Workshop on the Results of a Project to Develop a Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Zone

14-17 December, 2009, ***Kingston, Jamaica***

Background Document

1. Polymetallic nodule resources contain nickel, cobalt, manganese and copper. While they occur in all oceans, deposits in the Clarion-Clipperton Zone (CCZ) are considered to be among the richest, containing high grade and high abundance nodules. Presently, seven of the eight exploration contractors with the International Seabed have exploration contracts in this area. As part of its mandate to conduct resource assessments of prospective mineral deposits in the Area, the Authority met with representatives of the seven contractors to discuss ways of improving the results of resource assessments of polymetallic nodule deposits in the CCZ. In the absence of sampling data across much of this vast geographic area, participants in the meeting suggested that if the suspected relationships between high nodule grade and abundance, and factors such as sediments, volcanism, topography and primary productivity etc. could be established, they could be used as proxies for grade and abundance in poorly sampled nodulized areas. They therefore recommended that the Authority should establish a geologic model of polymetallic nodule deposits for the CCZ. *Figure 1* shows the Clarion-Clipperton zone CCZ with the Contractor and the Authority's Reserved Areas. 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 cause of action. Between 13 and 20 May 2003, the Authority convened a workshop in Nadi, Fiji 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.

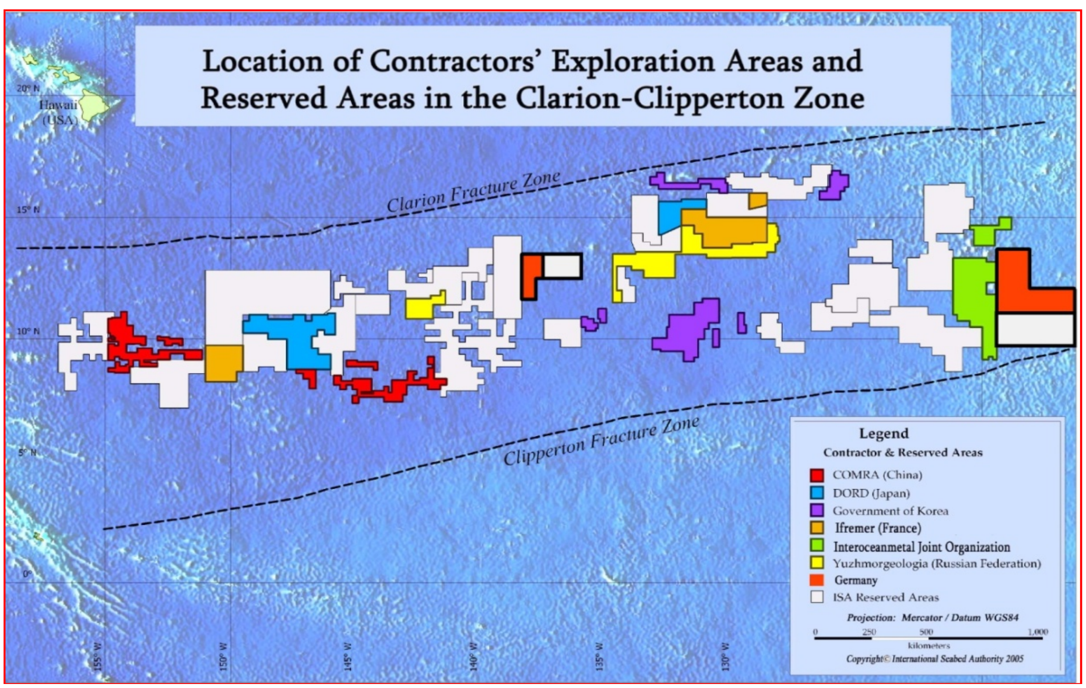

Figure-1: Location of Contractors' Exploration Areas and the Reserved Areas in the Clarion-Clipperton Zone.

2. Taking into account the results of the Fiji workshop, the seven member Group of Technical Experts identified the approach that it would use to generate the model, specified the proxy data that would be tested for use in predicting nodule grade 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. The area of interest for this study is 110° - 160° W Longitude and 0° - 20° North Latitude. 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.

3. The Authority served as the link between the contractors, their scientists and the Group of Technical Experts for the development of the Geological Model of polymetallic nodule deposits in the CCZ and Prospector's Guide. It set up a closed ftp site for the use of the consultants and contractor scientists (project members). It also uploaded to the ftp site all the data, reports and other related notes concerning the project and made them accessible to all project members.

4. The Authority regularly monitored the progress of the project by evaluating the interim reports and facilitating the resolution of any matters that arose during project implementation. The Authority conducted a mid-course review of the programme at the East-west Centre, Hawaii during October 2006. At the mid-term review meeting, the consultants and the Secretariat discussed the progress of the work under the project and the future course of action to complete it. To facilitate the project's completion and undertake a final review of the model and prospector's guide the tasks were reassigned to the team members.

5. 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. The drafts of both the reports are ready and have gone through the preliminary process of review by the Authority and by the contributing consultants. The contents and main results from the reports are presented in the following paragraphs

The Prospectors Guide:

6. Included in this report are the results of nine independent studies that provide extensive geophysical, geological, oceanographic, and biological information related to the CCZ deposits and general guidance, based on many years of study of these deposits, of why these deposits occur where they do and criteria for seeking undiscovered deposits elsewhere. This report includes 23 tables and 92 figures.

i. GRIDDED BATHYMETRY OF THE CCZ

7. The seafloor lies mostly between 4,000 and 6,000 meters water depth. The seafloor is characterized by a number of seamounts, some of which reach depths of less than 3,000 meters. The wide-spread seafloor spreading fabric, oriented approximately orthogonal to the trend of the bounding fracture zones, provides a large number of flat floored valleys, separated by irregular, often discontinuous ridges a few hundred meters high. The study used the Smith and Sandwell data set as the base map and incorporated proprietary data and paper maps from ISA Contractors to derive a series of bathymetric grids of the CCZ at resolutions of 1, 0.5 and 0.1 minutes of latitude and longitude. These data files are available at the ISA's Central Data Repository. *Figure-2* shows the 1 minute resolution bathymetric map of the CCZ.

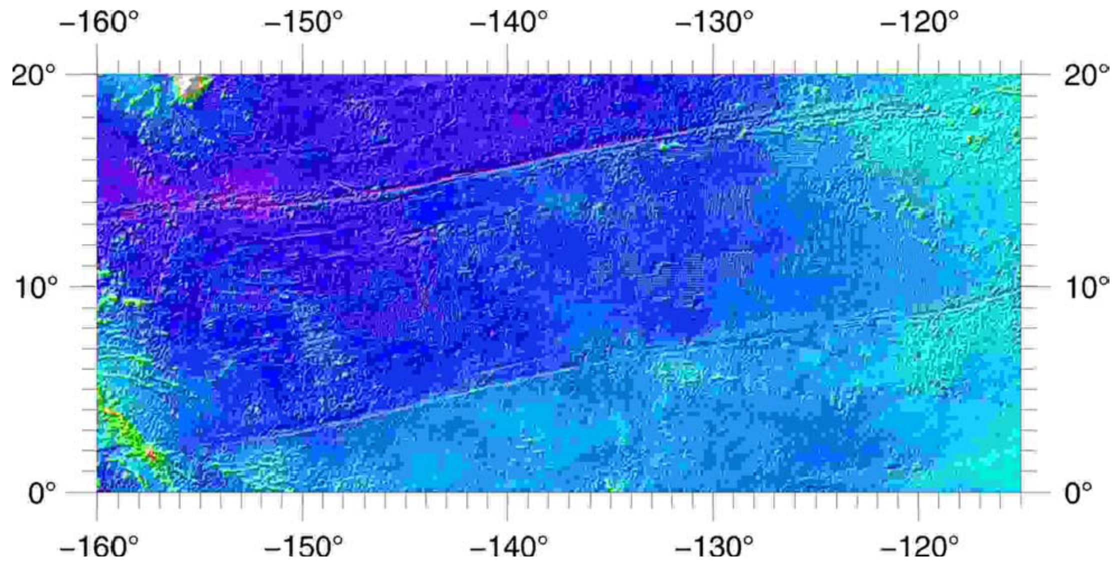

Figure-2: 1 min resolution bathymetry of the CCZ

ii. VOLCANIC, TECTONIC, AND SEDIMENTARY FACTORS

8. This study provides an analysis of the maps of volcanic and tectonic structural elements of the CCZ. The objective is to estimate the possible influences of static factors, (i.e. bathymetry, geomorphology, tectonic structure, and lithology), and dynamic factors (i.e. dynamic geological events such as tectonic movements and volcanogenic, hydrothermal, sedimentary, and erosive processes) on the growth of polymetallic nodules in the CCZ.

9. The bathymetric characteristics within the CCZ follow a pronounced order, most commonly consisting of trends that line up with the overall movement of the Pacific Plate and trends perpendicular to this direction. Generally, water depths and crustal age increase with distance from the East Pacific Rise. Recent seismic activity in the region has been also aligned with or perpendicular to the plate motion, suggesting that it is caused by strike-slip and normal faulting associated with the relief of stress caused by the rifting of the Pacific Plate to the northwest

10. The sediment facies exhibit a unidirectional gradient perpendicular to the fracture zones, trending from predominant carbonate sediments in the southeastern extreme to predominant siliceous red clay in the west-northwest. There are also regional-scale non-conformities, including latitudinal zonation of a variety of young (Pleistocene-Holocene) sediment facies; and a pronounced surface unconformity of Middle Miocene age, denoting an interruption of the sediment accumulation, dislocation and erosion of the earlier cumulated sediments

11. The analysis of the spatial distribution of nodule abundance and metal concentration suggests an axial line of maximum abundance that is approximately parallel to and midway between the bounding fracture zones. The spatial distribution of metal content is different. The Mn/Fe ratio clearly increases from north-south, while, less distinct, decreases from east to west. These observations suggest that volcanogenic-hydrothermal activity of the EPR is one of the main sources of the ore components, which, finally, are included in manganese nodules composition as the result of complicated processes of dispersion and transportation to the bottom in dissolved and organic-fixed forms.

iii. GROWTH MODEL FOR POLYMETALLIC NODULES

12. Polymetallic nodules are composed of both nuclei and concentric layers of iron and manganese hydroxides. Generally, according to their morphology, size and texture etc., polymetallic nodules are classified into three types: S-type (Smooth type), R-type (Rough type) and S-R-type (Smooth-Rough mixed type). They generally grow very slowly, at rates of 1-10 mm per 10^6 yr. Six factors are believed to be important to nodule formation These factors are;

a. Supply of metals to growing surface;
b. Presence of nucleus

c. The corrosive and erosive forces caused by benthic currents of Antarctic Bottom water
d. Occurrence of semi-liquid surface layer on the seafloor (sediment water interface)
e. Bioturbation and
f. Internal Stratigraphy of individual nodules.

iv. NODULE COVERAGE, MORPHOLOGY, AND DISTRIBUTION IN THE EASTERN CCZ

13. In order to understand the nodule distribution within this study area, an analysis was made to determine the correlations among such nodule parameters as coverage, abundance, morphology, size, genetic type, and the water depth, bottom morphology, and geographic region. A classification system for nodule morphology and formation mechanism separates hydrogenetic from diagenetic nodules, and isolates different morphological types (discoidal, spheroidal, etc.).

14. Throughout the eastern part of the CCZ diagenetic, discoidal and ellipsoidal nodules are the dominant types. In the areas of highest nodule abundance, nodules with multiple nuclei are the most common morphology. The highest percentages of seafloor covered by nodules are found in water depths between 4,100 – 4,200 m, and the highest abundance values are found between 12° to 16° N latitude.

v. SEDIMENTS IN THE EASTERN CCZ

15. Detailed examination of bathymetry and sediment distributions and compositions in the eastern CC has been carried out. The topography of the area is characterized by NW-SE to NNWSSE trending elongated seabed structures. Two predominant acoustic reflectors delineate Miocene and Oligocene unconformities. The surface sediments consist of Pleistocene-Holocene siliceous silty clay and ooze underlain by Miocene to Pliocene pelagic clay, zeolitic clay and zeolitic crust and hiatuses of Plio-Pleistocene and Late Miocene ages. The ocean floor is a hilly plain - plateau, crossed by a strictly north-south system of horst and graben structures. The surface relief of this hilly plain is generally less than 100 m in extent, with hills and ridges exceeding 100 m in plains.

16. The most common sediment types in this region include Reddish Brown clay and zeolitic clay (less than 5% amorphous silica content), slightly siliceous (with 5-10% amorphous silica content) and siliceous (10-30% amorphous silica content) silty clay as well as slightly calcareous (5-10% CaCO3 content) and calcareous (10-30% CaCO3 content) silty clay. The uppermost part of the sediment profile features predominantly siliceous, silty clay, which, down core grades into slightly siliceous, silty clay. Calcareous, silty clay and calcareous oozes are observed only in the southern part of the study area. Metal contents in these sediments generally follow the following trend of decreasing concentrations- Fe > Mn > Cu > Ni > Zn > Co

vi. NODULE GENESIS & SEDIMENT DISTRIBUTION IN THE KOREA ALLOCATED AREA

17. Nodule genesis and growth are affected by many environmental factors, especially (1) supply of biogenic, terrigenous and hydrogenetic material to the sediment and to the nodules; (2) deposition and reworking of sediments due to seafloor morphology; (3) bottom water composition and movement; and (4) bioturbation. Morphological and textural characteristics of manganese nodules in the study area are summarized as follows. The northern block (KR2) is characterized by relatively high nodule abundances, low Mn/Fe ratios, low Cu and Ni contents, and high Fe and Co contents. In morphologies, poly-nucleated and irregular-shaped nodules are dominant. In texture, smooth types and transitional types between smooth and rough are abundant. All these characteristics indicate that hydrogenetic process has been dominant over diagenetic one in the northern block. Taking account of the relatively slow growth rate of hydrogenetic nodules, the presence of smaller nodules in the northern block is consistent with other chemical, morphological, and textural characteristics of nodules.

18. On the contrary, the southern block (KR5) is characterized by relatively low nodule abundances, high Mn/Fe ratio, Cu, and Ni, and low Fe and Co contents. Figure 1 shows the abundance ranges in areas KR5 and KR2. Different from the northern blocks, rough-surface and dimorphic (rough on one side, smooth on the other) discoidal and ellipsoidal nodules are the dominant morphological and textural nodule types in the southern block. All these characteristics indicate that digenetic process have dominated over hydrogenetic ones in the southern block

19. The sediments in the study area consist of three major lithological units: Units 1, 2, and 3, which are distinctive in color and textures. Unit 1 comprises the topmost layer and shows dark grayish brown to dark brown colors. It is homogenous mud and characterized by very high water content with dominant occurrence of quartz and illite. Unit 2 lies below or alternates with Unit 1 in most cores. It consists of yellowish brown to brown colored mud and includes lots of burrows filled with overlying Unit 1 sediments. Burrow densities decrease downward. Unit 3 is overlain by Unit 2 in most cores where it occurs and shows very dark brown to black color. Both Units 2 and 3 contain abundant smectite minerals. Sedimentation rates for all units are estimated to be near 0.1 mm/1,000 yr.

20. The distribution of different nodule genetic types in the northern and southern blocks can be explained with topography and sedimentation rate. It is known that hydrogenetic nodules are formed preferentially in areas with high topographic variation and low sedimentation rates, consistent with dominant nodule types and geological settings found in the northern block. Diagenetic nodules are known to be formed preferentially in flat abyssal areas with high sedimentation rates. The southern block has a geological setting more preferable to diagenetic nodule formation than the northern block.

vii. BATHYMETRY AND SEDIMENTATION IN THE COMRA CONTRACT AREA.

21. The area explored includes two non-contiguous portions, an East Area and a West Area. Water depth in the East Area ranges from 3,901.8 m to 5,590.7 m. The West Area ranges in depth from 2,969.1 m to 5,986.6 m. The area deeper than 5,300 m in water depth covers about 8.5% of the East Area and about 11% of the West Area. Water depth in the COMRA area, in both portions of the area, is mostly between 5,000 m to 5,300 m. There are generally four types of sediment in surface layer of seafloor of the COMRA area, including siliceous clay, siliceous ooze, siliceous-calcareous ooze and calcareous ooze. Siliceous sediments are the most abundant sedimentary types in the East Area. Siliceous clay covers 72% of the area and siliceous ooze 22%. Siliceous clay is mainly distributed in abyssal hills and plains with an average water depth of 5,096 m. Siliceous ooze is mostly distributed in transitional areas between siliceous clay and calcareous ooze in the southeastern part of the East Area. Calcareous sediment is limited to seamounts in southeastern and western parts of the East Area. In general, calcareous sediments confined to the tops of seamounts, while the siliceous sediments cover the lower regions.

viii. REGIONAL EXAMINATION OF SEDIMENTS.

22. Data sets were provided to the study by three Contractors in the Area, including the French- IFREMER, Chinese contractor COMRA, and the multi-national consortium IOM. In addition, publically available sediment data within the CCZ study area were downloaded from the U.S. National Geophysical Data Center (NGDC). In order to investigate the relationships between the sediment type and nodule abundance and metal content, we interpolated a sediment type for each of the 0.1˚ grid points where nodule data are available. We then calculated the average metal content and abundance for each sediment type represented in the data set. The results generally confirm the qualitative conclusions noted by scientists for many years, i.e. that the highest abundances of nodules occur in the siliceous sediments and not in the calcareous sediments. However, somewhat surprisingly, siliceous, calcareous mud host the highest abundances, and the siliceous oozes have surprisingly low abundances.

ix. BENTHIC BIOLOGICAL DATA FROM THE CCZ

23. A number of research programs have sampled the abyssal North Pacific seafloor, many of which collected data for multiple parameters of interest to biogeochemical modeling efforts. Overall, meiofaunal (63-300 µm) and macrofaunal (300 µm-3 mm) abundances and/or biomass represent the most widely sampled biological parameters in this region, and these data sets also exhibit the greatest consistency in collection methods across field programs. Preliminary examination of the data indicates that, in general, the abundance of these benthic fauna is roughly proportional to the flux of nutrients available in particles settling from the surface.

Geological Model of polymetallic nodule deposits in the CCZ

24. In this report, the results of three independent approaches to establish the Geological Model for the CCZ 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. Report includes over 23 tables and 58 figures.

x. PRIMARY RESOURCE DATA SET

25. The area of interest for this study is 110° - 160° W Longitude and 0° - 20° North Latitude. 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. The additional data sets were generously provided by the Contractors (COMRA, Korea, IOM, France) and by the consortia Ocean Minerals Company (OMCO). These contributions of additional data increased the Nodule abundance data base to over 61000 data points (as against ~ 300 available with Authority's Central Data Repository-CDR) and the metal grade values to nearly 8000 data points (as against ~850 available with CDR). The methods used to produce this integrated data set and its basic characteristics are described in the report.

26. In order to preserve the spatial information inherent in these data while accommodating the proprietary concerns of the data owners, the above data were assembled into groups representing all data collected within a defined grid with dimensions of one-tenth of a degree of both longitude and latitude. For each grid block where data are available, the data values are averaged. For each resource parameter (abundance and metal content), the number of stations within the grid bounds, mean, minimum, and maximum values, and, where at least three stations are present, the standard deviation of the values are reported. The report presents the interpolated maps generated for the abundance and the metal values. The *Figures 3, 4* and *5* respectively show the original data, the gridded data and the interpolated contours for the abundance values.

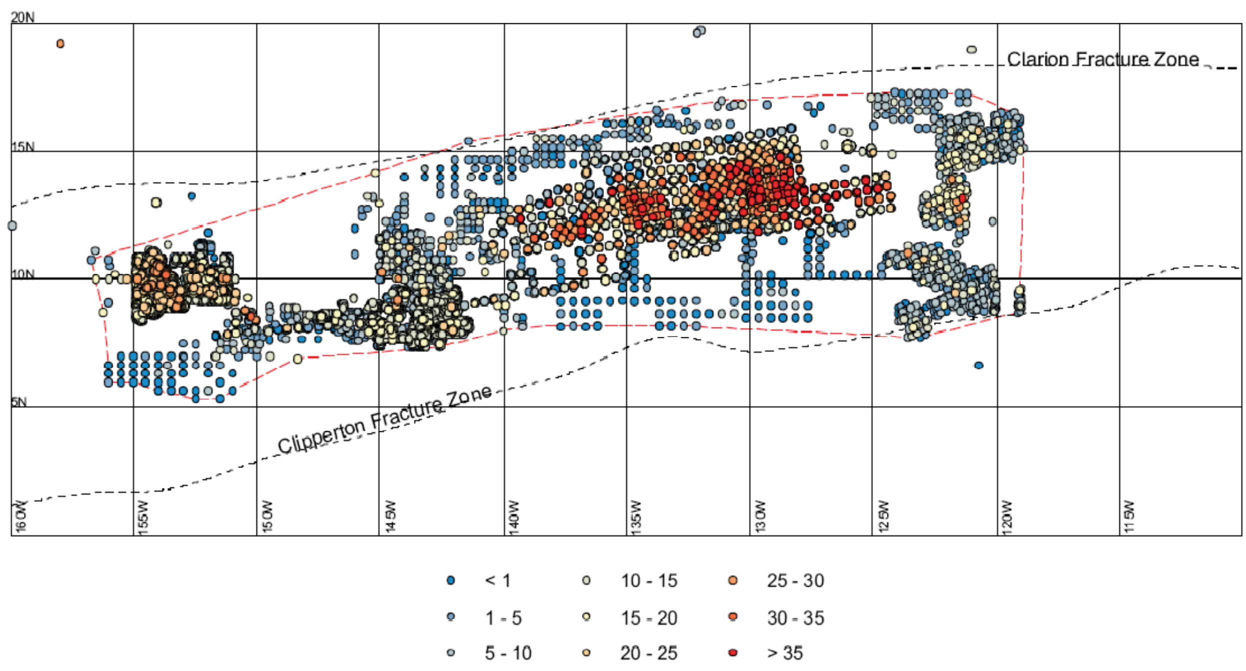

Figure 3: Abundance (Kg/m^2) Original Data locations and values

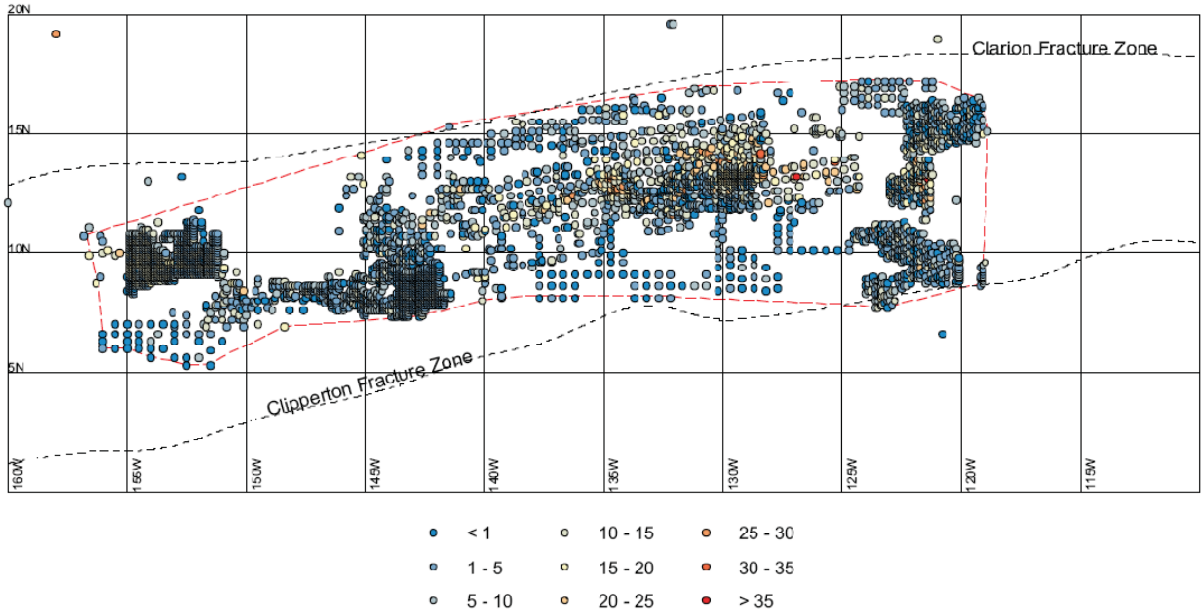

Figure 4: *Grid block data locations and values of Abundance (kg/m^2)*

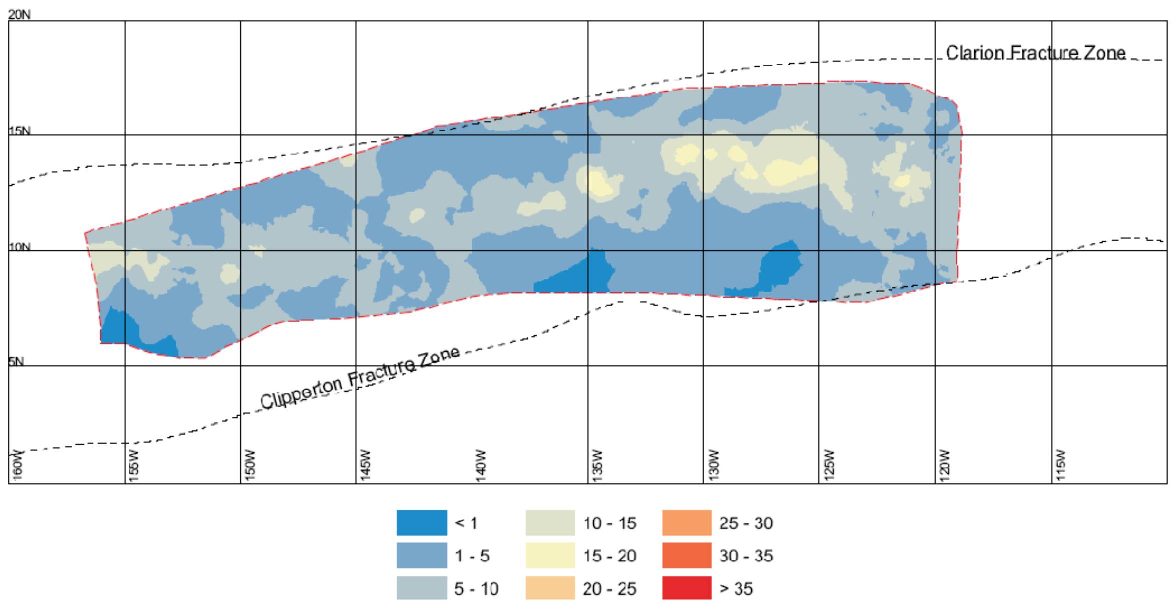

Figure 5: *Abundance- grid block data interpolated contours.*

xi. INFERRED RESOURCES

27. Several methods of estimating the quantities of polymetallic nodules and contained metals within portions of the study area. These methods range from interpolations made using standard kriging methods to extrapolations from the existing data to predict quantities outside of the areas covered by the available data. Table 1 lists representative values of these estimates. The first three rows of this table are derived from different interpolation schemes, while the last row uses extrapolations based on predictions from a linear regression model that uses specific proxy variables to predict metal content in the CCZ where no data are available.

Table-1: Estimated resources.

Source	Included Area (km^2 X 10^6)	Estimated Tons (metric tons X 10^6)				
		Nodules	Mn	Co	Ni	Cu
Reduced area	3.83	21,100	5,950*	46.4*	270*	234*
Total study area	4.19	30,700	8,657*	67.5*	393*	341*
Biogeochemical model	4.85	27,100	7,300	58.0	340	290
Potential resources of nodules	12.57	62,000	17,500	134.0	761	669

*Estimated using mean metal content values

xii. BIOGEOCHEMICAL MODELING

28. The model presented here predicts the geographical distributions of nodule metal content (Mn, Co, Ni, Cu, and Ni concentrations) and abundance (kilograms of ore deposits per square meter of seafloor) using as model components the values of other, known variables, including chlorophyll concentrations in surface waters, distance from the East Pacific Rise, and Carbonate Compensation Depth (CCD).

29. The general model of formation of the Clarion-Clipperton Zone (CCZ) polymetallic nodule deposits is illustrated in *Figure 6*. The primary sources of metals for these deposits are from terrigenous or volcanogenic sources on the North & Central America and the East Pacific Rise. The metals are adsorbed to the surfaces of fine-grained sediments and carried with them westward along the North Pacific Current. The sediments are consumed by filter-feeding zooplankton en route and converted into silt-and sand-sized fecal matter that is large enough to sink to the seafloor in the deep tropical Pacific waters. These fecal pellets can then be metabolized by benthic animal communities and bacterial processes after they reach the sea floor, processes that will remove the organic materials that bind the metals and will reduce them to cationic species that are readily absorbed by the anionic manganese oxide matrix that constitutes the bulk of these deposits.

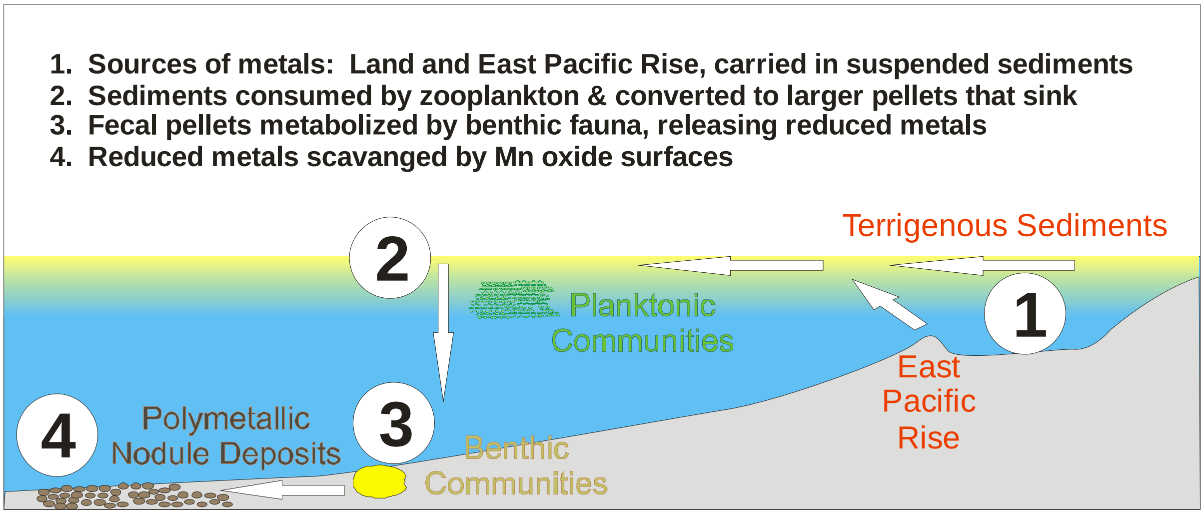

Figure 6: General Nodule formation model for CCZ.

xiii. SDSS (SPATIAL DECISION SUPPORT SYSTEM) MODELING

30. 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, 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 the 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 and from Fuzzy Logic are listed in the following figures. (*Figures 7, 8 and 9*). The 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, southwesters, or eastern areas

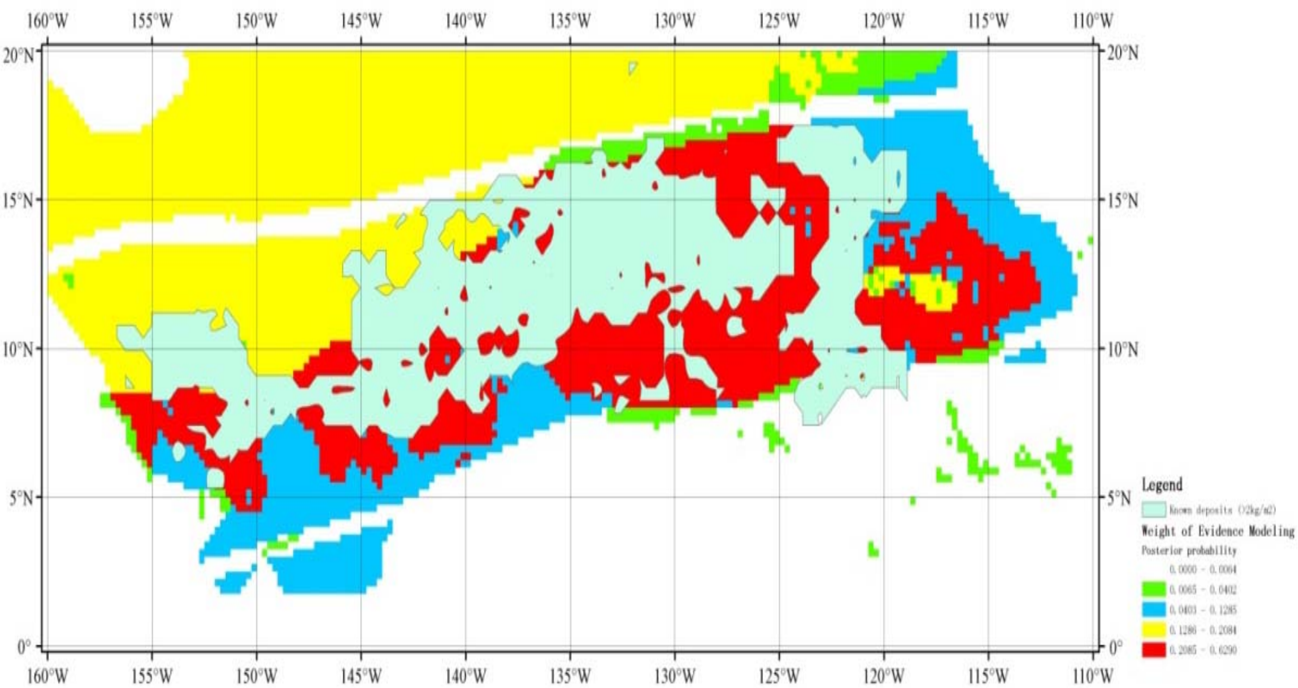

Figure 7: Likely Prospects for Nodule Occurrence, Weights of Evidence Modeling

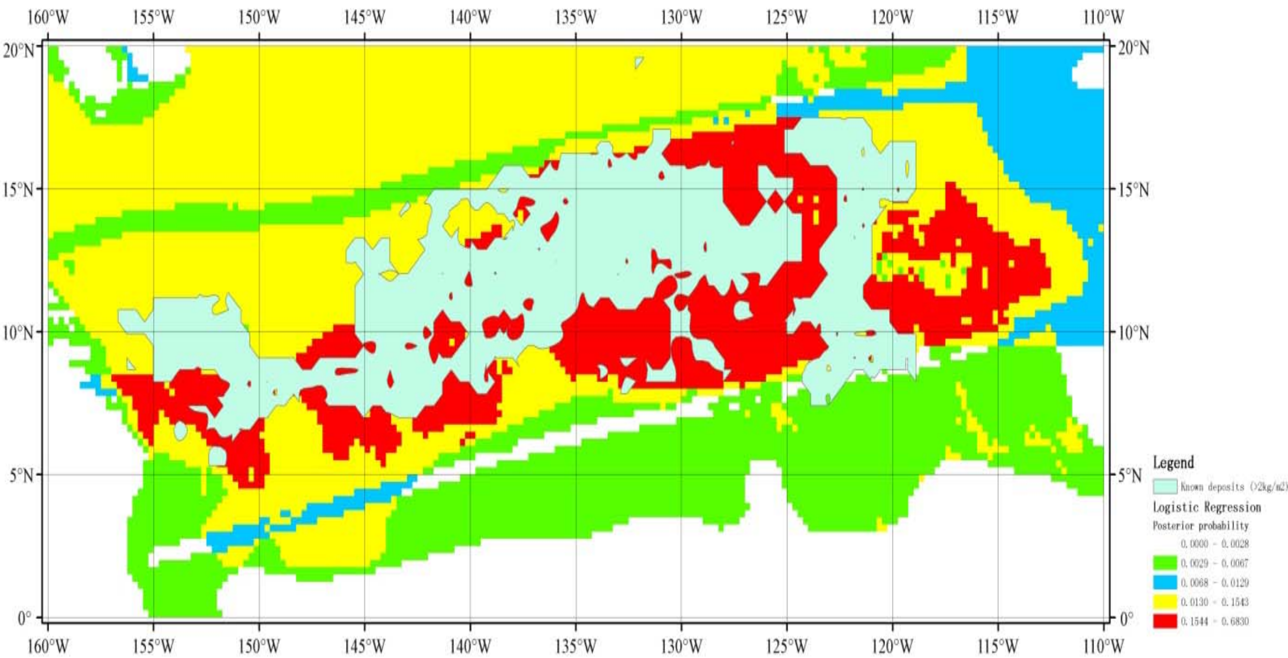

Figure 8: Likely prospects of nodule occurrence- Logistic Regression.

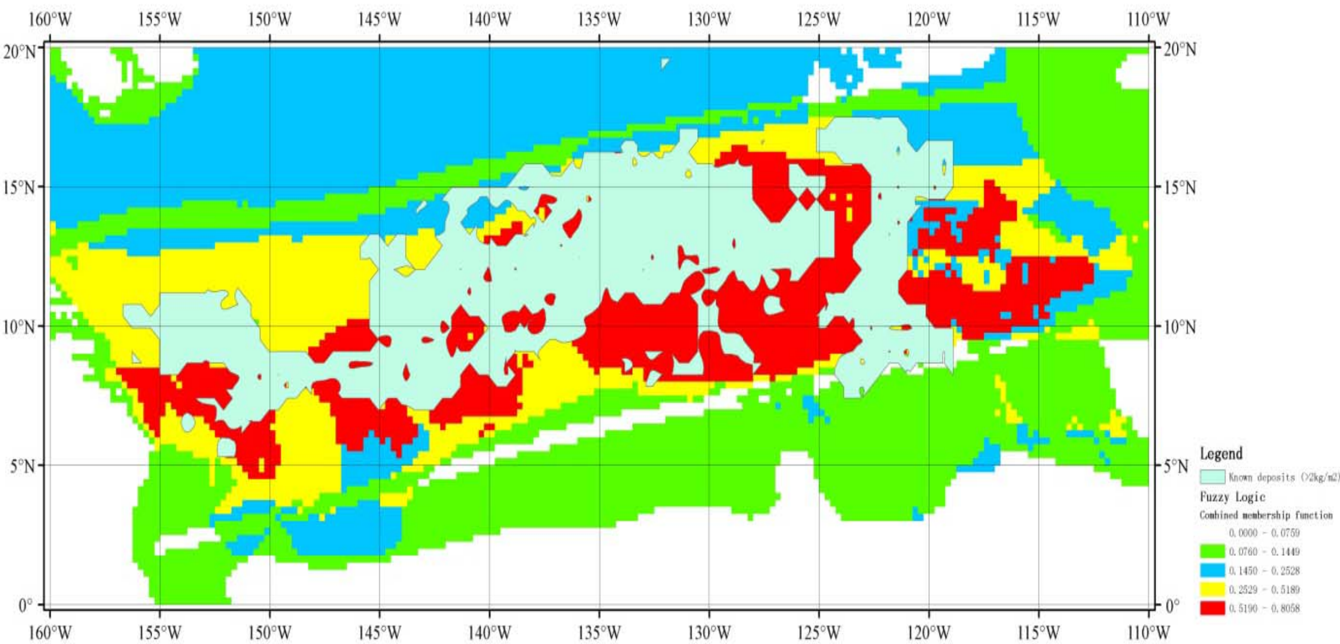

Figure 9: Likely prospects of nodule occurrence- Fuzzy Logic

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