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Summary report of the workshop on the results of a project to develop a geological model of polymetallic nodules in the Clarion-Clipperton Zone, held at Kingston, Jamaica, from 14 to 17 December 2009

1. Polymetallic nodule resources contain nickel, cobalt, manganese and copper. While they occur in all oceans, deposits in the Clarion-Clipperton Zone in the Pacific Ocean 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 Authority 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 Clarion-Clipperton Zone. 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 sediment, bathymetry, tectonics and primary productivity could be established, they could be used as proxies for grade and abundance in poorly sampled nodulized areas. They therefore recommended that the Authority establish a geological model of polymetallic nodule deposits in the Clarion-Clipperton Zone. 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.

2. The success of the programme, which started in 2005, has been greatly facilitated by the generous contribution of data, information and expertise by contractor scientists and other experts in this field. Now in its final stages, the programme has produced a geological model of polymetallic nodule deposits in the Clarion-Clipperton Zone, which provides three independent approaches to model development; and a prospector's guide containing a narrative description of the key factors relevant to exploration for polymetallic nodules in the Zone, including data and available information on known deposits. The geological model and the prospector's guide provide the results of nine independent studies yielding extensive

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geophysical, geological, oceanographic and biological information relevant to deposits in the Zone, and general guidance as to why these deposits occur, where they occur, and criteria for use in identifying such deposits in the Zone.

3. The Authority convened a workshop on the results of this project from 14 to 17 December 2009, at the Authority's headquarters in Kingston, Jamaica. The workshop was attended by a total of 24 participants, including some members of the Legal and Technical Commission of the Authority, representatives of contractors, representatives of member States and the experts who contributed to the development of the geological model and the prospector's guide. The workshop was broadly divided into three segments: presentations from experts; working group deliberations; and the concluding session.

4. The workshop was formally inaugurated by Nii Allotey Odunton, Secretary-General of the International Seabed Authority. Welcoming all participants to the workshop, the Secretary-General traced the chronology of the geological model's development. He thanked the contractors and experts for their services to the project and their generous contribution of data. The Secretary-General also informed the workshop that, for the first time, the Authority would stream the workshop live over the Internet, and that this would help the Authority to reach a wide audience across the world. He invited participants to offer critical review, suggestions and improvements during the deliberations of the workshop, so that firm recommendations could be reached at its conclusion. He wished the participants a fruitful and enjoyable workshop and stay in Kingston. James A. R. McFarlane, Head of the Office of Resources and Environmental Monitoring of the Authority, gave a briefing on the workshop's plan and logistics. Dr. Charles Morgan of Planning Solutions Inc., Hawaii, United States of America, who was the Chief Consultant for the geological model project, was designated as the coordinator of the workshop.

Expert presentations

5. The workshop heard 11 presentations on the results obtained for selected proxy variables, how they were incorporated into the model, the results of the resource assessment of the deposits in the Clarion-Clipperton Zone, and a review of the model's documents. The presentations commenced with a talk on geological model project implementation by Dr. Morgan. During the presentation, Dr. Morgan outlined the objectives of the programme and summarized the results. The main objectives of the programme were to improve resource assessment, integrate all available exploration and environmental data and provide guidelines for future prospecting and exploration. He also traced the project's milestones chronologically. He briefly presented the overall results of the project. Dr. Vijay Kodagali, Senior Scientific Affairs Officer at the Authority, then presented a review of the data used for the model. He described the diverse and huge data set that the Authority had gathered from the generous contributions of contractors in the Clarion-Clipperton Zone. He also presented the maps and figures relating to the additional data acquired for the model studies. He explained that during the project, the Authority had coordinated the efforts of contractors and consultants, set up secure FTP (file transfer protocol) and VPN (virtual private network) sites for the project, carried out periodic reviews of the project and ensured that the two products of the project — the geological model and the prospector's guide — were peer reviewed. An

interesting discussion on the quality, distribution and normalization of the data ensued.

6. Dr. Lindsay Parson of the National Oceanography Centre, Southampton, United Kingdom of Great Britain and Northern Ireland, presented the results for the proxy “bathymetry and base map”. He showed the different data sources used for preparation of the base map. In addition to the data available in the public domain, other information was used, including bathymetric data from satellite-derived gravity measurements, new multi-beam data provided by contractors and contractor analogue maps. The detailed maps were provided for six areas of focus in the Clarion-Clipperton Zone that cover the entire nodule zone. A one-minute grid interval was applied to the entire Zone and the key areas were mapped at 0.5-minute and 0.1-minute grid intervals. He presented the maps generated from his work and talked briefly about the tectonics of the region. During subsequent discussions, participants complimented Dr. Parson for the excellent assimilation of available data for the Clarion-Clipperton Zone region.

7. Dr. Valery Yubko of Yuzhmorgeologiya and Dr. R. Kotlinski of Interoceanmetal Joint Organization had worked on the volcanic and structural elements of the Clarion-Clipperton Zone. However, as neither author was present, their work was presented by their colleague, Dr. Valcana Stoyanova. The main objective of the work was to estimate the influence of factors such as bottom morphology, water depth, structural-tectonic setting and sedimentary, volcanic and hydrothermal activity on the formation of polymetallic nodules in the entire Clarion-Clipperton Zone. The data used for the study related to the structural setting of the Zone; volcanic and hydrothermal activity; type of sediment; type and distribution of nodules; and manganese-iron ratios. Dr. Stoyanova presented a tectonic sketch of the Clarion-Clipperton Zone and discussed the hydrothermal and volcanic activity data for the region. She also provided paleo reconstruction maps of the region for 5, 10, 15 and 20 million years ago. Participants showed keen interest in the results of the work, especially on the new Mahi-Mahi fracture zone, which seems to have a significant influence on nodule distribution in the region.

8. Dr. Charles Morgan presented the results of the proxy work on sediments as contained in the report entitled “Regional examination of sediments”. As part of the work on sediments, the consultants assembled available data from contractors and the public domain and integrated them into a common format. They also examined the relationship between sediments and abundance and metal content. Over 4,600 sediment station data were gathered for this study. The sediments have been classified into 13 types. A map of the sediments superimposed on the bathymetry of the Clarion-Clipperton Zone was also provided.

9. Deliberations on sediments continued on the second day with a presentation by Professor H. Zhou on bathymetry and sedimentation in the contract area of the China Ocean Mineral Resources Research and Development Association (COMRA). He presented detailed bathymetric maps of the eastern and western segments of the COMRA contract area. The COMRA area has three basic regions: abyssal hills, seamount chains and the abyssal basin. The seamounts have an east-west strike whereas the sedimentary graben is trending north-south. The seamount chains are more prominent in the eastern segment. Dr. Zhou also analysed about 1,600 sediment data from free-fall samplers. He said that he had used a sediment classification that comprised four classes. He presented a relationship between

sediment type and bathymetry. He compared deep tow data with bathymetric data to show their relationship to nodule abundance. During discussions, many participants touched on the scheme of classifications used by different presenters for different parameters and pointed out that there was no uniformity. This anomaly was attributed to contractors using different methods of classification. The need for a uniform classification methodology for all parameters was emphasized by participants.

10. One of the key results of the work on proxy variables for the geological model — the "biogeochemical model" — was presented by Dr. Morgan. The biogeochemical model predicts the geographical distribution of the metal content of nodules (manganese, cobalt, copper and nickel concentrations) and their abundance (kilograms of ore deposits per square metre of sea floor), using as model components the values of other known variables, including chlorophyll concentrations in surface waters, distance from the East Pacific Rise and the carbonate compensation depth. The primary sources of metals for the polymetallic nodule deposits of the Clarion-Clipperton Zone are terrigenous or volcanogenic sources in North and Central America, and the East Pacific Rise. The metals are adsorbed to the surfaces of fine-grained sediments which are carried westward by the North Pacific Current. The sediments are consumed by filter-feeding zooplankton en route and converted into silt- and sand-sized fæcal matter that is large enough to sink to the sea floor in the deep tropical Pacific waters. These fæcal pellets can then be metabolized by benthic animal communities and bacterial processes on reaching the sea floor. These processes remove the organic materials that bind the metals and reduce them to cationic species that are readily absorbed by the anionic manganese oxide matrix that constitutes the bulk of nodule deposits. Dr. Morgan presented several maps of nodule distribution generated from the model. Following Dr. Morgan's presentation, participants discussed the components of the model and the final results.

11. Dr. Valcana Stoyanova made a presentation on the relationship between nodule coverage, morphology and distribution. Dr. Stoyanova said that in order to understand nodule distribution within the study area, an analysis had been undertaken to determine the correlations among nodule parameters such as coverage, abundance, morphology, size, genetic type, water depth, bottom morphology and geographic region. She said that a classification system for nodule morphology and its formation mechanism separates hydrogenetic from diagenetic nodules, and isolates different morphological types (such as discoidal and spheroidal). She also said that throughout the eastern part of the Clarion-Clipperton Zone, 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 sea floor covered by nodules are found in water depths between 4,100 and 4,200 metres, and the highest abundance values are found between 12° and 16° N latitude.

12. Dr. Charles Morgan presented the work of Dr. J. K. Kang and others from the Korean Ocean Research and Development Institute (KORDI), Republic of Korea, on the appraisal of nodule resource potential using GIS (Geographic Information System) and geo-statistics. A summary of Kriging techniques and the results of other geo-statistical work were provided. Resource assessment was based on conventional methodology, and the data for the assessment were subdivided in

simple geometries to aid analysis. The results indicate about 20 billion to 30 billion metric tons of nodules in the study area.

13. Spatial decision support system, artificial neural network and fuzzy logic techniques were also used to model resources in the Clarion-Clipperton Zone. The results were presented by Professor H. Zhou of Tongji University, Beijing. Spatial decision support system modelling was employed to estimate the mineralization potential of selected areas of the Clarion-Clipperton Zone where nodule abundance and metal content data are not available. The study was based on data sets that included bathymetry, topography, sediment type, calcite compensation depth and surface chlorophyll. Specific techniques employed in the study included weights of evidence modelling, fuzzy logic, logistic regression and artificial neural network techniques. The results of this work provide differing assessments of the spatial distribution of areas within the study area in which nodule deposits are likely to occur. The results consistently indicate that the best prospects are found in the central and northern parts of the Clarion-Clipperton Zone, while the southern, south-western and eastern parts of the Zone are likely to be unfavourable to nodule deposit occurrence. Various maps generated from the study showing the areas of likely occurrence were presented by the author. The novel approach employed for modelling the resources was appreciated by a number of participants, who also provided many suggestions for the improvement of the results.

14. The two products of the geological model project were reviewed by two well-known experts, Dr. James Hein of the United States Geological Survey and Dr. Peter Halbach of Freie Universität, Berlin. Dr. Halbach presented the highlights of his assessment of the geological model and the prospector’s guide. He said that after his initial review of the documents, the authors had incorporated his suggested changes and updated the documents. He commented in detail on each chapter of each document. Dr. Halbach spoke about the genesis of nodules and commented on the biogeochemical model presented in the documents. He said that he also wanted the authors to consider the Peru Basin nodule province in the model development exercise. In a summary, he stated that the optimum conditions for high-quality nodule growth are not related to maximum growth rates or maximum manganese concentrations, but rather to the intermediate biogeochemical environment. A lively discussion on nodule genesis followed his presentation.

Working groups

15. On the third day of the workshop, participants were divided into four working groups. Leaders were chosen to conduct the deliberations of each group. The groups were:

- Working Group 1: Extension of the model to other world oceans (Indian, Atlantic, etc.)
- Working Group 2: Exploration technology (exploration, analytical methods, mapping, visualization, remotely operated vehicle/autonomous underwater vehicle, etc.)
- Working Group 3: Environmental component (research plan, time series, site plan and standardized data sets)

- Working Group 4: Education and outreach regarding the results of the model studies

Groups 1 and 2 met separately for the entire day. The members of Groups 3 and 4 met separately and also attended the meetings of Groups 1 and 2.

16. The fourth day of the workshop began with a plenary session on the working group deliberations. During this session, the chairs of each working group presented reports on their recommendations. All delegates took part in the discussions during this session. The working groups later met again to finalize their recommendations.

Working Group 1: Extension of the model to other world oceans

17. Working Group 1 deliberated on:

(a) Developing recommendations on establishing similar geological models of nodulized provinces in the Indian Ocean, Atlantic Ocean, Peru Basin, Mexico Basin and elsewhere;

(b) Identifying shortfalls, deficiencies and limitations of the geological model and prospector's guide of the Clarion-Clipperton Zone with regard to its application to other areas;

(c) Suggesting improvements to the model and prospector's guide.

18. The Working Group discussed the Central Indian Ocean Basin scenario and said that the immediate need was to extend the geological model to that region. In order to increase knowledge of the area, it was strongly recommended that contractors make data available to develop a model of the Basin. Participants felt that the Clarion-Clipperton Zone model needed to be tested in the Basin before it could be considered as a global model for polymetallic nodule deposits.

19. The Working Group also discussed the Atlantic Ocean scenario. Participants were informed that the limited data available on the South Atlantic Ocean, compared to other regions, would make a full test of the Clarion-Clipperton Zone model in that region impractical. Therefore, a two-phase project was proposed. The first phase would be an Authority-led initiative facilitating the collection of all available data (and analyses) for the South Atlantic, from coastal and other States, to be consolidated to create an integrated database. Participants agreed that that phase could be completed under a two-year programme. The second phase would be a test of the Clarion-Clipperton Zone model on suitable areas in the South Atlantic Ocean. Participants suggested that the proposal for the South Atlantic Ocean project could be a good opportunity for the application of the prospector's guide in that region. They also felt that the proposed project could provide the necessary framework to search for areas in the South Atlantic Ocean where factors and conditions that control Clarion-Clipperton Zone nodule formation also exist.

20. The Working Group recommended that the Clarion-Clipperton Zone model be revisited, taking into account the results from the Mexico Basin, and particularly the importance of hydrothermal input and lateral transportation of sediments and dissolved metals of terrigenous origin. It also recommended that the analyses and results from the Peru Basin, particularly the high manganese-iron ratios representing the type of end member composition of diagenetic nodules observed, also be considered in the Clarion-Clipperton Zone model.

21. Other recommendations of Working Group 1 included the following:

(a) There is potential for the application of the Clarion-Clipperton Zone model to the North Atlantic Ocean;

(b) Contractors should test the model in their areas, and the Authority should test the model in the reserved areas;

(c) Trace metals might be of high future importance considering market trends. For example, molybdenum, zinc, titanium, rare earth elements and others should also be used in the model to check its applicability in defining their resource potential;

(d) The geological model and the prospector's guide have dealt with nodule morphology, size and shape, and also with sediments. However, during the discussions following the presentations, it was observed that there is no uniformity in the classification schemes for these parameters. Contractors are using their own methods of classification. The Working Group, therefore, recommended that a standard classification scheme for all these parameters should be developed. It also suggested that the Authority convene a workshop or a meeting of experts on this issue and that the standardized schemes be adopted by the Authority and made applicable to all future publications and reports.

Working Group 2: Exploration technology

22. The Working Group discussed in detail the status of exploration and mining technology. With the relative maturity of components of exploration technology, the Working Group suggested that there should be a focus on gaps in the data that have to be provided by the contractors. Two needs seem to have become very important: environmental data; and nodule data for specific contractor fields. Environmental data and plans are needed in order to fulfil contractual obligations (particularly with respect to the Clarion-Clipperton Zone contractor areas). These needs appear to be similar for all contractors, so a collective effort should be considered to more speedily reach common or reference solutions to contractor needs. Additionally, data with sufficient detail are needed to inform decisions on the order of importance of nodule fields (and perhaps suggest whether tailored collection techniques are required) within each contractor's area. The Working Group also discussed biota and environmental data, micro-exploration, funding, standards, pilot harvest efforts and open architecture.

23. The Working Group recommended, among other things, that the Authority consider convening a meeting of the contractors to promote an open discussion on protocols and standards (for example, voltages, bus, communication, connectors) and publish the document on protocols and standards. The Working Group was of the opinion that proven and detailed methodologies could readily be adapted to Authority needs, which would drive down commercial off-the-shelf costs, force commonality and increase the possibility of multiple vendor competition.

24. The Working Group made further observations to improve the technological environment for exploration and operations in the Clarion-Clipperton Zone:

(a) Visualizing capability: exploratory research, combined with a higher volume of increasingly sophisticated sensor data, suggests that an important

baseline technology will be data fusion, which can be presented by ever-improving visualization techniques;

(b) Technical/programme management: the Authority should consider, as harvesting operations come closer to reality, that individual contractor advocacy within the Authority might be well served by programme managers who are able to work on issues with a more robust technical staff, to minimize the loss of lessons learned from previous research and operations.

Working Group 3: Environmental component

25. Working Group 3 was given the task of recommending how to interest contractors in the accomplishments of the geological model. It was suggested that this could facilitate the identification and definition of abyssal habitats in the Clarion-Clipperton Zone and help identify the data required to accomplish environmental assessments and determine their relevance to the future environmental protection of the seabed.

26. The Working Group made recommendations for the application of the geological model to future environmental monitoring and assessment, including:

(a) Improve understanding of the role of biological factors in the distribution and origin of nodules;

(b) Standardize methods, factors, resolution and other considerations;

(c) Encourage habitat scale studies and data gathering for future impact analysis and recovery experiments;

(d) Encourage contact with appropriate scientific research institutes;

(e) Continue promoting interaction between mining companies and relevant international scientific programmes;

(f) Develop a training and preparation programme for environmental assessment that helps standardize the resolutions used and information delivered;

(g) Integrate unpublished data that may add to the baseline understanding of the environment.

Working Group 4: Education and outreach regarding the results of the model studies

27. Working Group 4 was given the task of generating recommendations for educational and outreach strategies. Members of the Group actively participated in the meetings of the other three working groups. This operational approach was considered more efficient, given the cross-cutting nature of the tasks of Working Group 4. The Group’s main suggestion, after two days of deliberation, was that the Authority be charged with the responsibility of communicating the results of, and progress made in, scientific, cultural and environmental work conducted at the deep seabed to all parties that would be affected by or benefit from such work. The Authority should identify the target audience and decide upon a strategy for dissemination of this information.

28. Imperative communication and education objectives to be achieved include the development of the following tools and exhibits aimed at disseminating certain specific information:

(a) A visual road map of the history of deep sea mining (exploration, prospecting) technology;

(b) A visual road map of the important achievements of the Authority (including the geological model for polymetallic nodules);

(c) A visual road map of the Authority's regulation and policy creation and formulation processes;

(d) A visual road map of the environmental concerns related to the activities of the Authority;

(e) An exhibition entitled "Environmental awareness of the deep sea" including a historical perspective and state-of-the-art examples;

(f) A "deep sea techno-garden" highlighting the mining activities and technologies.

29. The Authority should publish the results of the workshop on its web page and permit use of all data used in the model by researchers and other member States.

Concluding session

30. The workshop ended with a concluding session on 17 December 2009. After the chairs of the working groups presented their recommendations, the coordinator of the workshop, Dr. Morgan, invited participants to share their views and experiences. All members of the Legal and Technical Commission who were present gave their views. By and large, they were appreciative of the enormous work done in connection with the geological model project. A few concerns regarding issues such as data validation, data inconsistency and non-standard classification of parameters were again highlighted. The representatives of the contractors and member States also spoke during the session. In his concluding remarks, the Secretary-General thanked all participants for attending the workshop. He recalled the words of Dr. H. Beiersdorf, late member of the Legal and Technical Commission, who had strongly advocated the geological model, saying that it was the only way the world could learn more about these resources. The Secretary-General said that it was always important to take the first step, and the Authority was happy to have done so in modelling the resources of the Clarion-Clipperton Zone. He added that there was always room for improvement and the Authority would strive to develop this work. He indicated that the workshop recommendations would be presented to the Legal and Technical Commission and to the Council, and that the Authority would move forward on the basis of the Council's advice. He stated that the work involved a very broad community of eminent international scientists and that the Authority was proud of their contributions. The Secretary-General thanked everyone for their contributions during the workshop.