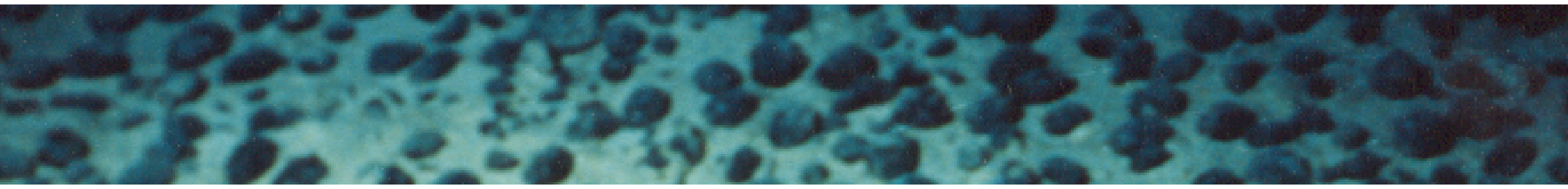

A Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone

Charles Morgan | March 2012

Submarine ferromanganese concretions were first discovered in the Kara Sea off Siberia in 1868. In the course of its round-the-world expedition from 1872 to 1876, the HMS *Challenger* collected many small dark-brown balls, rich in manganese and iron, which were named manganese nodules. Since the 1960s, manganese nodules have been recognized as a potential source of nickel, copper, cobalt, and manganese, which are likely to assume increasing importance as land-based deposits of these metals become depleted.

Manganese nodules are found on the seabed in many areas, and have been comparatively well studied because of their potential economic importance. The Clarion-Clipperton Fracture Zone (CCZ), the study area for this project, has been the focus of much international attention for many years. To date, the greatest concentrations of nodule deposits have been found in this region. The CCZ is defined for this study as the area between 110°-160° W Longitude and 0°-20° N Latitude (see *Figure 1*). Presently, nine of the ten contractors with the International Seabed Authority (the Authority, also the ISA) who are exploring for polymetallic nodule deposits have their contracts in the CCZ.

As part of its mandate to conduct resource assessments of prospective mineral deposits in the seabed outside of any national jurisdictions (termed the “Area”), the ISA Secretariat staff met with representatives of the contractors to discuss ways of improving the results of resource assessment efforts. Due to the absence of sampling data across much of this vast geographic area, participants in the meeting suggested that, if the suspected relationships between high metal content and abundance, and factors such as sediment type, volcanism, topography and primary productivity etc. could be established, they could be used as proxies for grade and abundance in poorly sampled areas. They therefore recommended that the Authority should develop a geological model of polymetallic nodule deposits in the CCZ.

At the ninth session of the Authority, its Legal and Technical Commission, recognizing that such a model would be useful for prospectors, contractors and the Authority, endorsed this course of action. The Authority convened a workshop in Nadi, Fiji, from the 13 to 20 May 2003 to consider the data that could be taken into account to develop such a model. It identified candidate proxy variables and devised a programme for the development of the model and a Prospector's Guide. Taking into account the results of the Fiji workshop, a group of technical experts assembled by the ISA identified the approach that it would use to generate the model, specified the proxy data that would be tested for use in predicting nodule metal content and abundance, and devised a programme of work over a thirty-month period to complete the work. The programme commenced in the 2005- 2006 biennium.

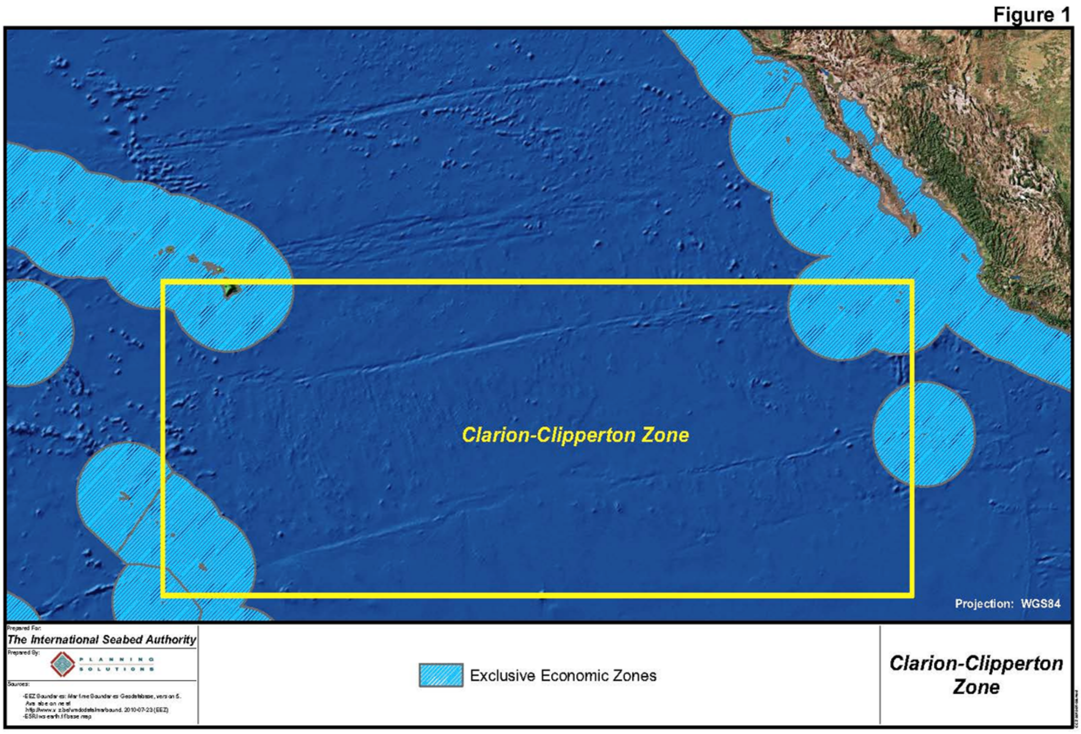

Figure 1: Clarion-Clipperton Zone

The primary products from the effort are (1) a Geological Model of polymetallic nodule deposits in the CCZ and (2) a Prospector's Guide containing a narrative description of the key factors relevant to exploration for polymetallic nodules in the CCZ, including data and available information on known deposits. Both reports have been completed and reviewed by the Authority and by the contributing consultants. They were further reviewed during a workshop on the matter at the Authority during December 2009. This technical study provides a concise version of the two products. The basic results from the Geological Model are summarized below.

In this briefing paper, the results of three independent approaches to establishing a Geological Model for CCZ polymetallic deposits are presented. No undisclosed or proprietary algorithms are used so that the Model can be subject to peer review in the short term and available for updating as better data or better algorithms become available.

Primary Resource Data Set

Five different data sets of polymetallic nodule abundance and metal content are used in the modeling work, including both publicly available and proprietary data sets (see *Figure 2*). They include:

1. All publicly available data on the Authority's Central Data Repository (CDR; http://www.isa.org.jm; Polymetallic Nodules - Major elements);
2. A proprietary data base used with the permission of the Lockheed-Martin Corporation (Ocean Minerals Company, OMCO);
3. Data sets provided by The Government of the Republic of Korea;
4. Data sets provided by The China Ocean Mineral Resources Research and Development Association (COMRA) of the People's Republic of China; and
5. Data sets provided by The Interoceanmetal Joint Organization (IOM), composed of the Republic of Bulgaria, the Republic of Cuba, the Czech Republic, the Republic of Poland, the Russian Federation and the Slovak Republic.

Virtually all the data were obtained from analysis of free-fall grab sampler recoveries, though a few results from box core recoveries are also included. Except for the data extracted from the Authority's Central Data Repository, the metal content estimates were determined by commercial laboratories set up by the respective Contractors. Abundance (mass of nodules per unit area on the seafloor, usually with units kg/m^2) is estimated simply by the division of the mass of recovered nodules by the surface area covered by the open jaws of the sampler (~0.25 -0.5 m^2 coverage). Free-fall grab samplers are the best tools available for the assessment of nodule abundance, but they consistently underestimate the actual abundance present. Thus, the resource assessment values presented here are likely to be underestimates. The numbers of stations available for the study are shown in *Table 1*.

Inferred Resources

Several methods of estimating the quantities of polymetallic nodules and contained metals within portions of the study area were utilized. *Table 2* lists representative values of these estimates. The total area of the CCZ, as defined here, includes approximately 12.1 million km^2 of seabed. As shown in *Figure 3,* a significant portion of this area (1.39 million km^2) is within the Exclusive Economic Zones of various nations (the U.S., Kiribati, Mexico, and France); some 5.48 million km^2 are within the ISA's jurisdiction and also lie between the Clarion and Clipperton Fracture Zones. This is the area that has attracted the most interest from commercial explorers. As shown in *Table 2* and in *Figure 4* to *Figure 8*, the survey areas available to this study include most of this area. Finally, about 5.19 km^2 of seabed are within the study area and within the Authority's jurisdiction, but not within the bounds of the fracture zones. Very little survey effort has to date been committed to this area.

Table 1: Source Data for Resources Assessment

Data Source	CDR	KORDI	OMCO	COMRA	IOM	Totals
# Stations: Abundance	253	329	7,738	52,473*	790	61,583
# Stations: Manganese	879	258	5,875	716	664	8,392
# Stations: Cobalt	711	258	5,900	716	664	8,249
# Stations: Nickel	799	258	5,923	716	664	8,360
# Stations: Copper	882	258	5,924	714	664	8,442

Source: ISA
*Indirectly inferred from acoustic backscatter data
CDR: ISA Central Data Repository, polymetallic nodules, major metals
KORDI: Korea Ocean Research and Development Institute
OMCO: Ocean Minerals Company, Inc.
COMRA: China Ocean Mineral Resources Research and Development Association
IOM: Interoceanmetal Joint Organization

Table 2: Inferred Polymetallic Resources in the Clarion-Clipperton Region

Source	Included Area (km^2 X 10^6)	Inferred Resource (metric tons X 10^6)				
		Nodules	Mn	Co	Ni	Cu
KORDI (low estimate)	3.83	21,100	5,950	46.4	270	234
KORDI (high estimate)	4.19	30,700	8,657	67.5	393	341
Ordinary kriging	4.85	27,100	7,300	58.0	340	290
Annual world production	-	-	31 (2006)	0.07 (2009)	1.4 (2007)	16 (2010)
Source: *ISA Technical Study no. 6*						

Figure 2

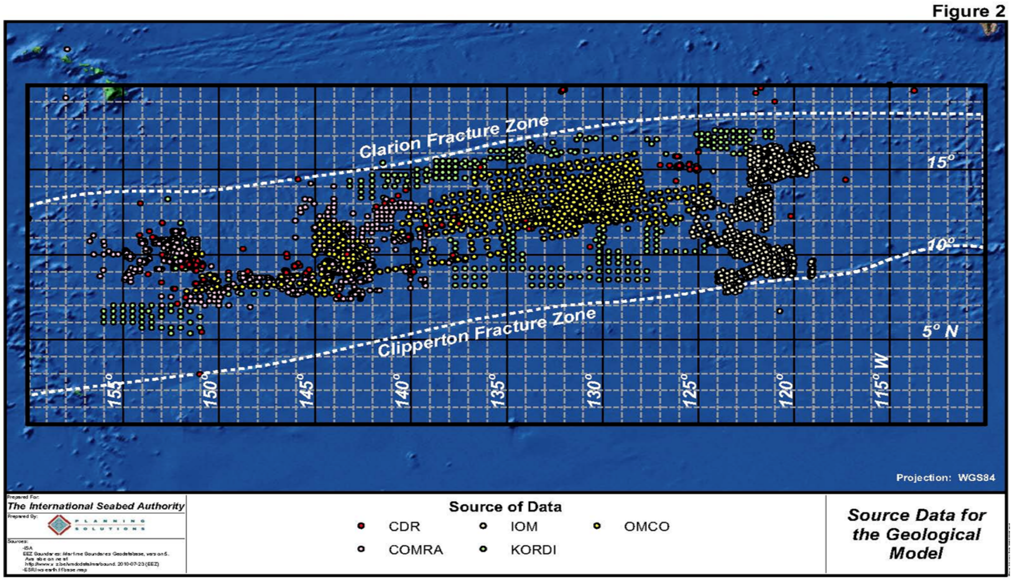

Figure 2: Source Data for the Geological Model

Figure 3

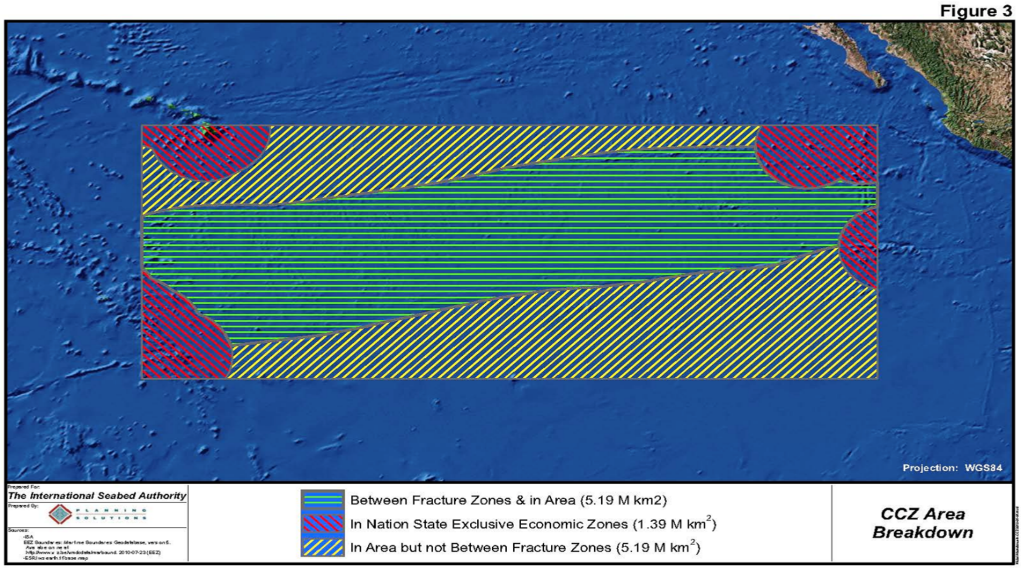

Figure 3: Clarion-Clipperton Zone Area Breakdown

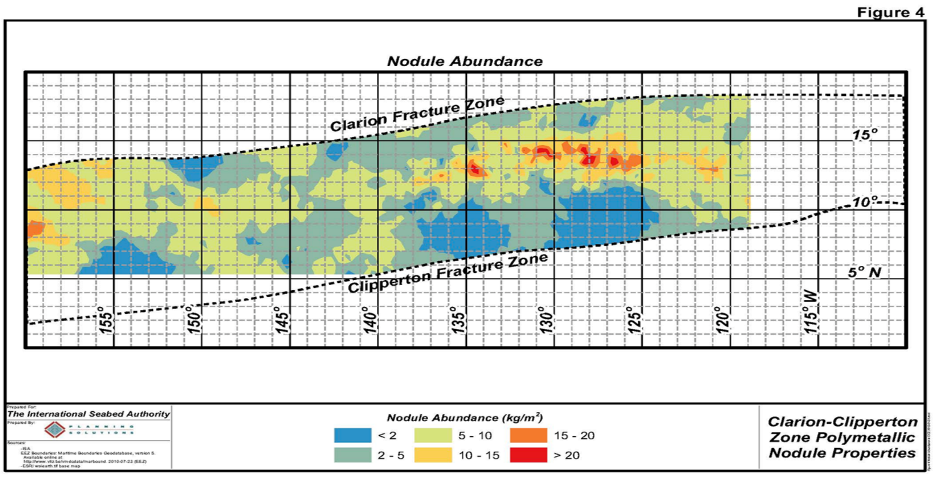

Figure 4: Nodule Abundance in the CCZ

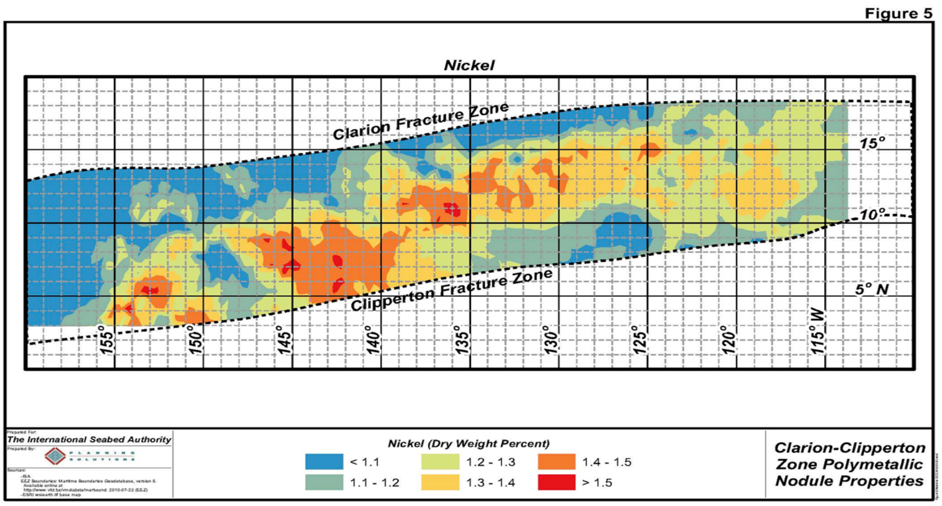

Figure 5: Nodule Nickel Content in the CCZ

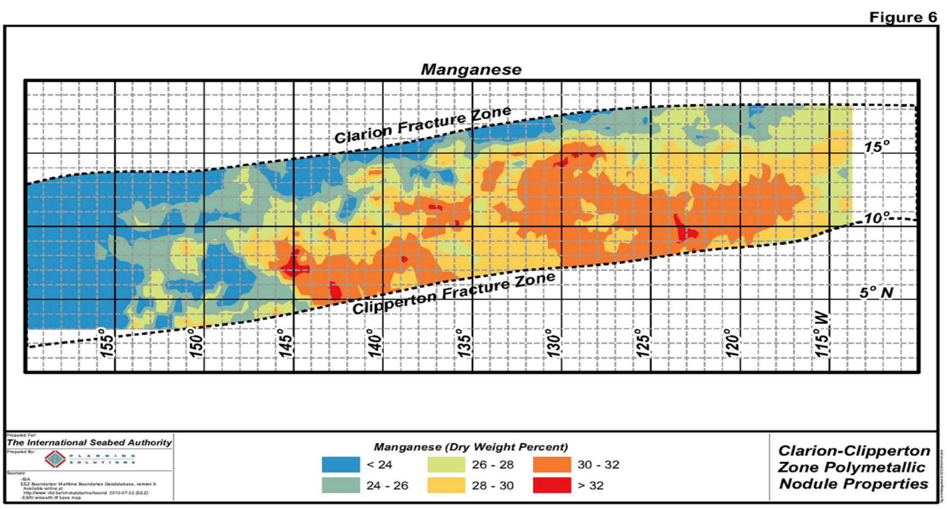

Figure 6: Nodule Manganese Content in the CCZ

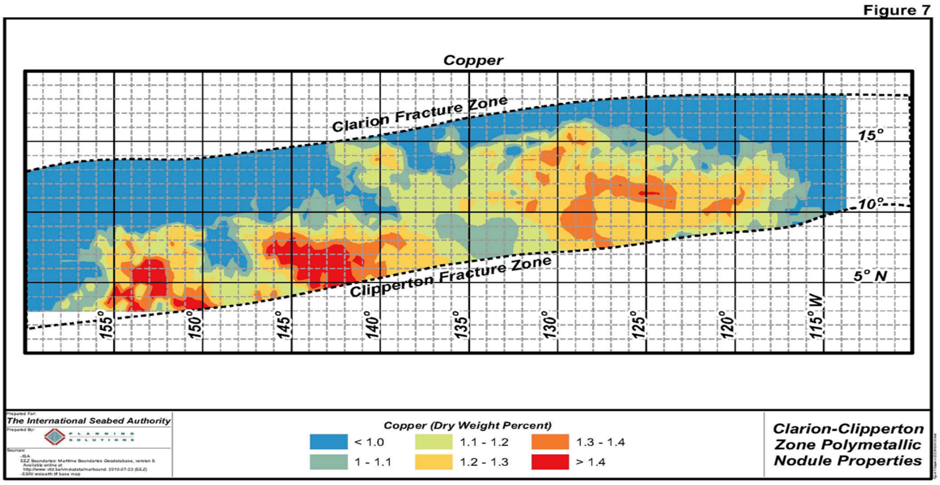

Figure 7: Nodule Copper Content in the CCZ

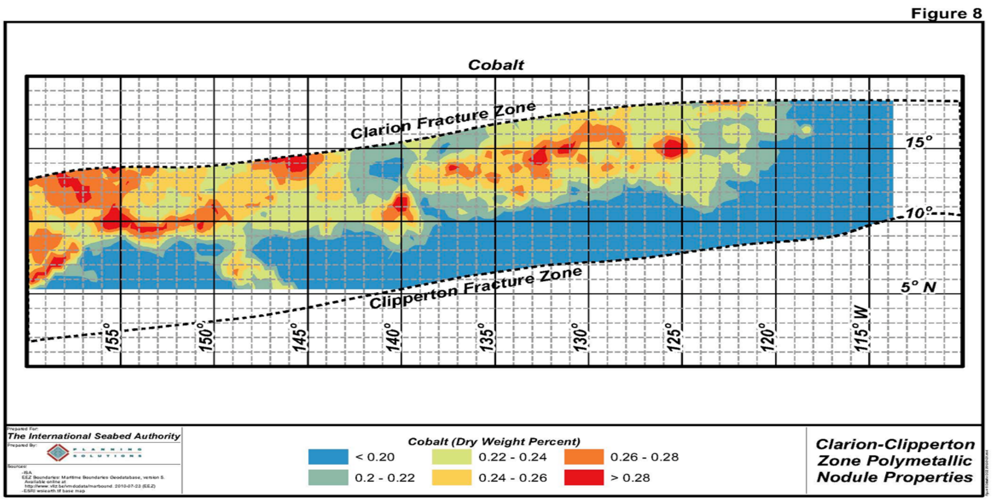

Figure 8: Nodule Cobalt Content in the CCZ

Biogeochemical Modeling

The general hypothesis for metal accumulation (specifically manganese, nickel, and copper) in the CCZ polymetallic nodule deposits is illustrated in *Figure 9*. It is based on ideas originally introduced by Greenslate, Frazer, and Arrhenius, (1973)[1] which have been refined here as the basis of a regression model. Cobalt, which also is an important valuable metal of nodule composition, is not included in this statistical study, since it is believed to accumulate via hydrogenetic processes that are independent from the biogeochemical model described below. Iron, which is the main antagonist to manganese in nodule composition, exists in the ocean water as colloidal iron oxyhydroxide particles and is mainly supplied to nodule growth after release to the water column due to dissolution of calcareous skeletons.

The general sequence of metal accumulation proposed is as follows:

The primary metal sources of manganese, nickel, and copper to the oceans, and presumably for these deposits, are believed to be from continental run-off, volcanogenic, and atmospheric sources. The terrigenous metals exist as dissolved ions and complexes or are adsorbed to the surfaces of fine-grained particles that carry them westward within the North Pacific current.

[1] Greenslate, J. L., Frazer, J. Z. and Arrhenius, G. (1973). Origin and deposition of selected transition elements in the seabed. In: M. Morgenstein, *The Origin and Distribution of Manganese Nodules in the Pacific and Prospects for Exploration*. Honolulu: Hawai'i Institute of Geophysics, 45-69.

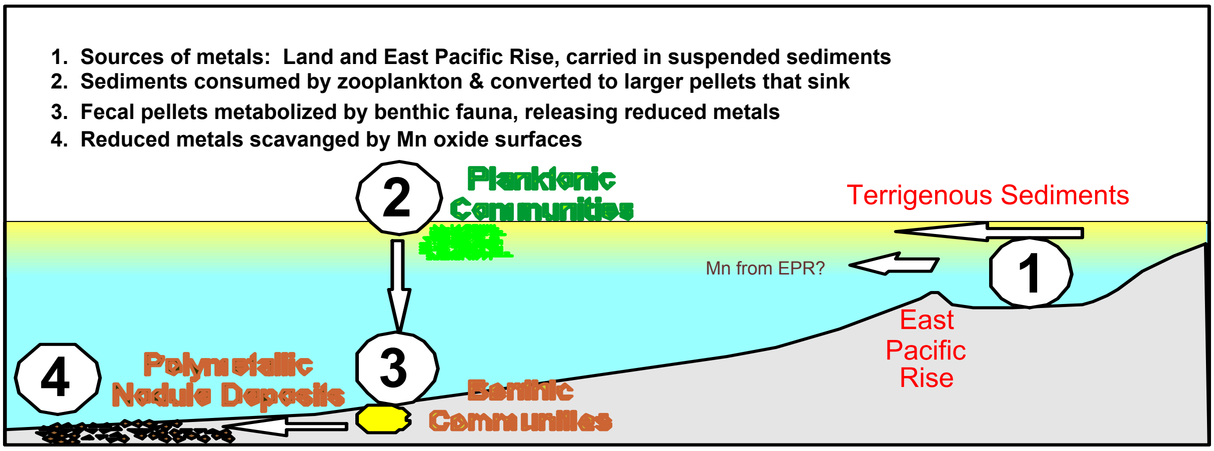

Figure 9: General Nodule Formation Model in the CCZ

Volcanogenic metal injected into the water column from the East Pacific Rise probably consists predominantly of Mn. Some portion of the dissolved and/or adsorbed Mn may reach surface layers of the Pacific Ocean, and be then transported to the west. By the time these metals reach the deposit sites in the CCZ, the postulated terrigenous, volcanogenic, and atmospheric sources would not be distinguishable from each other.

Most of the fine-grained organic and inorganic particles in surface waters, which are mainly products of the biological processes in the photic zone, are too small to sink directly to the seafloor. However, these, as well as dissolved metals, can be taken up by the plankton in their organic tissue and shells during their life and growth, and later through adsorption processes after death. Some of the dissolved metals are also taken up at the particle surfaces and are released throughout the deeper water column. One very important particle type for the proposed vertical transport to the seafloor, especially for Mn, is fecal pellets.

Some portions of these metal-laden organic particles are deposited on the seafloor, where they are metabolized by benthic animals and are degraded through bacterial metabolic processes. These biological processes will reduce metals and make them soluble. The main process of metal fractionation takes place under early diagenetic conditions in the pelagic siliceous ooze sediment. The organic material of the fecal pellets gets degraded, causing suboxic conditions in the pore water environment of the upper sediment layer consisting of a semi-liquid surface layer and a sublayer with suboxic to reducing conditions reaching down to about 30 cm.

Under these circumstances manganese is reduced, and other metals like nickel and copper are leached from their surface positions on sediment particles such as opaline skeletons. Thus, the pore water in the sub-layer contains enhanced concentrations of dissolved metals. Since oxidizing conditions prevail at the surface of the sediment, the metals migrate upwards via diffusion through this oxidation gradient. Mn is then oxidized in the uppermost surface layer and forms manganese minerals like todorokite or birnessite. These minerals have interstitial layers that are able to scavenge metals like copper, nickel and others. This results in a selective incorporation into these manganese oxide mineral lattices and explains the particular enrichment of these and other metals in the nodules.

If this model of nodule growth has a basis in fact, and if the regional trends in surface water circulation and biological primary productivity have been persistent for the past several million years, then the metal content of the polymetallic nodules in the CCZ should reflect the intensity of the biological processes that are evoked to explain the metal transport from the surface waters to the deep water precipitation sites and the re-arrangement of metals during early sediment diagenesis.

Also important to this model is a hypothesized balance between increasing supply of metals from biogenic sedimentation and the increasing dilution of metals from excess biogenic sedimentation (*Figure 10*). At very low levels of biological activity, the supply of reduced metals to the seafloor is insufficient to produce substantial nodule deposits. At the other extreme, under regions with relatively high biological activity, as found in the eastern tropical Pacific and near the equator, the flux of organic matter will exceed the rates at which the benthic nodule-forming processes can extract.

The chlorophyll content in surface waters is closely related to the level of biological activity taking place and also to the export productivity at the site, (i.e. the flux rate of biogenic material out of surface waters) and is used as a proxy for primary productivity here. In this study we use the estimates of chlorophyll content that were determined by blending historical archives of in situ (National Oceanographic Data Center) and satellite (Coastal Zone Color Scanner) chlorophyll data, which were combined using the blended analysis method of Reynolds in an attempt to construct an improved seasonal representation of global chlorophyll distributions. These data are available as seasonal and annual averages. *Figure 11* shows the annual average used in the modeling runs described here.

To identify empirical relationships between metal content and this proxy variable we used a regression method. Because the general hypothesis assumes that primary productivity (approximated using the chlorophyll concentration in surface waters) should be related in a non-linear way to metal content, we used a regression equation that is second order with respect to chlorophyll content. The results in general suggest that a little less than half of the variability of the metal content in these deposits can be explained by this model. For example, the results for nickel are shown in *Figure 12*. These values give some support to the general hypothesis, but are not sufficient to provide confident predictions of nodule content in areas with no survey data.

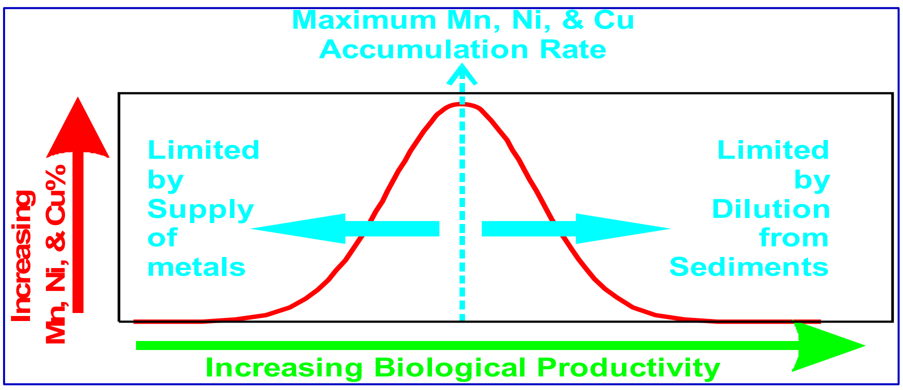

Figure 10: Hypothesized Optimum Level of Biological Productivity for Nodule Growth

Spatial Decision Support System Modeling

Another, more objective modeling procedure, called Spatial Decision Support System (SDSS) modeling, was employed to estimate the mineralization potential in selected areas of the CCZ where nodule abundance and metal content data are not available. The study is based on data sets that include bathymetry, topography, sediment type, carbonate compensation depth (CCD) and surface chlorophyll. Specific techniques employed in the study include Weights of Evidence Modeling, Fuzzy Logic, Logistic Regression and Artificial Neural Network (ANN) techniques. The results of this work provide differing assessments of the spatial distribution of areas within the study area where the occurrence of nodule deposits is likely. The results consistently indicate that better prospects can be found in the center and northern parts of the CCZ, while the southern, southwestern and eastern parts of the CCZ are likely to be unfavorable for nodule deposit occurrence. Likely prospects of nodule occurrence in CCZ from Weights of Evidence Modeling, Logistic Regression, Fuzzy Logic, and neural network simulations are shown in *Figure 13*, *Figure 14*, *Figure 15*, and *Figure 16*. These predictions are represented by color from the most likely to least likely areas to host nodule deposits as follows:

Red > Yellow > Blue > Green

Thus, future explorers might expect to get better results from exploration efforts that focus on the center and northern areas of the CCZ than the southern, southwestern, or eastern areas.

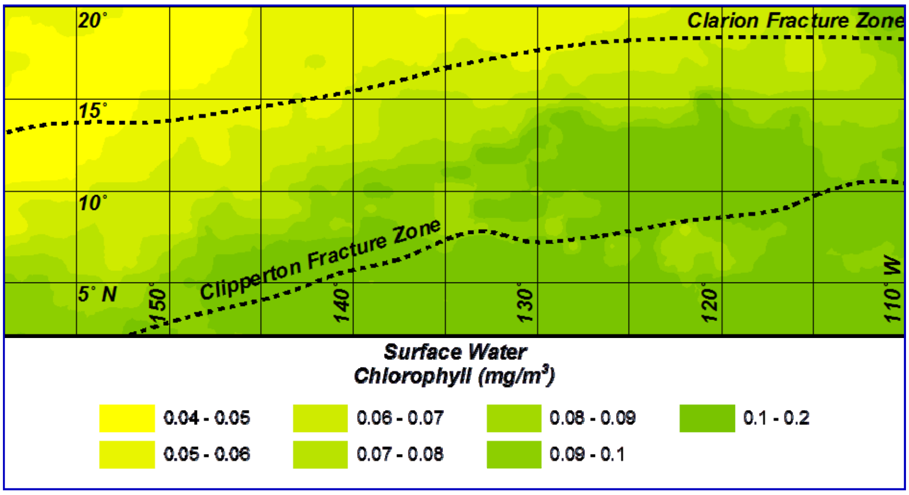

Figure 11: Chlorophyll in Surface Waters of the Clarion-Clipperton Region

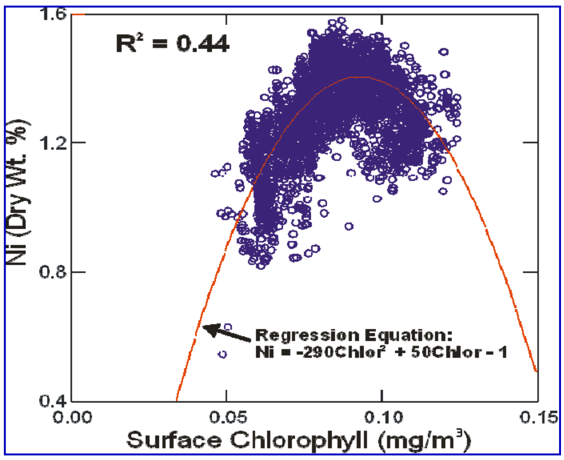

Figure 12: Nickel vs. Chlorophyll Regression

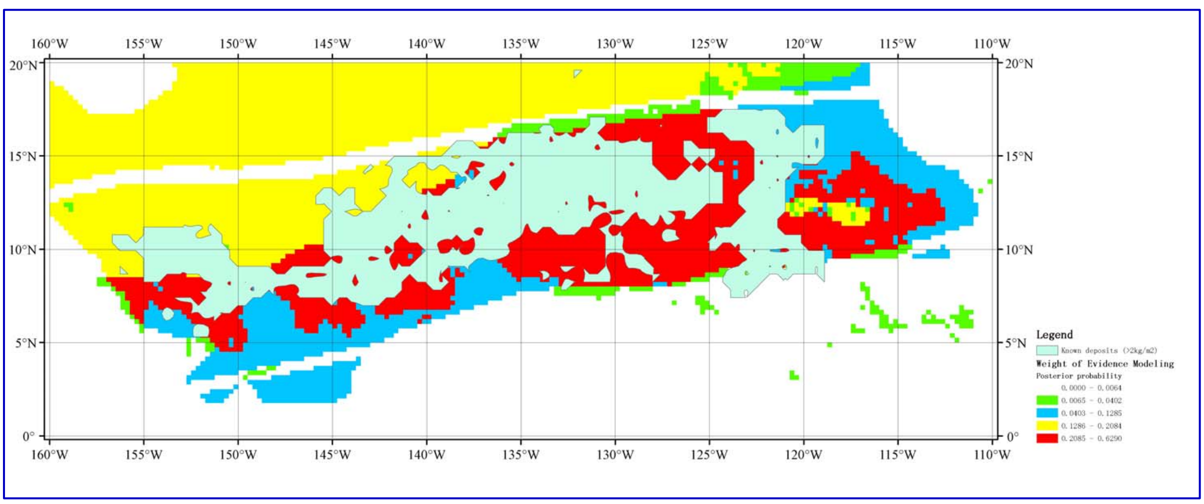

Figure 13: Likely Prospects for Nodule Occurrence, Weights of Evidence Modeling

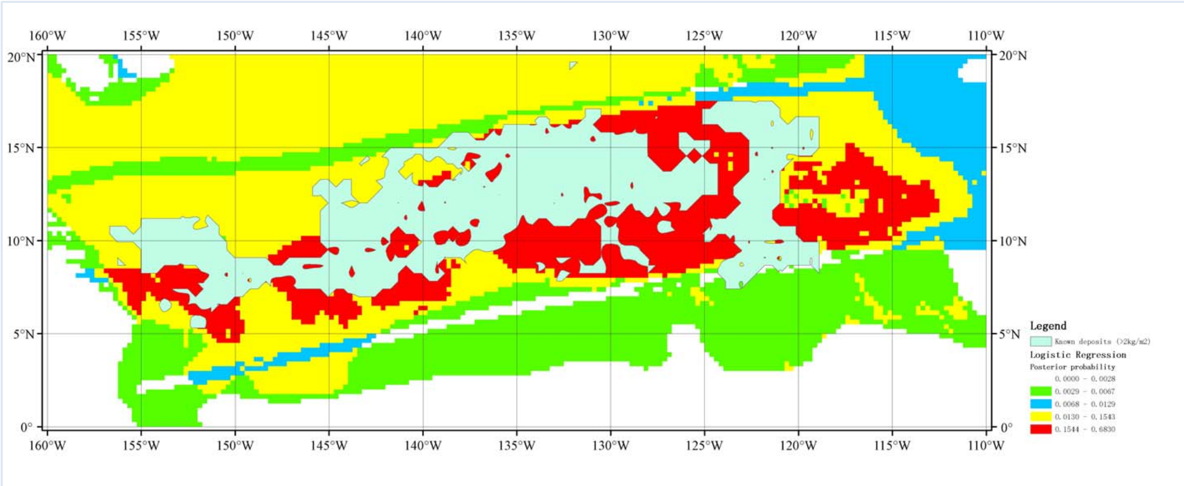

Figure 14: Likely Prospects for Nodule Occurrence, Logistic Regression

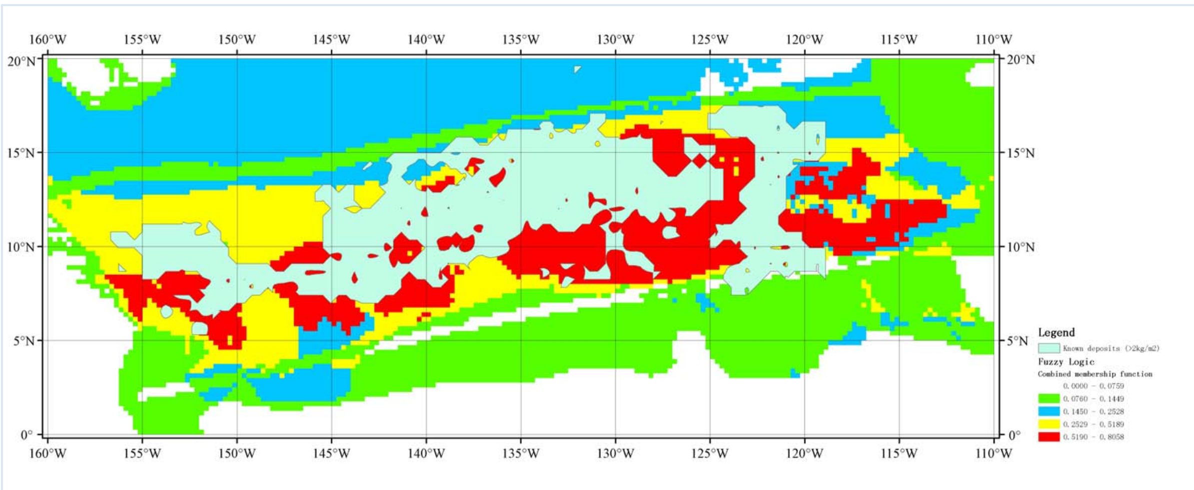

Figure 15: Likely Prospects for Nodule Occurrence, Fuzzy Logic

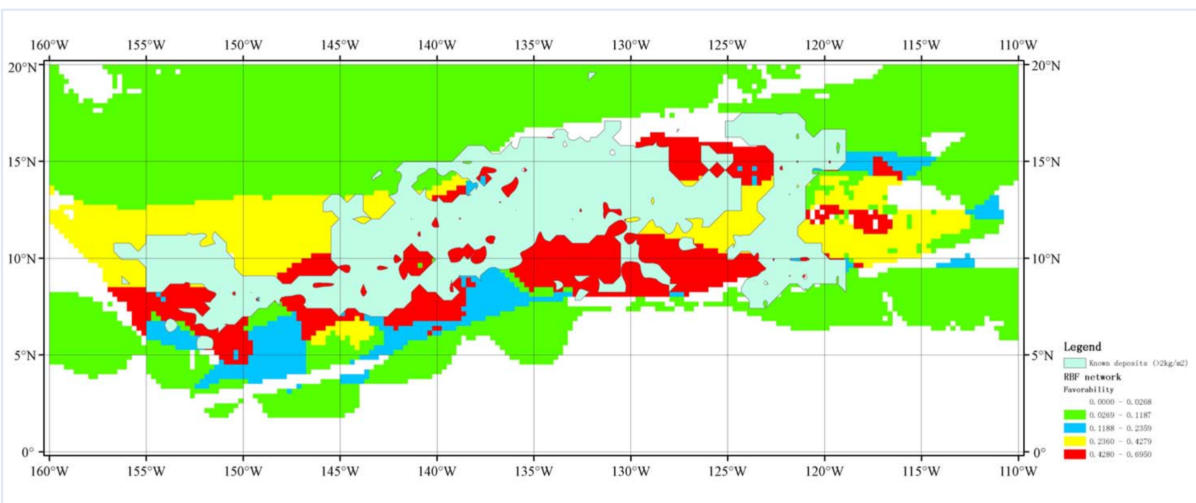

Figure 16: Likely Prospects for Nodule Occurrence, RBF Network Modeling

Application to New Contractors

Since the Geological Model was completed in 2009 there have been two new exploration contracts issued by the ISA, to Nauru Ocean Resources Inc. (NORI), and Tonga Offshore Mining Limited (TOML). These are the first contracts issued to developing countries for Reserved Area exploration programs. Through personal communication directly with Mr. David Heydon, the Managing Director of NORI and the individual directly responsible for the delineation of both the NORI and TOML exploration areas, it is clear that the Geological Model was used to help define the areas included in these claims. As shown in *Figure 17*, the areas selected are, with one exception in the extreme west, from Reserved Areas showing the highest available nodule abundance. Thus, the Geological Model has already borne fruit in a very practical way by guiding these developing countries in their initial selection of exploration areas.

Figure 17

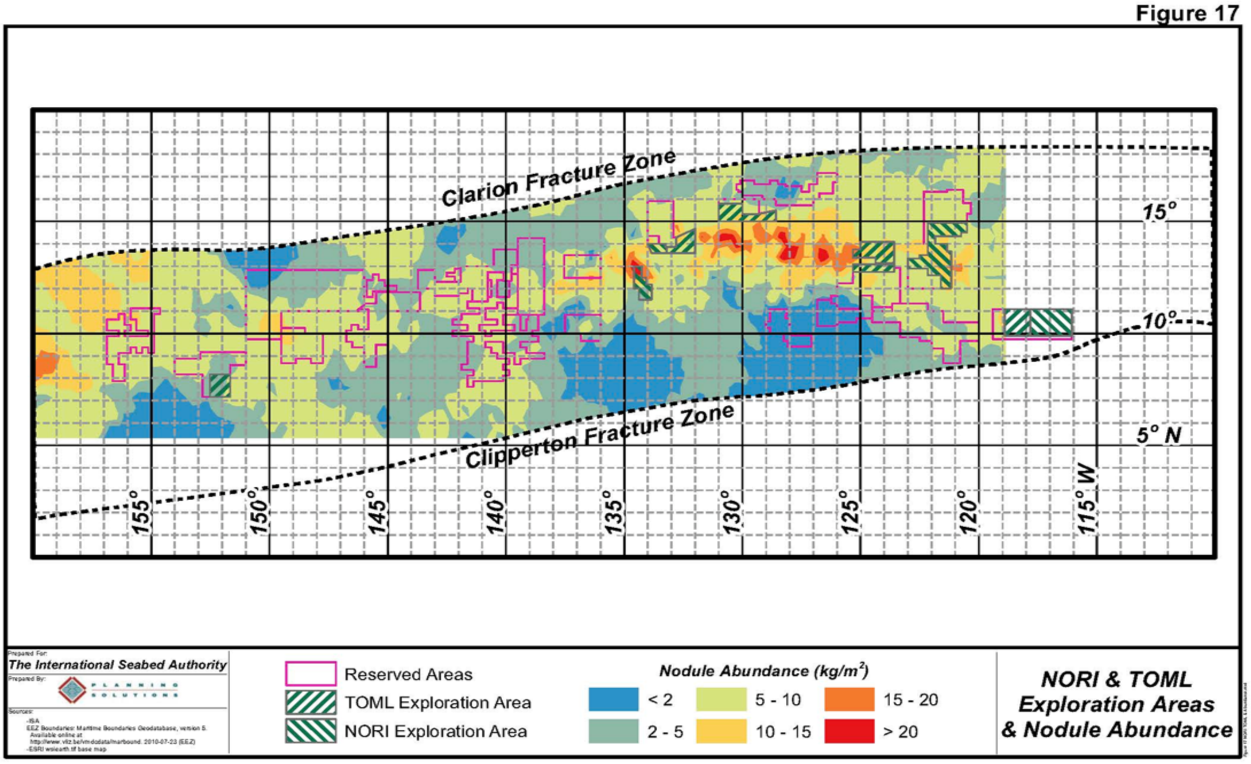

Figure 17: NORI and TOML Exploration Areas and Nodule Abundance in the CCZ

This paper was prepared for the International Seabed Authority sensitization seminar held in New York on 16 February 2012 on the work of the ISA and current issues relating to deep seabed mining.

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The International Seabed Authority is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. The Authority is the organization through which States Parties to the Convention shall, in accordance with the regime for the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction (the Area) established in Part XI and the Agreement, organize and control activities in the Area, particularly with a view to administering the resources of the Area.

As part of its mandate to conduct resource assessments of prospective mineral deposits in the Area, the Authority, together with its contractors and scientists, joined forces with a group of technical experts to establish and develop a Geological Model of polymetallic nodule deposits in the Clarion-Clipperton Fracture Zone. The publication *(A Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone: ISA Technical Study No. 6)* is available online on www.isa.org.jm/files/documents/EN/Pubs/GeoMod-web.pdf.

The Geological Model consists of a set of digital and hard copy maps and tables describing the predicted metal content abundance of deposits in the CCZ, along with associated error estimates. The Prospector's Guide examines all potential proxy data variables identified as important indicators of metal content and abundance, and outlines specific data sets that qualify for use in the Geological Model.

The area of interest for this study is 110°-160° W longitude and 0°-20° N latitude.

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