicious ooze

[6] In requesting data, ISA should specifically define areas of importance, based on other factors, for the acquisition of data and within those areas acquire only those data that can be geospatially located and subsequently integrated with other data.

- Zeolitic clays
- Geologic hiatuses

The Authority should acquire information on heat flow within the Clarion-Clipperton Zone and evaluate these data in the context of:

(b) Their influence/association with nodule occurrence, distribution and metal content.

- Influence/association with regional nodule facies.
- To define or refine existing/future exploration models it is proposed that the ISA extend the existing NEM and PEM modelling activity to develop exploration models, based on specific structural areas, that would focus on the interaction of:

(c) Bathymetry

- Differing spreading rates
- Differing nodule facies
- Sedimentation types and rates

(d) Nodule abundance

- Undertake the above recommendations the Authority should undertake and support the following activities:

- Request for additional information (as detailed above) with appropriate metadata from the registered pioneer investors (for critical areas of the reserved areas of the Authority and adjacent areas of the pioneer investors); from national and international agencies and programs; and from national data centres.

- Compile_special studies by international experts/pioneer investors, requiring access to confidential basic data or unique knowledge, to resolve specific issues of concern for the ISA model programme.

- Develop an open system of data access, to the research community, of Authority's data for the purposes of fostering additional research on the reserved areas.

Proposed work plan

Based on the above recommendations it is proposed that the Authority undertake, as appropriate and within a reasonable period, the following work plan:

- Based on the defined data needs for the Predictive Exploration Model, the Authority should enter into discussions with the registered pioneer investors and other institutions to gain access to needed data, specifically bottom photos and geophysical data.

- A framework programme for undertaking the palaeo-reconstruction of the CCZ for the last 20 million years, including specific data needs and potential sources, should be defined and initiated.

- As recommended, basic data acquired by the Authority should initiate a series of specific studies to characterize "nodule basins" and nodule characteristics (abundance, distribution, morphology and controls within its' reserved areas.

- An evaluation of palaeo to recent heat flow within the CCZ should be undertaken.

- To the extent possible, based on the above activities, specific exploration models for differing tectonic areas should be developed.

Working Group on Sediments and the Water Column

Chairs: Prof. David Cronan and Dr. Philomene Verlaan

Originally, the Workshop participants decided to convene two separate groups, one devoted to sedimentary processes and the other devoted to processes that take place in the water column. However, the groups agreed that there was considerable overlap in interests, so they decided to combine into a single group to discuss both types of oceanographic processes. This combined working group developed the following recommendations:

Water Column

Surface Currents

These were not thought to be significant in affecting the grade and abundance of the nodules.

Variable Metal Sources

While it was recognized that there may be more than one source of metals to the nodules, it was not felt that possible local sources of metals would have any regional impact. More important are extraction processes in determining nodule grade and abundance.

Primary Productivity

The export fraction of total biological productivity was believed to be an important transporter of metals to the sediment interface. However, nodules grade and abundance were not linearly related to productivity. Rather they increased as productivity increases up to a certain point and then decrease as productivity increases further. At what value of productivity does this point occur?

> *Task*: To determine relationships between nodule parameters and productivity, map nodule grade and abundance in the CCZ and compare with productivity, as done in the South Pacific.

Oxygen Minimum Zone Depth and Intensity

The oxygen minimum zone was variable in both depth and intensity through the CCZ. Its position and nature were largely determined by productivity. Thus it was not an independent variable. However, it could modify the metal signal sent down by productivity and as such should be investigated.

> *Task:* Conduct analysis of variance of oxygen minimum zone depth and intensity against nodule grade and abundance in the CCZ to see whether it differs from the relationship of those variables to productivity.

Calcium Carbonate Compensation Depth

In some areas greatest nodule abundance occurred near the CCD because of the reduced sedimentation rates there. In the South Pacific high productivity area the nickel and copper content of the nodules was related to distance from the CCD.

Task: Do an analysis of CCD depth in 5º longitudinal blocks from east to west across the CCZ, using the same methods as used in the South Pacific. Then plot copper and nickel in nodules with distance from the CCD.

Benthic Currents

No evidence was presented of composition of variability in bottom water currents in the CCZ that could be held to account for nodule grade. They were considered to be more important in affecting nodule abundance by influencing the sedimentation rate.

Sediments

Sediment Type and Sedimentation Rate

Carbonate ooze. As outlined above both grade and abundance were low on carbonate ooze because of its generally high sedimentation rate. *Siliceous ooze*. Nodules were most abundant on siliceous ooze. However, there were two types of siliceous ooze, diatom and radiolarian, and the relative sedimentation rates and importance of these in influencing nodule grade and abundance in the CCZ was unknown.

Task: Evaluation of the nature of siliceous sediments in the CCZ in relation to nodule grade and abundance based on similar studies in the South Pacific. This may give a proxy for sedimentation rate, which is probably more important than sediment type in influencing nodule parameters.

Red clay. Nodules were very abundant on red clay because of its very low sedimentation rates. They were also low in nickel and copper but rich in cobalt because of lack of dilution of hydrogenous phases by diagenetic phases. They were not present to any significant extent in the CCZ.

Labile Organic Material

This was thought to be the main carrier phase for manganese, nickel and copper. It was negatively correlated with calcium carbonate and siliceous ooze. Few data were thought to be available from the CCZ.

Task: Do correlation analysis of calcium carbonate and biogenic silica with organic carbon in limited areas of the CCZ where data are available, in order to test the interrelationship between these variables found in the South Pacific. This may lead to the development of a proxy for organic carbon.

Other Sediment Parameters

- Degree of dissolution (from smear slides)
- pore water data, and bioturbation.

There were probably insufficient data available for these to be useful model parameters.

Rankings

This working group established the following rankings for the value of candidate variables for use as proxy variables in the development of a geological model for nodule abundance and grade.

Most Important

- Sediment type and rate
- Productivity (export production)

- Distance of seafloor from CCD
- Sediment organic carbon contents

<u>Less Important</u>

- Surface currents
- Oxygen minimum zone
- Pore water composition
- Benthic currents

<u>Matrix of Proxy Variables</u>

Table 1 indicates the relationships between the candidate proxy variables and the key criteria of utility for the development of the geological model. An "X" in the "Grade" or "Abundance" columns indicates that the Working Group believes that the variable indicated in the marked row should be useful as a proxy variable for either of these key nodule resource variables. An "X" in the column headed "Availability" indicates that the Working Group believes that sufficient data sets for the indicated proxy variable are available for the variable to be useful in the development of the geological model. A question mark denotes uncertainty among the Group.

<u>Table 1</u>
Assessment matrix for candidate proxy variables from the water column and sediments

Candidate proxy variable	Grade	Abundance	Availability
Sediment type and sedimentation rate	X	X	X
Productivity (export production)	X	X	X
Distance of seafloor from CCD	X	X	X
Sediment organic carbon contents	X		X
Surface currents			X
Oxygen minimum zone	?		X
Pore-water composition	X		?
Benthic currents		X	?

Initial work Needed for Model Development

The working group recommended that the ISA investigate relationships between productivity, calcium carbonate dissolution, biogenic silica nature and abundance, organic carbon content of sediments and nodule grade and abundance in CCZ to see whether they were similar to those already observed in the South Pacific. If significant relationships were found they could be used directly in the model. If not, the ISA should try to establish why there was no apparent relationship.

Integrated Recommendations

After the working groups presented their recommendations, the entire assembly discussed the common factors and priorities expressed and the implications for implementing development of the geological model. The following sections summarize the results of those deliberations.

Programme Strategy

The ISA should adhere to the following general strategy.

- The primary products for the overall programme of work should include a prospector's guide and a geological model. The prospector's guide would consider all the data types recommended by the workshop and would examine and document all available data. Particular emphasis would be given to those data types that could contribute to the better understanding of local-scale deposit characteristics.

- In parallel with the development of the prospector's guide, the ISA should also develop a quantitative geological model, which should be developed using *available* data with *defined* and readily *testable* quantitative links to the abundance and grade of polymetallic nodules. An iterative, statistically based approach should be used to construct the model.

The Prospector's Guide

The prospector's guide would consist of a narrative description of the key factors relevant to exploration for polymetallic nodules in the CCZ. The guide would take advantage of the enormous professional experience available among the programme participants and would provide a general framework for the integration of qualitative, experience-based information with the more quantitative results from the geological model. It would include an examination of all the data types identified in section 2.0 as being important indicators of grade and abundance. It would identify specific data sets that qualify for use in the geological model. It would also focus on the high-resolution characterization of specific deposit sites.

The Geological Model

When a specific dataset (which might include one or more candidate proxy variables) and associated mathematical algorithms were proposed for inclusion as a proxy for abundance and/or grade, they should be calibrated with one subset of the available nodule data and then tested with another subset. The results of the testing should be made available to all participants in the model development and then, if appropriate, the algorithm could be modified and tested repeatedly until the specific data set was either included or excluded from the resultant model.

The final product would be a set of digital and hard-copy maps and tables describing predicted ore grade and abundance and associated error estimates as well as complete documentation that described the model testing procedures and all algorithms used in producing the final model results. No undisclosed, proprietary algorithms would be acceptable for use in the model. In that way, the model could be subject to peer review in the short term and would be available for updating when better data or better algorithms became available.

Reporting and Coordination

The Workshop participants recommended that the ISA adopt the following key elements of reporting while the model and guide are being developed:

- Maintain an Internet site (ftp or http) that could be used by programme participants for exchanging data and draft reports. Such a site would facilitate the timely and efficient exchange of data sets and report drafts during the development of the model and guide.

- Provide periodic status reports to the Authority's Legal and Technical Commission (LTC), including written status reports and summary data sets on the ISA Central Data Repository, as well as occasional oral presentations before the assembled LTC.

- Collaborate on a regular basis with the environmental research programme currently being undertaken under the leadership of Professor Craig Smith. That coordination could be used to provide inputs to the development of the model and guide from the ongoing field work that would be conducted for the environmental research programme and could also be used to provide guidance to the environmental research for the description and delineation of benthic habitats.

Programme Phases

The programme would be executed in three phases, each of approximately one year's duration. General task descriptions for each phase are described in the following sections. Detailed scopes of work and schedules that are guided by these general task descriptions should be worked out by the ISA in collaboration with independent experts.

Phase 1

Task 1.1: Define the contents and initiate the drafting of the prospector's guide

Using the working group recommendations presented in section 2.0 above as general guidelines, initiate the acquisition and evaluation of global (entire CCZ) and regional (large contiguous areas within the CCZ with common geological or bathymetric features) data for inclusion in the prospector's guide and potentially also the geological model. By the end of Phase 1, all data types and almost all of the data sets to be used in the programme should be specifically identified and, if possible, acquired. The outline for the prospector's guide should be completed and drafting of the guide should be well underway before the end of Phase 1.

Task 1.2: Acquire high resolution data from intensively studied deposit sites

Acquire and evaluate specific local (small areas within the CCZ with good data coverage) data sets for incorporation into the geological model. The overall objective of this effort is to characterize local-scale variables such as the sizes and shapes of continuous nodule coverage, local variability of ore grade and nodule size, and relationships with local environmental variables such as sub-bottom acoustic signatures and local topography. The objective for the Phase 1 component is the acquisition of appropriate data sets and definition of the analytical efforts that will be completed in the following phases of the programme.

Task 1.3: Produce the first iteration or iterations of the geological model

Using currently available model algorithms, nodule data sets, and proxy data sets, generate the first predictions of nodule grade and abundance for the entire CCZ. Integrate the model components into well-defined procedures that can be applied independent of computer platforms or proprietary software systems. Document all data sets and procedures used. Generate standard error estimates for grade and abundance at every location throughout the CCZ. Make all results available on the Central Data Repository. As additional proxy data sets and model algorithms become available, use them, as appropriate, to generate comparative models or to refine the initial models.

Task 1.4: Complete a bathymetric model for the entire Clarion-Clipperton Zone

Acquire or generate a bathymetric model for the entire CCZ, to be used as the base map for the geological model and for regional analysis efforts included in the prospector's guide. Include documentation of the estimated resolution and accuracy of the model and the source data and methods used to generate the model.

Task 1.5: Initiate the development of a tectonic framework for the past 20 million years

Begin the development of a general tectonic framework for the CCZ that will use published studies to assemble the tectonic, bathymetric, and sedimentation history of the CCZ for the past 20 million years. The framework will be used as a basic input for the development of time-integrated estimates of how various proxy variables have influenced nodule grade and abundance over time.

Phase 2

Task 2.1: Complete the first draft of the prospector's guide

Before the end of Phase 2, all datasets to be included into the programme of work should be acquired, evaluated, and documented. These evaluations and the documentation of the data sets will constitute most of the contents of the prospector's guide, which will include the completed bathymetric model and tectonic framework. The guide will also include the results of local-scale deposit characterization initiated as Task 1.2. The completed draft should be reviewed by all participants in the programme of work at least 30 days before the Workshop, described below in task 2.3.

Task 2.2: Complete description of inputs and methods for geological model

Before the end of Phase 2, the specific data sets to be used in the modelling and the general aspects of the mathematical algorithms to be used for their incorporation into the model should be completed. The data sets and descriptions of the algorithms should be reviewed by all participants in the programme of work at least 30 days before the Workshop, described in the next section.

Task 2.3: Convene a workshop to review the progress of the programme of work

In the fourth quarter of Phase 2, convene a workshop attended by all programme participants as well as independent experts. The purpose of the workshop will be to review the reports and data products generated to date in the programme and to guide the completion of the programme. The workshop will permit final changes to be made, if necessary, to the model and to the guide.

Phase 3

Task 3.1: Complete prospector's guide

Complete the guide, after final review by the Secretariat and possibly independent experts. Include the approved document in the ISA Central Data Repository.

Task 3.2: Complete the geological model

Complete the model, after final review by the Secretariat and possibly independent experts. Include the approved document, digital maps and data sets in the Central Data Repository. If deemed worthwhile, submit portions or the entire model to peer-reviewed journals for possible publication.

Anticipated benefits of the programme

The Workshop identified the following benefits of the programme:

Improved resource assessment

The immediate and most direct benefit of the programme will be a substantial improvement in the extent and quality of resource assessment for the CCZ. The programme will also provide a summary of available resource and indicator variables that can be used for evaluation of existing claims and for guidance in the selection of new claims. Because the model will be thoroughly documented and include only reproducible methods, it will also provide a mechanism for improving resource assessment in the future as methods and available data improve.

Direct support for environmental impact assessment

To predict and manage the environmental impacts of polymetallic-nodule mining, an understanding of the biogeography of the benthic biota is essential. In particular, species ranges and rates of gene flow within and beyond the CCZ must be understood to evaluate the chances of species extinctions resulting from mining disturbance.

At the abyssal CCZ floor, as in other ecosystems, a variety of habitat variables play key roles in regulating the nature and abundance of life. The presence and abundance of individual species, as well as community structure, often are controlled by (or at least correlated with) specific physical and geological characteristics of the habitat. Knowledge of the distribution of these habitat characteristics thus provides critical insights into regional variations in the structure of the abyssal seafloor ecosystem, and the potential limits of species distributions.

Biological habitats are distinctly different for different types of seafloor. The abundance, size, percent cover, and morphology of manganese nodules, which will be evaluated in the programme, are critical habitat variables. The patch structure of nodule fields (e.g., the average length and width of nodule fields within an area) also contains important habitat information, because field size and shape may control the distribution of nodule-dependent species. Sedimentary characteristics, especially grain-size distribution, organic-carbon content, and sediment type, may also be strongly correlated with benthic-community structure.

Seafloor bathymetry substantially influences the current regime (e.g., by steering and intensifying bottom currents), the dynamism of sediments (e.g., by facilitating the slumping, erosion or deposition of sediments), and even the type of substratum (e.g., rocky substrates on slope too steep to sustain the accumulation of sediment). Because all of these factors influence the structure of benthic communities, fine-scale bathymetry, which will be evaluated in the programme, also provides important insights into the nature and distribution of seafloor habitats.

The primary source of food material for abyssal communities in the CCZ appears to be the rain of organic particles, ranging from individual phytoplankton cells to dead whales, which sink to the seafloor from the euphotic zone (i.e., export flux). The organic matter in the smaller of these particles degrades and is consumed by midwater animals during transit through the water column, generally yielding a very low flux of food to the CCZ seafloor.

Consequently, seafloor assemblages of the CCZ are among the most food- and biomass- poor on the Earth's solid surface. As might be expected in an energy-poor ecosystem, the total biomass and abundance in many size classes of benthos (e.g., the meiofauna, macrofauna and megafauna) at the CCZ floor often is correlated with the annual rain rate of particulate organic carbon. In fact, it has been suggested that the biomass in certain benthic size classes, in particular the macrofauna, might be useful as an index of the annual flux of labile particulate organic carbon to the deep-sea floor. Thus, characterization of regional variations in export flux, which is believed to be an important proxy variable for predicting nodule grade and abundance, may be very useful in defining the nutrient regime and habitat distribution of the underlying benthos.

We believe that the geological model will provide insight into variations in many of these key habitat variables over a range of spatial scales (local to basin). Thus, it should yield fundamental insights into regional distributions of seafloor habitat types and their associated species and communities. In short, the model should provide a very useful regional habitat framework in which to interpret biological data (e.g., species occurrences, rates of gene flow) obtained from the Kaplan-funded project and other biological studies. Close integration of the development and output from the geological model with biological studies in the CCZ is considered extremely important.

Other benefits

In addition to the above benefits that are directly related to the mission of the ISA, completion of the programme of work will have other, indirect benefits that may be substantial. The work will provide a uniquely integrated, multi-disciplinary examination of an important oceanic regime. The programme will examine large-scale water-column processes and their relationships to important geological and benthic biological processes in what is arguably the most purely oceanic environment on Earth. It is quite possible that the links that are found between nodule grade and abundance and the various proxy variables included in the programme will lead to significant advances in our basic understanding of general oceanic processes.

SUMMARY OF THE DISCUSSION

The Chairman, Dr. Charles Morgan, said that there had been great results from the working groups. The reports constituted a more or less uniform set of tasks that were being recommended for completion by the ISA. He said he had formatted them with respect to the original programme of work, the purpose of which was to see whether anything had been missed and to provide a common framework for the results, because many of them were overlapping and had been stated in different ways, and to show consistency with the work that had been done in January.

The Chairman wanted to have just two discussion topics: the first very short one was to just reiterate what the general January recommendations were, and then he would move on to a list of the activities in the programme of work and corresponding workshop recommendations that were before the meeting. He then added a third topic, namely, priorities, and announced that he had assigned preliminary priorities for the tasks, and had put them into three phases, corresponding roughly to three years, and then set in priorities within each of those years. He said he expected that much of the discussion would take place on the latter topic.

He said that generally, the groups had recommended the need to achieve reliable geological model within three to four years. The model input should be based on standards developed by the International Seabed Authority. The present workshop represented a broad range of expertise and stake holders in the process. It was necessary to implement the programme of work. The workshop topics from that meeting had been to include nodule formation processes, Clarion-Clipperton Zone structure, key nodule characteristics, research that should be supported, review of methods, and review of the ongoing environmental impact programme. The Chairman said that he believed all of those had been covered, so he was proud to say that a good job was being done at the workshop. The programme of work recommendations would be divided into the following categories:

- Project establishment – i.e., setting up the programme
- Data acquisition and processing
- Topography
- Proxy variables
- Relevant nodule parameters
- Modelling

The Chairman said that things had been reorganized in the workshop; primarily because of the desire to have modelling directly involved with the data acquisition and selection and processing, and also because the modelling itself was a very important part of the selection process for the data. Therefore, modelling had been included in each of the topics reviewed in the Workshop.

With regard to the programme of work – the Chairman said that, to reiterate the Scientists' meeting, the workshop would be implemented by the ISA. If the job was done right, the implementation would be straightforward and direct; if not, it would take a long time to get things going.

He said another activity was data acquisition and processing and that applied actually to most of the kinds of data available to the workshop, alone. He therefore did not have specific workshop results that applied to that, but certainly the general steps that were identified in the programme of work were applicable to each of the data types that had been dealt with in the Workshop. The sources would be identified, public and private institutions would be contacted, registered pioneer investors would be surveyed and met with for their support, the data would be added to the Central Data Repository, and summarized.

A further activity would be in regard to seafloor topography. The items that were identified in the programme of work were to process the registered pioneer investors' data, include consortia data where possible, get the best possible source of public data, then integrate those data into the Central Data Repository and generate maps at the appropriate scales.

The Chairman said that the Workshop recommendations, were quite analogous, but more specific, and more directly easily achievable, were to acquire the known one-minute bathymetry model for the regional basement and to augment that map if possible, with whatever data that could be obtained from the pioneers or other sources. Acquiring local scale bathymetry was possible, chiefly from the pioneer investors, but also possibly from the other research organizations, and examining and reporting general transfer of the local bathymetric data, and generating maps that integrated the data. The Chairman therefore thought that a good job had been done in defining more precisely the tasks related to topography.

According to the Chairman, the biggest activity by far was the ocean floor. Most of the work done in the working groups has related to one or more facets of the ocean floor. The programme of work stated that the Workshop should deal with age, composition, structure, tectonics, volcanic activities, sediment layers etc., and those topics had certainly been dealt with.

The Workshop recommendations were:

- To generate a digital map series describing the current tectonic regimes in the region
- To generate a regional model of tectonic evolution over the past twenty million years
- To delineate possible internal fracture and fault systems of possible relevance
- To examine current and ancient volcanic structures and evidence, and their possible relevance
- To examine evidence of hydrothermal activity and its relevance, and
- To examine available acoustic heat flow and other ocean floor to identify relevant regional and local constraints

The Chairman said that the last one was a big topic and that it proved many of the specific variables, such as pore water chemistry that had been identified by the sediments group, and also included a lot of the geophysical data that had been identified by the tectonics group. He said he had not had time to ensure that he had a comprehensive list of variables, so he had created something that included available pore data and geophysical data, and specifically, separated them into things that would provide some clues as to regional trends and local constraints. Those could be changed or stated differently; that was his concept of how it related to development and use of the geological model. There might certainly be other ideas on how to state the general difference between how regional, local or small-scale data were treated.

Also in the programme of work was the water column structures, oxygen minimum zone, carbonate compensation depth, currents and biology. The Workshop recommendations for these were very specific:

- To estimate the regional export productivity, both current and integrated, over the past twenty million years in the Zone
- To map the CCD in the region of interest and compare it with the nodule parameters deriving project
- To look at ocean currents, oxygen minimum zone, and perhaps other parameters, to determine whether or not they're relevant to the development of the model; whether they're available enough to be used for the refining of the model

Nodule parameters, abundance and grade, and abundance and coverage, and other compositional features (which a lot of time had not been spent on), and geo-statistics and cut-offs were also part of the programme of work. The Chairman felt that there had been general agreement in the group that cut-offs, that is, economic cut-offs (how low a grade or an abundance was useful), were to be addressed in this Workshop, because they were in every economic and implied existence of a mining model. The Chairman said that he had included it, because it had been listed, but it had not been specifically covered to any extent in the Workshop, and his suggestion was that it not be covered in the programme.

For nodule parameters, the recommendations were:

- To generate prediction and error maps for abundance and grade from the available sample data. Of course there were many sub-tasks involved with that. The wish was to do whatever could be done with the publicly available data; and to acquire whatever data was possible from the pioneer investors, consortia and perhaps other sources;
- To look at the available photos and video coverage to derive the regional trends and local constraints for abundance. Presumably an argument could be made for their expressing regional trends if there were three or more, maybe even five sites, where there was extensive coverage. It might be possible, certainly many participants believed there were regional trends, and these data would provide a really good idea of how well the local picture could be extrapolated regionally. This was a very important general topic and the aim was to get something out of it with photographic data;
- To examine nodule morphology data throughout the same kind of study, but this might be directly coupled with the photographic work; it might also include independent data from samples. Its value depended on how much data was available. Again, with regard to grade and abundance cut-offs, the decision had been taken not to do that.

Other activities included local scale modelling tasks that were in the original programme. The view was that it was important to include those up front and to make the development of the model a truly iterative process that started with relatively simple kinds of surfaces, and tried to introduce complexity as it was useful for public or predicted capability. Certainly involved in this effort were these three items that were specified in the programme of work:

- Local scale modelling. The potential applications with photographs had been discussed. It was also true with such things as the transparent layer, perhaps the side-scan sonar; the need to acquire those data, if possible, had been highlighted. Of course, the first step was to acquire as much as possible, and then it would be possible to find the kinds of things that were needed;
- Incorporating proxy variables. More time had been spent on that than on any other particular topic in the Workshop, and very productively so. The list of things in hand, the Workshop recommendations that were identified were very specific data that were available and it was strongly felt that they were related to grade and abundance. A great deal of progress had been made there.
- The construction of mathematical models would be part of the process.

The Chairman said that he had tried to identify what he had gleaned as the general consensus of what the priorities should be. He had listed them in three phases, approximately three years, but some of those phases could overlap and could certainly be rearranged. His objective was to present something with which to get the group thinking about how it wanted to proceed and where it wanted to start; what kinds of things should be done first, and what kinds of things could more productively be done later.

Phase One

At the top of the list would be the prediction and aerial maps for abundance and grade from the available data. First of all, those data had to be obtained, and then it would be relatively quick to generate those predictive surfaces, which were really the basis for incorporation of any proxy variables, and for the modification of resource assessments as we move forward.

The Chairman felt that many participants would agree that the acquisition of bathymetric data, both on a local and regional scale was probably the number two priority in the entire Workshop.

Following that would be the generation of maps describing the tectonic regimes as they presently existed, and then integrated models of tectonic evolution over the past 20 million years. It was necessary to start acquiring photos and videos immediately, so that the definition or elimination of those tasks could begin. It was also necessary to look for the local-scale bathymetry as soon as possible, so that the tasks associated with that could be defined, again looking at the regional trends and local constraints that those data might imply.

It was also necessary to acquire and assemble the information on the internal faulting, the volcanic and hydrothermal activity that Dr. Kazmin had identified. That had been surprising to many and it would certainly change the general picture if specific data could be obtained that could be compared to the Workshop's prediction. Thus, getting those data and organizing them together would also come under Phase One efforts.

Phase Two

According to the Chairman, Phase Two was in many ways examining the data collected in Phase One. He said that he would place photos and videos right on top. The potential for really helping to identify what nodule deposits looked like was probably greatest in that data source. Of course, the other one was the acoustic detail and other ocean floor data, which included many of the variables that had been defined in the sediments and water column working groups, as well as the bathymetry, seafloor working group. Thus, a lot of the work would be in, and once the kinds of data that were available and useable had been identified, examining them in several different efforts would be, in his view, a top priority. Looking at the bathymetric data, this of course would disappear if we can't get sufficient amounts of more bathymetric data, but it would be very enlightening and similar in value to the photographic data, if we can obtain such data.

Also, looking at these poorly-known geophysical and geological variables, and examining nodule morphological data are probably also well worth doing. And they would probably start before the end of Phase One, or into Phase Two, depending on when the data were collected.

Phase Three

Phase Three priorities would be bringing it together - completing the reports that documented the input data and the preliminary modelling results. The Chairman said he believed there would have to be another workshop during that period to really finalize the inputs that were going to be used to demonstrate to each other that those were the right inputs and that that was the way to incorporate them. Assuming that the Workshop went well, it would be desirable to complete the model production, and more importantly, it had to be very clearly documented. This was not a black box project. The model had to be defined in such a way that any other group could take the input data and arrive at the same predictions as the Workshop did, and similarly look at the methodology and say where it was wrong. Also, when future data became available, it was necessary to be able to use them in a similar set of algorithms; otherwise this would become a static programme and much less useful, and also less credible, than just generating maps and things like that.

The Chairman said that he presumed that one of the last steps would be submitting the results to the members of LTC for their input. There were quite a few LTC members present, so a lot of that was being done in real time. Finally, would be the formalization of the results, their incorporation into the central repository, and generation of the appropriate publications.

The Chairman said he was very happy with the interchange that had taken place and that he thought it had all been extremely productive, and had helped him to focus on the things that were really important. He said he would present the synthesis of all that had been worked toward in outline form. Of course, in the final workshop recommendations, it would be augmented and made complete by the workshop reports as well. He said he had not listed everything, but that he believed it was quite clear and represented a fairly complete listing of what the Workshop wanted to deal with.

He first wanted to reiterate the basic programme objectives that had been stated and set forth by him at the beginning of the Workshop, and then to go over briefly the strategy for model development; he clarified that the term “strategy” had been suggested by Yuri [Kazmin] and that he thought it was a good term. The strategy led to the production of basically two products for the programme:

(a) An analytical model
(b) A narrative

He said that he wanted to discuss the key elements of those briefly.

The Chairman said that another very important aspect of the programme was going to be reporting and coordination, to make sure that the iterative nature of the programme was maintained and that the proper coordination was done to ensure that the best product was obtained. He wanted to go over briefly the task descriptions and how each phase could be carried out and, finally, to go over what he thought the programme benefits were; both to the Seabed Authority and to the oceanographic and scientific community at large.

He reiterated that the programme objectives were to clarify the processes that formed nodules, provide a guide that explored all those, and to develop a model which could improve and extend the resource assessment and provide inputs to the explorers' guide and that could be refined and improved. It would be a workable and transparent model that could be updated and upgraded as new data became available.

The strategy for the development of the model was in two parts.

Phase One

The Chairman said that it was necessary for the geological model to use available data that could provide testable links to nodule grade and abundance. Those were the criteria for the data to be used in the analytical model, and an iterative and statistically-based approach would be used, testing with the data types when they satisfied those criteria. All the data that were evaluated would be documented in an explorers' guide, which would be developed in parallel with the analytical model.

The geological model would produce a set of digital and hard-copy maps representing the key variables of abundance and grade for the nodules, and also the error estimates associated with those variables. That was fundamentally what the product of the modelling is.

The explorers' guide was going to consist of a narrative assembly of the factors that were relevant to exploration; and it would take advantage of the enormous expertise that was available in the Workshop and perhaps elsewhere; it could also provide a framework for the integration of qualitative experience-based information that would coordinate and complement the model results. Recording and coordination were very important and would have at least three elements.

An Internet (either ftp or http) site would be maintained for data and draft record exchange among the participants, so that they could be done in real time and there would be a rapid turnaround and review time for the intermediate products and development of both the quantitative products and the documents that support them, and development of the explorers' guide.

Status reports would be provided to the ISA and the Legal and Technical Commission, as specified by the Authority. Very important also, as had been raised by Dr. Craig Smith, was the need to collaborate in the programme with the ongoing environmental programme, which was going to be in the field several times. It was necessary to do whatever could be done to obtain inputs from that work and vice versa, in order for them to provide a framework to delineate benthic habitats in the Clarion-Clipperton. This was seen as a potentially very synergistic and positive kind of collaboration and it was desirable to specifically include it in the model development.

The programme would have three phases, of roughly one year’s duration each, but a detailed schedule needed to be hammered out. Phase One would produce the first iterations of the geological model and would initiate the evaluation and acquisition of other data types that would go into the model and or into the explorers' guide.

The Chairman outlined the specific tasks that came out of the workshop recommendations, as follows:

- For the geological model, the first order of business was to generate prediction and error maps for abundance and grade; using the currently available data. That has been done with more data readily available for input into generating a map.

- A global topography model has to be generated - most of the work for has also been done although it was doubtful whether it was possible to improve on the one minute model that has already been developed and available from the National Geophysical Data Centre.

- A little bit more difficult, would be the generation of a tectonic model for the past 20 million years. Since there was a pretty good idea how that Pacific plate had been moving, that was not expected to be an enormous time-consuming job.

The Chairman said that he thought three things were absolutely essential, do-able, and would allow the next iteration to be developed with the use of the proxy data. As could be done in Phase One, depending upon the availability of the proxy data, that could be incorporated into the model as well. In parallel with that, it was desirable to evaluate candidate global and regional proxy data, as well as candidate local data, for either inclusion into the model, if they met the criteria, or for documentation in the explorers' guide, if they did not. It was necessary to prepare digital datasets and algorithms for the data that made the cut to be included in the model. The algorithms would describe specifically how they impacted and how they were to be used to generate or improve the geological model. Finally, it was necessary to document the evaluation of all the candidate data that were used in Phase One for the explorers' guide.

The Chairman referred to candidate data for global and regional data, that is, data for the whole Clarion-Clipperton Zone, or major portions of it. The sediment thickness and composition was known, as these data came from cores and seismic data. It was desirable however, to look at export productivity as it was a very important variable, and maybe one of the first of the variables used as a proxy parameter. It was desirable to look at the water column and sediment parameters, including the CCD, the oxygen minimum zone, and perhaps other things, such as organic carbon, although the working group was not too optimistic about the availability of those data. It was necessary to see whether or not they could be used. It was necessary to take the available data that Dr. Kazmin had looked at, and develop it further to see what more could be done, given the initial iteration of the geological model - whether something quantitative that could be used and that was related to the geophysical and tectonic characteristics that Dr. Kazmin talked about could actually be generated. The variables needed to be documented even further and more clearly for the exploration model. In addition, it had yet to be seen how ocean currents could be used quantitatively, but it was known qualitatively that they were certainly important, and there was no doubt that they needed to be documented for the explorers' guide.

Of course, as had been discussed in many ways, we could end very much on the availability and the comparability of the local data from one side to the next; the value of the data would totally depend on those things. But, it was certainly necessary to look at microtopography, which came from multibeaming, and side scan systems. Sediment thickness and composition had to be looked at, where there was closely-spaced data, closely-spaced cores, seismics, things like that, which would accompany in most cases the microtopography data, and also the photos and videos. The Chairman said that in most programmes, all three kinds of data were collected in specific areas by the different consortia, and this was a sort of summary of the kinds of data that would be sought to see whether they would be appropriate or not for further development, and at the very least documenting them.

Phase Two

The first of the explorers' guide would be completed, so that there would be a product that could be reviewed carefully. The inputs and methods for the geological model would be finalized. One had to stop looking for more proxy data at some point and before the end of Phase Two would be a very good time to stop. All of the inputs to be used in the geological model would have to be defined before the end of Phase Two.

The Chairman said that, to conclude that phase, there would probably be a need for another workshop that would review the draft of the explorers' guide and geological model, and see whether there were any mid-course changes that needed to be made.

Phase Three

Phase Three would be the completion of the explorers' guide and the geological model, and submission of the results to the Central Data Repository and; if appropriate, publication of the results in period journals, if indeed, there were something worth publishing.

Benefits for the International Seabed Authority

First of all, this would doubtless provide the best possible resource assessment for the Clarion-Clipperton zone

It would also provide a mechanism for improving the resource assessment as time goes by, as the methods would be clearly documented so that they could be repeated and improved beyond the generation of this product.

Not least important, and in fact, possibly one of the most important things that would come out of this, was that it would provide a framework for delineating benthic habitats, so that the biological assessment, the environmental assessment would have a very important set of environmental data within which to place their biological data. It would allow them to extrapolate and to look for places where they expect differences, based upon the data characteristics generated by the geological model and exploration guide.

On a more general level, it would provide an authoritative description of an important oceanic regime. It would be a useful reference for many persons in the future. It would hopefully integrate large-scale water column processes with geological and benthic biological processes to perhaps allow examination of larger variables and even address such issues as large-scale mass flux to the oceans, global warming and a host of large oceanographic problems. This would have the potential to contribute to those kinds of efforts as well.

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CONCLUDING REMARKS

Ambassador Satya N. Nandan,
Secretary-General,
International Seabed Authority

Thank you Charles for the meeting round-up. I was amazed at the level of discussions and the convergence of ideas that have lead us to agree on the model, and allowing us to proceed to developing the model. I'm very grateful to all participants for their contribution. This group has tremendous knowledge, some going back to very many years, and some others who have been engaged along the way. They have all brought their expertise and experience to us to help the Authority develop the elements for the model that we want to establish.

One of the concerns that I've always had, is for us to utilise the knowledge and experience that have been developed over the years, before we go into retirement. And I thought it was important that we try to take advantage of their participation in this stage in their life, and bring together their experiences. We now have this model so that we can retain all the great work they have done, and benefit from the great knowledge and wisdom that they have derived over the course of their lives. That is a really important aspect as far as we are concerned. No doubt there will be others who will come along and do more work in the Clarion-Clipperton, and do more extensive research, but these are the pioneers who established the foundation for the work.

Thank you all for your contributions and your achievements. When we came here, we were not sure whether we would finally achieve that goal. However, with all your efforts during this week, you've done marvellous, marvellous, work. I thought that you might be tempted to spend more time outside this morning, and do less work but you have all continued to work very intensively and I'm grateful for that, and appreciate it.

One aspect of the model which I thought was very pleasing was the fact that you've incorporated the environmental benefits, I have always been trying to tell people that the two are interrelated somewhat, and that it wouldn't be a good model unless the environmental people can do the studies relating to the organisms and their distributions in the Clarion-Clipperton Area. If we superimpose the two, I think it would be very good. It would be a great contribution and quite a unique contribution. So, I think its going to benefit the environmentalists as well. As you know the Kaplan Project is on its way. We've already had samples etc, and now the next thing is for us to get this project on its way, now that we have the concept. It is my intention to continue to communicate with all of you to develop the project and then expand it, and get the model going. It is my intention to have a meeting of the contractors, and now that we have a project, something I can put to them and explain to them what we are doing and what we hope to achieve, and see where they can incorporate it when building this model. We need to get as much information as we can to ensure that we can count on their cooperation. I think it's important to know what it is that you want.

Finally, I also thank SOPAC for all the assistance which they've provided to us in every way. The technology is superior; perhaps more advanced than we'd find elsewhere. And I also want to thank the Government of Fiji; the Minister for Home Affairs, and the Foreign Minister. I also want to than the Director of Mines for all the assistance and guidance they've given us in setting up the field trips.

I hope before you go, you'll see a little more, if you have time, of the beautiful surroundings here. This is in some ways a holiday resort area, so I hope you can see a little more of it.

I thank you very much, and all of my gratitude.

Alf Simpson
Director
SOPAC Secretariat

I agree with Satya, that you all came to Fiji and sampled the general island, however, trying to predict the rest of the country will give you a distorted model so you really need to visit a few more places to give you a bigger and more realistic picture of what Fiji is all about.

I'd like to thank Charles for his chairing. I presume that he had no real idea where he wanted to go. But the development of the model becomes slightly easy if you just jump in and say "develop a model." I presume the Seabed Authority itself also has a model on how we can develop the areas; because what we are developing is actually beyond the Seabed Authority, but for the common heritage of mankind. If we know where we want to go, and what we're doing it for, then I think that everything will be easy.

For this Fiji conference obviously, we thank our hosts for facilitating us; also, the Seabed Authority and Satya Nandan for bringing this meeting here to Fiji. Sometimes we sit in Jamaica, and we sit in the buildings, and we sit in our flights, and the way we operate sometimes is slightly different when we are taken out of that environment; and the way we work suddenly changes. I think we have a common goal, and I hope we can call this the common goal model. We stand for a common goal and not only that, we drink from the same cup; and I think that's the general idea. When you take people out, and we work together and we share, we find that we come to a different conclusion. I think that method of working together may be the way for the future. It's a good model for us to follow in the future.

Thank you. Thank you to everybody. I'd like to apologise for shortcomings from our side; there's all these things that we should have done. But I hope we managed to facilitate running this workshop. I think we had a lot of time to play; and I think that's always good, because I think developing the human relations is equally important as the other part of work.

I'm really grateful for those who've been at the meeting; and for those working in the hotel, and those of us who speak English obviously. Sometimes, I think how I would get on if I went to another place and speak another language; we take it for granted all the time. I think it's something that we should be grateful for; we should thank all the speakers – the French speakers, and the Russian speakers, and the Indonesian speakers.

I'd like to just address my fellow Pacific Islanders at the end of this. For some of us, its come along, and its part of the education and learning process. I think many times there are various things that had just gone way, several metres above our heads; but I hope we'll be able to see the processes. We'll largely focus on the data and the information. That data and information will be there at the end of the day and it will be stored as well.

There is a process of moving the information across into models; and models to knowledge and knowledge to wisdom. This is a human element. When you put together that huge databank of brain power and memory, the things behind the data are very, very important. We need to facilitate collecting all that information and producing those little maps. But if we don't have that common brainpower and history and information, and if we don't somehow find a way to capture that and keep that and use that, then all the data in the world is going to highly useful. So we really need to find a way to keep that, and this our workshop; when we meet again in another ten, twenty, fifteen years time, probably half of us won't be here. So it's important to recognize that those who work on that are equally as important as the information we carry. But if we don't have this input this way, we can get the input from the various people that I think we've lost. As I said earlier on, when we've got a group like this, what we've got to do is simplify things, so we come to a common understanding.

Everyone can sign on. But we mustn't forget that the diversity of knowledge that people have. We've talked about all these various things and they're all information and important. We really need to find a way in which all these layers and information can be accumulated in one place. Maybe we need the development of a separate website where people can put data; not to come to a final synthesis like this one, or as a one-stop shop; but I think we need to find something. This is the kind of model that will bring everything together. I don't think we should compromise and draw and come up with one; this is all right for the Seabed Authority, but for everyone to use, and for those who come later on, this is the way that to help people. Because the human thought can never be replaced; if we try to synthesize it, then all the years and years of experience are lost; that would be a great loss for mankind. Maybe we need to as a group think about this.

So, people of the Pacific, this thing has been going on for ages; we're just starting. Don't be disillusioned by the fact that we didn't understand too much of what was going on. We need to find a way to bring all this information so that we can find a way so we have a better understanding of everything. It goes without saying that the Clarion-Clipperton does not have four walls around it; and what happens here does affect everyone else. We've got to work together.

Sorry I've gone on, but I'm just trying to end this on a human note. At the end of the day, it is humans working together that actually develop these models that actually will use these models. And as much as we, for our own scientific gratification, produce scientific publications or whatever, that's fine. But at the end of the day what is it for? We've all been working together. Nothing can take that away from this meeting.

SOPAC and the participants, is very small and insignificant in terms of the global distribution. But we think that we have an obligation to look after quite a lot of the seabed and seafloor; and the only way to do that is to develop partnerships. We will continue to work and try to develop partnerships with the Seabed Authority; we hope following this we can share what data we have for a greater database.

I thank my staff for their long hours they put into this meeting. I'd like to thank the director of music for being here; they were with us in the other place as well, last week; running around behind the scenes, kept the music system working. I'd like to thank the hotel for hosting us. We hope you enjoyed yourself. We hope you travel safely.

Thank you very much.

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