2nd Expert Scoping Workshop

"Charting Future Horizons: Harnessing Advanced Technologies for the Protection and Sustainable Use of the International Seabed Area" organized by the International Seabed Authority

"Monitoring"

Background Document

10 to 13 June 2025

Kobe, Japan

I. Context and Rationale

1. In accordance with the UN Convention on the Law of the Sea (UNCLOS) and the 1994 Agreement relating to the implementation of Part XI of the Convention, the International Seabed Authority (ISA), on behalf of the States Parties to UNCLOS, is mandated to administer the mineral resources located in the international seabed area (the Area) for the benefit of humankind. To that end, ISA is tasked to control and organize current exploration activities, as well as future mining activities, in the Area and take the necessary measures to ensure effective protection for the marine environment from harmful effects which may arise from such activities. In so doing, ISA has the obligation to take the necessary measures to acquire technology and scientific knowledge relating to activities in the Area; and to promote and encourage the transfer to developing States of such technology and scientific knowledge relating to activities in the Area and to enable capacity building, so that all States Parties benefit therefrom.

2. Following the proclamation by the United Nations General Assembly of the United Nations Decade of Ocean Science for Sustainable Development (UN Ocean Decade), all ISA Members unanimously adopted a dedicated Action Plan for marine scientific research in December 2020 (MSR Action Plan). The MSR Action Plan serves as the global deep-sea agenda for facilitating scientific research according to six overarching strategic research priorities. One of them specifically relates to the need to "facilitating technology development for activities in the Area, including ocean observation and monitoring".

3. Building on the knowledge acquired during more than 40 years of marine exploration and the forecasted increasing demand for critical metals and minerals, particularly in the context of the implementation of the Paris Agreement and the transition to a low carbon economy, different actors have expressed increasing interest in engaging more actively into the opportunities of the blue economy which could be provided by seabed minerals in the Area. A major imperative for such an industry to develop is to ensure that any environmental impacts are minimized. This requires advanced technologies and intelligent solutions to support exploration activities, observations, mineral extraction, monitoring and enforcement.

4. Each of such phases relies on the best technology available, which, in turn, favorably supports progress and innovation in deep-sea-related technology and the equipment to be used. The need to ensure reliable, transparent, and cost-effective systems for prediction and continuous monitoring of environmental impacts by exploration and future exploitation activities is of fundamental importance for developing such technology. ISA and its Legal and Technical Commission (LTC) are currently establishing environmental thresholds which require close monitoring and high-resolution measurements. Considering the extreme conditions within which monitoring systems need to operate, emphasis is also placed on ensuring that activities integrate technology and novel solutions to operate autonomously in remote areas whilst providing close to real-time data for the regulator where possible to carry out its supervisory functions, for contractors to successfully perform against the conditions set out by the legal and regulatory framework and other interested stakeholders to address these key capacity development needs and have access to all necessary information.

5. ISA has carried out several studies and activities related to the actual state of marine technologies in the past. An expert scoping meeting on advancing technology to support sustainable development of mineral resources in the Area was organized online in collaboration with the National Oceanography Centre (NOC), Southampton, UK, in September 2021. An ISA Technical Study (ISA Technical Study No. 29) highlighted the importance of establishing a system of remote monitoring for exploitation activities in the Area, in addition to the use of physical inspections, to record information concerning mining activities (the 1994 Agreement, Section 2). In ISA's ADSR programme involving national experts from African countries, aspects of geodata, geothermal energy, metallurgy and metal processing were addressed in 2022 by using ISA's DeepData data repository. A technology roadmap was defined in cooperation with atdepth LLC consultancy (Deep-Sea Mining Technology Roadmap: Resource Definition

Systems and Operations, Monitoring & Modeling, 2023). A first expert scoping workshop "Charting Future Horizons: Harnessing Advanced Technologies for the Protection and Sustainable Use of the International Seabed Area" was organized with Portugal's INESC TEC (Institute for Systems and Computer Engineering, Technology and Science) in Porto in 2024, addressing technologies of significant importance for activities in the Area and on the seabed. The outcomes further informed capacity development needs for technology transfer.

6. In this context, the ISA Secretariat assessed the current state of technology used in deep-sea exploration, monitoring and associated research. In this process, five priority areas were identified, including: (i) ocean observation and communication; (ii) monitoring, (iii) autonomy, automation and robotics; (iv) machine learning and artificial intelligence; and (v) mining, energy and processing.

7. Ocean observation is key to modern global understanding in terms of environmental protection, the development of national and international blue economies, the security and protection of food supply, early forecast mechanisms for and monitoring of natural hazards (earthquakes, sea-level rises, submarine avalanches, volcanic eruptions), geological and environmental baselines, and to scientific research. Activities include a wide range of technological approaches encompassing satellite data, ship-borne measurements, autonomous systems, moorings and lander systems, submarine cable systems. Ocean observation includes a complex spectrum of data acquisition and advanced subsea communication and data transfer at larger distances through the water column to surface installations or from a specific site via cable systems for data analysis.

8. Monitoring represents local intervention during ocean observation and communication, and includes the online, transparent and reliable observation of all human activities in the oceans from shipping to fishery and marine fish farming to seabed mineral exploration and potential exploitation. ISA's Technical Study No. 29 by Det Norske Veritas (DNV) provided recommendations for monitoring activities and highlighted the importance of establishing a system of remote monitoring for exploitation activities in the Area, in addition to the use of physical inspections, to record information concerning mining activities (the 1994 Agreement, Section 2). Remote monitoring technologies already exist in other sectors such as offshore petroleum installations, submarine pipelines, submarine cables and fisheries. Technological solutions include satellite data, ship-borne measurements, autonomous systems, moorings and lander systems, submarine cable systems, data dashboards, machine learning.

9. Any of the formulated objectives require autonomous, automated solutions and so do any activities in the deeper water column and on the seabed. Several ISA member countries invested in autonomous systems (AUV) to better define their continental shelf, and the available systems largely improve rapidly. The developments largely depend on the innovation of sensor systems. Autonomous platforms are used to monitor offshore installations in the oil and gas industry but also inform the Seabed2030 initiative to map the seabed at high resolution by 2030. Automation and robotic systems are cost- and time-efficient and therefore critical for any activities in the

deep sea. Spin-offs exist from the oil and gas industry and can be created for the land mining industry working in abandoned mining districts, open pits, deep and drowned underground mines as well as remote habitats or for catastrophic events by natural hazards.

10. Machine learning by artificial intelligence (AI) represents a new frontier in all ocean activities and aspects of the blue economy. It builds on data obtained by ocean observation and monitoring and the collection of key information on water column and seabed habitats, mineral occurrences, potential natural hazards. AI has the potential to build more accurate spatial and temporal models, and predict all aspects of oceanography, geology, mineral resources, biodiversity, environmental effects of all human activities.

11. The oceans offer a wide variety of resources including seabed minerals and wind, wave and geothermal energy. ISA's contractors and pioneer investors developed technological concepts and tested innovative and advanced prototypes. Should the commercial exploitation start based on adopted environmental regulations, the mining technologies still require innovation for best industrial and environmental practice offering a wide field of technical, low impact and cost-effective future improvements. Carbon-free transportation is of key importance. Cost-effective and environmental innovation is also required for the mineral treatment and processing after recovery. Solutions are required for zero waste approaches and for carbon-free processes. Preliminary concepts exist for the harvesting of energy resources including offshore wind, tides, oceanographic heat and wave and seabed geothermal. All energy resources offer a great opportunity to produce so-called green hydrogen then transported on shore. None of these resource options have been tested at an industry-like scale and a wide variety of technological innovations are required for their development.

12. In preparation for the 2024 workshop, a process was undertaken to compile background documentation and analyse existing literature and activities. This comprehensive endeavour was conducted in collaboration with ISA's stakeholders, ensuring a forceful foundation for the discussions ahead. The focus was on addressing key priorities identified as critical for advancing technologies to support the protection and sustainable use of the international seabed area. The report produced provides an overview of the current state of technologies relevant to activities carried out in the Area.

13. The second Expert Scoping Workshop, "Charting Future Horizons: Harnessing Advanced Technologies for the Protection and Sustainable Use of the International Seabed Area", is hosted by ISA and partnered by the Kobe Ocean-Bottom Exploration Center (KOBEC) at Kobe University in Japan and will discuss the key findings of marine technology innovation, focusing on all aspects of technical and environmental monitoring, its design and future requirements. The workshop discussion will result in additional input and elements to produce a reliable, transparent, integrating and comprehensive monitoring scheme for all seabed activities.

14. Constant, reliable measurements of environmental parameters against defined standards and their timely reporting to the authority are regulatory requirements set by ISA's legal

framework. Workshop outcomes should include concepts for the regional monitoring of areas beyond ISA contracts to further inform ISA's Regional Environmental Management Plans (REMPs) and Areas of Particular Environmental Interest (e.g., APEIs in the CCZ) as well as internationally recognized transitional zones of specific environmental significance for the protection of global biodiversity in the Area.

15. Meeting background, scope and expected outputs addressing key technologies, technological needs, research and development activities will be presented. Each workshop day is summarized by the compilation of thematic discussions leading to successful monitoring. The final day of the workshop will host a plenary session with open discussion and consolidation of future steps following guiding questions for current and available technologies for technical and environmental monitoring, the best industry practices, and strategic partnerships to build and develop the capacities of developing States, members of ISA current needs and priorities. Emerging technologies and strategies for targeted research and development efforts with respect to sensor-based environmental monitoring activities, data acquisition and transfer and developments towards net zero emissions will be discussed for the impacted ocean surface, water column and seabed to establish technological approaches for the entire ocean ecosystem.

16. As a follow up to the workshop, the publication of the final report to be released in the form of an ISA Technical Study on Monitoring will be delivered in August 2025, summarizing the current landscape, the potential pathways forward and activities ISA could support on establishing forceful schemes and designs delivering on integrated, efficient, reliable and transparent environmental and technical monitoring for all seabed activities in the Area. The resulting monitoring designs will be promoted to be included in national expert programmes, the training programmes of contractors, capacity development, mining equipment tests and future test mining.

II. Objectives of the Workshop

17. The expert workshop to be organized in June 2025 (10-13) aims to provide the opportunity to:

a) review existing deep-sea technology that is relevant to seabed exploration, exploitation and monitoring, including data management;

b) identify trends as well as opportunities/constraints for advancing technological solutions, particularly for capacity development, including automation, robotics, and machine learning which can be taken into account in the work of ISA;

c) identify practices, including technological innovations to address knowledge and technological gaps and priorities for ensuring ocean knowledge, effective monitoring, low-impact mineral recovery, protection of the marine environment, and compliance with environmental thresholds and data transfer and management;

d) identify key actors and consortia to be engaged in facilitating the advancement of effective monitoring for the sustainable development of mineral resources in the Area, and discuss possible modalities for cooperation among key actors, including through the development of collaboration;

e) progress in the identification of activities and partnerships the ISA Secretariat could engage with to build and develop the capacities of ISA member States leveraging the full capacities of regional-to-local ocean monitoring based on progress in the identification of needs, the advanced digitization, and the scientific use of artificial intelligence for the benefit of the global common;

f) identify and progress readiness levels for effective environmental monitoring, the protection of the marine environment, improved capacity building towards technology transfers, innovation and technological applications.

III. Expected Outcomes

18. It is anticipated that through the preliminary work undertaken as well as the discussions and exchanges of views and lessons learnt from the workshop, it will be possible:

(i) to be in a position to better assess and understand the current innovation and future trends in advanced deep-sea monitoring technologies;

(ii) to promote the development and regional design of technological tools for intelligent, safe, integrated and environmentally effective monitoring and automation;

(iii) to identify key areas for enhanced collaboration and innovation among key actors;

(iv) to identify strategic partnerships the ISA Secretariat can engage with to build and develop the technological capacities of ISA member States pursuant to the priority needs identified by developing States members of ISA and the ISA Capacity Development Strategy.

19. It is further envisaged that the results of this workshop will respond to the priorities and actions identified in the ISA Strategic Plan and High-level Action Plan as well as to progress the implementation of the ISA MSR Action Plan and ultimately the objectives of the UN Decade of Ocean Sciences for Sustainable Development, as well as to inform the work of the organs of ISA.

IV. Participants

20. Invited participants are recognized experts/practitioners with documented experience and professional expertise with offshore and deep-sea technologies for ocean and seabed monitoring, seabed installations, ocean observation, exploration-exploitation, surveys, inspections, production, automation, machine learning etc.

21. Attention is paid to ensure a balanced representation amongst participants from ISA member States and organs, including dedicated LTC members, "technology champions", contractors, multilateral organizations, and marine technology companies.

22. The number of expected participants is about 130. The participants are expected to apply for participation and have multi-year experience in technology-related marine affairs (administration, research, development, construction, application). Participants with experience in marine scientific research only will not be accepted as this is not the focus of the workshop. Participants from developing countries should have a technological mining or monitoring background.

V. <u>Methodology and Format:</u>

23. The expert scoping workshop constitutes a hybrid meeting, with in-person as well as online presence and presentations. All question-and-answer sections and all discussions, will be done in a hybrid mode, including the opportunity to place questions in the chat during the entire workshop. The workshop will be recorded; recordings will be made available in addition to presentation materials upon the authors' agreement with the technical study by August 2025.

24. The expert scoping workshop will approach the topic of technical and environmental monitoring in detail in dedicated technology sessions, with presentations to introduce the topics. The workshop aims to assess the types of current and available technologies, existing challenges and best industry practices, and asks for strategic partnerships to build and develop the needs and capacities of developing States, members of ISA current needs and priorities, as well as discuss emerging technologies to identify the strategic directions for targeted research and development efforts towards developing effective technologies for local-to-regional monitoring in the Area. It addresses the opportunities for future cooperation and aims to identify emerging fields of joint efforts for contractors, companies, research institutions and technology experts. It is also the intent to highlight and strengthen the linkage between exploration activities and the development of specific monitoring technologies towards advancing and applying innovative technological solutions to support responsible exploration, exploitation and regional surveys, also to address the important aspects of compliance with a variety of identified thresholds. The discussions will identify existing and potential partners, as well as ways and means to facilitate innovations for advancing smart technologies to effectively support the work of ISA.

25. The plenary session will define and consolidate existing technological solutions for the monitoring of any ISA-related activities on the oceans' surface, in the water column and on the seabed, identify best practice solutions and the strategic directions for targeted research and innovation efforts towards developing effective monitoring in the Area.

EXPERT SCOPING WORKSHOP

ITEM 1. OPENING OF THE MEETING

26. H.E. Mrs. Letitia Carvalho, Madam Secretary-General of the International Seabed Authority (ISA), welcomes the participants and delivers her opening remarks.

27. Mr. Yuzo Yamaguchi, Deputy Director, Ministry of Economy, Trade and Industry of Japan (METI) welcomes the participants and delivers his opening remarks.

28. Prof. Masato Fujiwara, President of Kobe University, Japan, welcomes the participants and delivers his opening remarks.

29. Prof. Katsuhiko Suzuki, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), welcomes the participants and delivers his opening remarks.

ITEM 2. MEETING BACKGROUND, SCOPE AND EXPECTED OUTPUTS ADDRESSING KEY TECHNOLOGIES, TECHNOLOGICAL NEEDS, RESEARCH AND DEVELOPMENT ACTIVITIES

30. Mr. Ulrich Schwarz-Schampera (ISA secretariat) provides a presentation on meeting background, scope and expected outputs and moderates the meeting deliberations.

31. Prof. Tomohiko Fukushima (Kobe University and Legal and Technical Commission [LTC]) discusses expectations for technological development from the perspective of the rule-making process.

32. The expert scoping workshop covers key elements with respect to the status, trends, and challenges of marine and deep-sea technologies, with particular focus on technical and environmental monitoring, identifies current best industry practices and provides guidance for strategic partnerships to build and develop the capacities of members of ISA, especially developing States.

ITEM 3. MARINE MONITORING – SETTING THE SCENE (REQUIREMENTS, EXAMPLES)

33. Monitoring intervenes at the local scale and includes the online, transparent, and reliable observation of all human activities in the oceans, from shipping to fishery and marine farming to seabed mineral exploration and environmental baseline surveys and future exploitation. Technological solutions include satellite data, ship-borne measurements, autonomous systems, mooring and lander systems, submarine cable systems, and data dashboards.

34. This agenda item aims to identify state-of-the-art, available, and advanced technologies in the field of ocean and seabed monitoring, the definition of current best industry practices, and the identification of strategic partnerships to build and develop the capacities of ISA members, especially developing States.

35. Under this item, the following participants deliver theme presentations:

(i) Pedro Madureira (University of Evora, Portugal): The Draft Regulations for Exploitation and Existing Regulations and Guidelines for Deep-Sea Monitoring.

(ii) Menhyao Zhu (OPRI, Japan): Bridging Science, Policy, and Society through the "Ocean Shot" Initiative: Innovations in Monitoring for Ocean Discoveries.

(iii) Muhammad Zarar (Geo-Tech Consultancy Services, Pakistan): Technological Barriers for Deep-sea Monitoring and How to Over-come them by using Geo-spatial & Geophysical Data Collection Technologies integrating with AI & Gen-AI pathways.

(iv) Musa Animashaun (ST Hudson Engineers, Inc., United States): Hydrography in the Deep Sea: Enabling Transparent, Scalable Monitoring of the International Seabed Area.

(v) Discussion (20 min.)

(vi) Haiyan Yang (BPHTDC, China): Monitoring Program under Low-Disturbance Polymetallic Nodule Collecting Condition.

(vii) José Miguel Almeida, Alfredo Martins, Betina Neves, Eduardo Silva (INESCTEC): TRIDENT: Project, Updates and Tech Insights for Long-Term Deep-Sea Monitoring.

(viii) Matthieu Straub (NineNorth, USA, France): The Visualization of Environmental Data and the Possible Outreach Solutions.

(ix) Discussion (20 min.)

36. Abstracts of the above presentations are provided in annex II to this report.

37. The discussions at the end of the section offer the opportunity for participants to ask questions and exchange their views, insights, and suggestions, in response to the presentations above.

ITEM 4: DATA HANDLING AND COMMUNICATION

38. Data handling and communication are key to modern global understanding in terms of environmental monitoring, the security and protection of the environment, early forecast mechanisms for and monitoring of human activities in the water column and on the seabed as well as natural hazards (earthquakes, tsunami warning, sea-level rises, submarine avalanches, volcanic eruptions), the collection of geological and environmental baselines, and scientific research. Activities include various technological approaches encompassing satellite and USV data collection, ship-borne measurements, autonomous systems, moorings and lander systems, and submarine cable systems. Ocean observation and data handling includes a complex spectrum of data acquisition and advanced subsea communication and data transfer at larger distances through the water column to surface installations or from a specific site via cable systems for data analysis.

39. This agenda item aims at the identification of state-of-the-art, available, and advanced technologies as well as innovation in the field of ocean data collection and handling, the definition of the best current industry practices in ocean communication, and the identification of strategic partnerships to build and develop the capacities of ISA members, especially developing States.

40. The following participants deliver thematic presentations:

(i) Susumu Takatsuka (Sony, Japan): High-precision Direct Observation of Particles on the Seafloor Using an Event-based Vision Sensor (EVS).

(ii) Hina Muranaka (NEC Networks & System Integration Corp., Japan): Seafloor earthquake and tsunami observation system for issuing Earthquake Early Warnings and clarifying earthquake mechanisms.

(iii) Curtis Lee (QYSEA Technology, China): Intelligent Underwater Drones for Seabed Monitoring, Water Quality Assessment, and Infrastructure Inspection.

(iv) Discussion (20 min.)

41. Abstracts of the above presentations are provided in Annex II to this report.

42. The discussions at the end of the section offer the opportunity for participants to ask questions and exchange their views, insights, and suggestions, in response to the presentations above.

ITEM 5. COMPILATION OF THEMATIC DISCUSSION FOR RELEVANCE AND PRIORITIES IN MARINE MONITORING, DATA HANDLING AND COMMUNICATION

43. Prof. Tomohiko Fukushima (Kobe University) and Mr. Ulrich Schwarz-Schampera (ISA) will summarize the key elements regarding the status, trends, and challenges of marine monitoring activities, data collection, handling and communication, and the results of the group discussions, with a focus on innovation and current and available technologies, best industry practices and ways and means to facilitate innovations for advancing smart technologies and the potential to provide guidance for strategic partnerships to build and develop the capacities of developing States and members of ISA. The participants are invited for a thematic discussion.

44. Prof. Junichiro Ishibashi (KOBEC), Mr. Kioshi Mishiro (ISA secretariat) and Mr. Ulrich Schwarz-Schampera (ISA secretariat) provide a summary of Day 1, based on presentations and workshop discussions, and align the presentations and expected discussions during Day 2 with the achievements, regarding status, trends, and challenges in marine monitoring, data acquisition and handling, and opportunities in (real-time) communication.

ITEM 6: INTRODUCTION INTO RESEARCH ACTIVITIES AT KOBE OCEAN-BOTTOM EXPLORATION CENTER

45. Profs. Hiroko Sugioka, Tokihiro Katsui and Jun-ichiro Ishibashi (Kobe Ocean-Bottom Exploration Center, KOBEC) are delivering an introduction into KOBEC’s research activities. KOBEC’s main activities at present include advanced seabed exploration, the promotion of international ocean science programs such as The International Ocean Drilling Programme (IODP3), and joint research programmes with other institutions such as JOGMEC, JAMSTEC, AIST, and the University of Tokyo. Activities also include the development of technologies for underwater vehicles and sea bottom drilling equipment, among others.

ITEM 7: TECHNICAL REQUIREMENTS FOR PLUME DETECTION AND MEASUREMENTS

46. Seabed mining activities likely produce sediment plumes. The evolution and fate of these particle plumes are a critical concern and their detection and the assessment of the potential impact on the biodiversity and ecosystem function of the deep ocean are key in monitoring of potential environmental impacts of deep-sea mining. The scale of the sediment plumes that will be generated and transported away from mining sites by background ocean currents is a central aspect of environmental impact assessments. Sediment plumes have the potential to evolve under the effect of buoyancy while interacting with the background environment, before being passively transported by the background ocean current. The multiscale nature of sediment plumes and the importance of understanding and modeling their behavior to determine their potential extent are challenging and complex, and require reliable and precise sensors and monitoring devices, as well as improved modelling approaches.

47. This agenda item aims at the identification of state-of-the-art, available, and advanced technologies as well as innovation in the field of plume detection, measurements and modelling. Presentations and discussion will focus on the definition of the best available (industry) practices and required innovation in plume detection and modelling, and the identification of strategic partnerships to build and develop the capacities of ISA members, especially developing States.

48. The following participants deliver thematic presentations

(i) Thomas Peacock & Souha El Mousadik (MIT, atdepth LLC, United States): Monitoring and Modeling Deep-Sea Nodule Mining: Lessons from Recent Collector Trials in the CCZ.

(ii) Yasuo Furushima (JAMSTEC, Japan): Estimating Near-Seafloor Turbulence using Acoustic Doppler Velocimeters (ADVs)

(iii) Scott Loranger (Kongsberg, Norway): Acoustics Technologies for Particles [TBC]

(iv) Discussion (20 min.)

(v) José Miguel Almeida, Alfredo Martins, Betina Neves, Eduardo Silva, Carlos Almeida (INESCTEC, Portugal): PETRA: Innovative Robotics for Deploy/Recover and Monitoring in the Deep Sea for “Shipless” Operations

(vi) Berit Floor Lund (Kongsberg, Norway): Machine Learning for Interpretation of Hydroacoustic Data Streams, Real-Time and Post Processing.

(vii) Hiroyuki Yamamoto, Tetsuya Miwa (JAMSTEC, Japan): Monitoring System and Technical Story of Edokko Mark-I.

(viii) Discussion (20 min.)

49. Abstracts of the above presentations are provided in annex II to this report.

50. The discussions at the end of the two sections offer the opportunity for participants to ask questions and exchange their views, insights, and suggestions, in response to the presentations above.

ITEM 8: MONITORING OF ACTIVITIES ON DIFFERENT MARINE MINERALS (POLYMETALLIC NODULES, POLYMETALLIC SULPHIDES, COBALT-RICH FERROMANGANESE CRUSTS: SURFACE, MID-WATER AND SEABED)

51. Three different types of marine mineral resources are being actively considered for extraction: polymetallic nodules (PMN), polymetallic sulfides (PMS), and cobalt-rich ferromanganese crusts (CFC). Any potential deep-sea mining or testing operations include operational vehicles to obtain the ore, which is then raised to the surface via a vertical transport system. At the ocean surface, an operational vessel handles the ore and may perform some preliminary preparation of it before shipment to a land-based processing facility. Some dewatering operations for safe transportation may produce a return water discharge into the ocean. While the mining and recovery operations must differ for the three marine mineral types, the requirement of technical and environmental monitoring remains for the mining operations on the seabed, the lifting through the water column, the ocean surface operations towards the twilight (mesopelagic) and sunlight (epipelagic) zones, the splash zone and the operations on the operational vessel.

52. This agenda item aims at the identification of state-of-the-art, available, and advanced monitoring technologies as well as innovation in the monitoring of the seabed, the ocean water column and the surface, for the three different types of marine mineral resources. Presentations and discussion will focus on the definition of the best available (industry) practices and required innovation in monitoring and modelling of the entire ocean water column and the seabed, and the identification of strategic partnerships to build and develop the capacities of ISA members, especially developing States.

53. The following participants deliver thematic presentations:

(i) Dhugal Lindsay (JAMSTEC, Japan): Leveraging AI for Image-Based Monitoring of Pelagic Communities.

(ii) Akira Tsune (DORD, Japan): Application of monitoring technologies to polymetallic nodules' exploration activities and the technical transfer.

(iii) Hiroko Kamoshida (JOGMEC, Japan): Environmental Monitoring and Simulation: Knowledge-Gap and Assignments.

(iv) Fadhili Malesa (BAS Cambridge, UK): Modelling of Sediment Plumes from Deep Sea Mining: Current Approach and Future Direction for Advanced Monitoring.

(v) Georgios Salavasidis (NOC, UK): Novel Sensing and Autonomous Platforms for Deep-Sea Mining Impact Monitoring.

(vi) Discussion (20 min.)

54. Abstracts of the above presentations are provided in annex II to this report.

55. The discussions at the end of the section offer the opportunity for participants to ask questions and exchange their views, insights, and suggestions, in response to the presentations above.

ITEM 9: COMPILATION OF THEMATIC DISCUSSION FOR TECHNICAL REQUIREMENTS FOR THE MONITORING OF ACTIVITIES ON DIFFERENT MARINE MINERALS

56. Prof. Tomohiko Fukushima (Kobe University) and Mr. Kioshi Mishiro (ISA) will summarize the key elements regarding the technical requirements for the monitoring of activities on different marine minerals, the status, trends, and challenges of marine monitoring activities for different mining operations based on different technological concepts for various marine minerals, the data collection, handling and communication, and the results of the group discussions, with a focus on innovation and current and available technologies, best industry practices and ways and means to facilitate innovations for advancing smart technologies and the potential to provide guidance for strategic partnerships to build and develop the capacities of developing States and members of ISA. The participants are invited for a thematic discussion.

57. Prof. Junichiro Ishibashi (KOBEC), Mr. Kioshi Mishiro (ISA secretariat) and Mr. Ulrich Schwarz-Schampera (ISA secretariat) provide a summary of Day 2, based on presentations and workshop discussions, and align the presentations and expected discussions during Day 3 with the achievements, regarding status, trends, and challenges in marine monitoring, data acquisition and handling, and opportunities in (real-time) communication.

ITEM 10: MONITORING SCHEMES AND DATA REPORTING

58. Monitoring activities include the online, transparent, and technically reliable observation of all human activities in the oceans, from shipping to fishery and marine fish farming to seabed mineral exploration and environmental baseline surveys and future exploitation. Monitoring is also critically important for the observation and assessment of potential natural hazards (seismic and volcanic events, submarine landslides). The planning and the design of the monitoring of any activities in the Area require the identification of environmental and technical parameters considered critical in any ocean and seabed operations. Technologically, monitoring includes the deployment and use of state-of-the-art, available, and advanced equipment and measurement tools. Owing to the remoteness of the Area and its seabed, any technological solutions must include a multitude of sensors, ship-borne measurements, marine and underwater autonomous systems, moorings and lander systems, submarine cable systems, satellite data, and data connectivity and dashboards. The final recommendations for adequate monitoring designs must consider various aspects, not at least the local to regional differences in geology and oceanography, seasonal annual and multiannual changes, biodiversity, ecology. The resulting monitoring scheme has to adapt local to regional characteristics and distinctive oceanographic features. Thresholds, once defined for a distinct region, need to be controlled effectively. The data recording must comply with the requirements of high precision and real-time reporting. Ocean and seabed monitoring must use best industry practices while leaving opportunities for technological innovation, adaptive management and progress in scientific evidence. ISA aims to promote strategic partnerships to build and develop the capacities of member countries, particularly developing States.

59. This agenda item aims at the identification of advanced monitoring technologies as well as innovation in the monitoring of the seabed, the ocean water column and the surface, to develop monitoring schemes and required data reporting systems for all three different types of marine mineral resources. Presentations and discussion will focus on different monitoring designs for different purposes and provide information and examples of (industry) practices and required innovation in monitoring, modelling of and (real-time) data reporting from the entire ocean water column and the seabed. It is

intended to encourage and promote the identification of strategic partnerships to build and develop the capacities of ISA members, especially developing States.

60. The following participants deliver thematic presentations on the topic of monitoring designs and schemes, and for data reporting:

(i) Kanae Komaki (Chowa Giken Cooperation, Japan): AI-Supported Structural Review of Deep-Sea Environmental Monitoring Reports: A Conceptual Framework

(ii) Matthias Haeckel (GEOMAR, Germany): Mining Impact, DISCOL, Monitoring of the Patania-II Trials, and the Ongoing Threshold Discussions

(iii) Timoteo Badalotti (ABS, United States): MRV (Monitoring, Reporting, and Verification) – The Role of Class Society

(iv) Jens Laugesen (DNV, Norway): Environmental Monitoring of Seabed Activities – how can this be done correctly and at the same time within acceptable economic constraints?

(v) João Carvalho (Deep Focus, Portugal): Application of Machine Learning for Deep-Sea Mineral Resource Assessment and Habitat Mapping and Monitoring: Challenges and Opportunities

(vi) Discussion (20 min).

61. Abstracts of the above presentations are provided in Annex II to this report.

62. The discussions at the end of the section offer the opportunity for participants to ask questions and exchange their views, insights, and suggestions, in response to the presentations above.

ITEM 11: COMPILATION OF THEMATIC DISCUSSION FOR MONITORING ASSESSMENT, DESIGNS AND SCHEMES – WORKSHOP SUMMARY

63. Prof. Tomohiko Fukushima (Kobe University), Mr. Kioshi Mishiro (ISA secretariat) and Mr. Ulrich Schwarz-Schampera (ISA secretariat) will summarize the key elements and group discussions regarding the technical requirements for the effective and real-time monitoring of activities on marine mineral resources and potential natural hazards. The participants' views and information on the status, trends, and challenges of marine monitoring activities and operations, based on different technological concepts, the data collection, handling and communication, and the results of the assessment and potential strategies, designs and regulatory schemes and frameworks will be captured. Innovation and available technologies, best industry practices and ways and means to facilitate innovations for advancing smart technologies are addressed. The participants are invited to discuss the potential to provide guidance for strategic partnerships to build and develop the capacities of developing States and members of ISA.

ITEM 12: PLENARY SESSION: OPEN DISCUSSION AND CONSOLIDATION OF FUTURE STEPS

64. The plenary session aims to define and consolidate existing technological solutions for the monitoring and data reporting of any ISA-related activities on the oceans' surface, in the water column and on the seabed, identify best practice solutions and strategic directions for targeted research and innovation efforts towards developing effective technologies for activities in the Area.

65. The meeting co-chairs provide a summary of the presentations and discussions with respect to the identified priorities in transparent and technically reliable monitoring, with the best available technologies in ocean observation and communication, autonomy, automation, and robotics, and machine learning and artificial intelligence.

66. The outcomes include the summary of the state of the art of current and available monitoring technologies, best industry practices and ways and means to facilitate innovations for advancing smart technologies and the potential to facilitate strategic partnerships to build and develop the capacities of developing States and members of ISA.

67. Based on the results of the discussions and identified priorities, participants are invited to consolidate their input in preparation for updating the mapping exercise carried out in preparation of the workshop.

68. Participants will discuss key considerations for a strategy to facilitate technological advancements for the sustainable development of seabed minerals and the monitoring of any activities in the context of ISA. This includes a collaborative approach to advancing smart and environmentally sound technology and possible modalities and topics for capacity-building activities.

69. Based on the identified priorities, the plenary discusses the best practice design and requirements for effective monitoring and data communication. The aim of the workshop is the consideration and development of state-of-the-art monitoring concepts for the safe and orderly recovery of seabed minerals, the effective and responsible protection of the marine environment, and progress in marine scientific research and opportunities for strategic partnerships and cooperation between contractors, companies, researchers, with special emphasis on enhanced capacities of developing States and members of ISA for the benefit of humankind.

70. The meeting co-chairs will summarize the plenary discussion and outcomes and consolidate future steps.

ITEM 13. CLOSURE OF THE MEETING

ITEM 14. KOBE ACTIVITIES

PORT OF KOBE CRUISE

KOBE MARITIME MUSEUM: A JOURNEY THROUGH KOBE'S MARITIME HISTORY AND FUTURE

Annex I

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Annex II

Summary of Presentations

Agenda Item 1: Opening of the Workshop

Second expert scoping workshop: Charting future horizons – harnessing advanced technologies for the protection and sustainable use of the international seabed area Focus theme: Monitoring

Kingston, Jamaica 10 June 2025

Opening Remarks by ***Ms. Leticia Carvalho, Secretary-General of the International Seabed Authority***

Distinguished guests,

Ladies and gentlemen,

I am pleased to welcome you to this second expert scoping workshop, "Charting future horizons - harnessing advanced technologies for the protection and sustainable use of the international seabed area," with a thematic focus on monitoring.

The workshop is organized in collaboration with the Kobe Ocean-Bottom Exploration Center (KOBEC) at Kobe University in Japan. It marks the first tangible outcome of the partnership between the International Seabed Authority (ISA) and KOBEC, established through a joint letter of cooperation signed in 2024.

I wish to express my sincere appreciation to Mr. Yuzo Yamaguchi, Minister of Economy, Trade and Industry of Japan, Prof. Masato Fujiwara, President of Kobe University, Prof. Hiroko Sugioka and Prof. Junichiro Ishibashi, KOBEC, including Prof. Tomohiko Fukushima, a member of ISA Legal and Technical Commission, for their excellent support in organizing this workshop.

I also wish to extend my gratitude to all participants, both those joining in person and those participating online.

As many of you know, the United Nations Convention on the Law of the Sea (UNCLOS) entrusts the ISA with the unique mandate to organize and control mineral resource-related activities in the Area for the benefit of humankind as a whole. In fulfilling this responsibility, the ISA is mandated to ensure the effective protection of the marine environment from any harmful effects that may arise from such activities. The ISA also has a duty to design and implement mechanisms to promote and encourage the transfer of technology to developing States.

In 2021, the ISA Assembly unanimously adopted an Action Plan in support of the UN Decade of Ocean Science for Sustainable Development. It identifies six strategic research priorities, including one that specifically targets the development of technology to support activities in the Area.

In line with the principles of UNCLOS, ISA's work to facilitate the development and transfer of deep-sea technology will add significant value to increasing our knowledge of the deep ocean and ensuring sustainable and equitable use of seabed resources in the Area, recognized as the common heritage of humankind.

Technological innovation is key to establishing reliable, low-impact, transparent and cost-effective systems for the monitoring of exploration and future exploitation activities, which is precisely the focus of this workshop. It is also central to ISA's ability to fulfil its regulatory responsibilities and ensure an evidence-based approach to decision-making.

To advance this work, ISA has launched a series of workshops that explore the role of technological innovation within its mandate. Five specific areas were identified for focused consideration: (i) ocean observation and communication (ii) monitoring (iii) autonomy, automation and robotics (iv) machine learning and artificial intelligence and (v) mining, energy and processing.

To inform discussions currently under way across ISA's bodies, the ISA Secretariat is initiating studies to assess the state of available technologies in these five specific areas, identify the best industry practices and explore the need for further technological innovation.

This workshop in Kobe will focus on technical and environmental monitoring, as well as the technologies needed to support scientific and technological discussions, including those related to the development of regional environmental management plans and environmental thresholds. It aims to assess the current design, challenges and future requirements of ocean and seabed monitoring.

Discussions will cover a broad range of topics, from existing and emerging technologies to advanced monitoring designs, best industry practices, innovation and opportunities for strengthening the capacities of developing countries in this field.

I am confident that your exchanges over the coming days will help identify synergies and foster strategic partnerships that facilitate innovation, technological development and capacity-building.

I trust that your collective engagement will help us design and implement tangible actions that promote sound and innovative deep-sea technologies for the sustainable management of the Area and its resources, benefiting all humankind.

I thank you all for your participation and continued support of the ISA's work.

I wish you fruitful and productive discussions and look forward to the outcomes.

Thank you.

Agenda Item 2: Meeting Background, Scope, and Expected Outputs Addressing Key Technologies, Technological Needs, Research and Development Activities.

Concept Paper

Technological Innovation for Environmental Monitoring of Activities in the Oceans and the Seabed

– by Ulrich Schwarz-Schampera (ISA Secretariat)

Monitoring activities include the online, transparent, and reliable observation of all human activities in the oceans, from shipping to fishery and marine fish farming to seabed mineral exploration and environmental baseline surveys and future exploitation.

The planning and the design of the monitoring of any activities in the Area require the identification of environmental and technical parameters considered critical in any ocean and seabed operations. Technologically, monitoring includes the deployment and use of state-of-the-art, available, and advanced technologies. The field of ocean and seabed monitoring can be used to define best industry practices while leaving opportunities for technological innovation, adaptive management and progress in scientific evidence. ISA aims to promote strategic partnerships to build and develop the capacities of member countries, particularly developing States.

Owing to the remoteness of the Area and its seabed, any technological solutions must include a multitude of sensors, ship-borne measurements, marine and underwater autonomous systems, moorings and lander systems, submarine cable systems, data communication and connectivity, satellite data, and data dashboards.

The industry requires clearly defined targets and tasks from contractors and the regulator to develop innovative solutions that meet various constraints, including physical limitations, financial capabilities, market opportunities, and political support. Technological requirements also include the stationary versus mobile setup of mining and monitoring equipment, depending on the targeted mineral type. Cobalt-rich ferromanganese crusts (CFC) and polymetallic sulphides (PMS) require mostly stationary installations with limited lateral movements. In contrast, polymetallic manganese nodules (PMN) demand mobility of the entire set up over larger distances in short times. Cost-effectiveness plays a significant role in the development of comprehensive monitoring systems and schemes.

Several aspects need to be addressed for a complete technological scheme of comprehensive and successful ocean and seabed monitoring allowing for fast, if not real-time, reporting and inclusive and responsible decision taking.

- *The 'Black Box' Concept and Communication*

Monitoring, both environmental and functional, requires ocean observation and communication, to enable fast data measurement, recording, transportation, and presentation from the data source to the mining company, the regulator, future inspectorate, and the interested public stakeholders, against environmental thresholds, technical parameters and constraints, production rates. Given the slow and power-consuming nature of acoustic communication from the seabed to the surface, monitoring systems could be accessed much faster by short range communication to centralized access points with umbilical connection for fast data transfer or to other vehicles present on the seabed (e.g., collector/'miner', AUV, glider).

'Black box' systems as mandatory data repositories for regulators have been a reality in fishery and coastal shipping (e.g., ferry box) since many years. These systems collect, store and provide information on activities, location, technical parameters. An independent 'black box' system is suggested to provide sensor data, near-field information, and the mining system's location and activities independently from the operators. Such a system may also provide an access point for the communication and navigation of the mining system as well as with other monitoring assets on the seabed. A 'black box' monitoring concept will transmit data and information to the mining and monitoring operators on the vessel and then to the other stakeholders (e.g., the ISA inspectorate, ISA organs) for control, quality checking, and access to environmental monitoring data. Any 'black box' concept must include, integrate and connect multiple sets of sensors (e.g., navigation, sonars, nephelometers, chemical and physical parameters, etc.), without increasing the noise production, energy consumption, size and weight or challenging the sensor's physical interaction with its surroundings. System design optimization for optimal sensor positioning, reading, storage and data transmission is required. Redundancy might be required for operational and independent monitoring systems.

Data transmission from the seabed to surface is complex and requires technological innovation. Currently, transmission is limited to acoustic and optical methods. Acoustics can serve low bandwidth requirements only, and physical data mulling may account for intermediate bandwidth. Terabyte-level data transmission requires new physical solutions. Efforts must standardise acoustic communications and ensure interoperability of different seabed technologies.

Wireless data transmission from the seabed, through the water column to the vessel is traditionally done by sounding. Although the speed of acoustic signals under water is faster (1,481 metres per second at 20° C) than through air (340 metres per second), bandwidth limitations increase with distance reducing data transmission capacity. Cabled collector or monitoring systems provide high-speed optical cables for fast data transmission. Autonomous untethered vehicles and landers require acoustic communication and demand smart communication hierarchies and structures only for the critical information of interest. An optimised physical architecture with hierarchical structures for real-time capacity and data recording for later recovery will facilitate fast, reliable, and critical communication. Deep water depths may be approached by engineering and data hubs etc. Technical solutions exist to communicate video acoustically underwater. Current research on using light, such as lasers or LEDs to transmit data through the water column shows promise for higher data volumes at higher speeds over short distances, though alignment of the light in turbulent waters remains a challenge. The capacity of leveraging multimode fiber (MMF) in the field of optical communication to encode information in optical frequencies rather than raw data, is leading to a significant advancement in seven-fold boost in capacity over traditional methods. This new technology enhances data transmission at high capacity but also proves remarkably effective in accurate analysis and interpretation even in noisy environments.

Real-time communication includes the time between arrival of information and decision-making. A balance is necessary between the recording of data, the transmission to surface, available bandwidth, transmitting it to land, and deciding on required actions. The type of operation, data, and information as well as the assessment, time to conclude correctly, and necessity for action, all need consideration for the communication set-up and monitoring infrastructure, and for the required bandwidths on the seabed and in the water column. The regulator must establish a data classification scheme related to the urgency of reporting (seconds, minutes, hours, days, and years) and consider several scenarios, their probability and warning systems (green/yellow/red).

An example for interoperability of networked underwater communications is the JANUS protocol (NATO STO Centre for Maritime Research and Experimentation). JANUS is a digital underwater coding standard providing a common baseline for underwater acoustic communications. It includes the potential interoperability of vessels, gateway buoys for underwater communication via acoustic modems and traditional radio waves at surface, underwater interaction and information exchange by submarines, AUVs, and unattended sensors interacting with the submersibles and collecting and transmitting data autonomously. Such a system will pave the way for a standardised internet of underwater stations and (temporary) installations. Low Earth orbit satellite constellations for fast data access and global transmission would allow for high bandwidth access from the ocean's surface.

Addressing real-time communications involve actual data transmission and latency for various observations. For threshold monitoring, the regulator may require a decrease in latency which increases system expense and complexity exponentially. Early definition of latencies would drive technological advancement and significantly benefit the industry.

- *Autonomy*

The trend in deep-sea technologies is towards autonomous systems (e.g., 6,000 metre-rated AUVs) to serve scientific interests and to cover about 98 % of the global seabed. These deep depth ratings are a positive driver for deep-sea technologies and activities on the seabed, including marine minerals and environmental baseline research. Various sensors including sonars, receivers, recordings, and CTDs have characteristics which are of key interest for marine exploration, exploitation, ocean observation, environmental monitoring and potential industry. Managing innovation in deep-sea autonomy demands clearly defined requirements (e.g., a very defined setup of sensors and tools), particularly for different research activities, mineral types, mining targets, and monitoring requirements. The definition of individual interests and tasks may also lead to technical solutions designed for single-use applications, which could limit market opportunities; kit-based approaches for multiple and diverse technical applications may limit the economic specialization and dependency.

Remote services will require a vehicle fleet that includes remote ROV operations, an autonomous inspection drone, and uncrewed surface vehicles (USV) for low-footprint solutions. An example for ship-based remote services is the USV Ocean Challenger, commissioned in early 2025. The vessel is 24 metres long and equipped with a working-class ROV. The USV will not have crewed surveillance but is not completely autonomous according to regulatory demands. It is operated by remote control, has supervised autonomy, and aims at full and continuous endurance at sea for 30 days.

Numerous options exist for the feasibility of remote surveys by USVs. A common scenario involves deploying the vehicle with an ROV/AUV inspection and survey facility on board, with a multibeam mounted on the ROV/AUV, and with hull-mounted systems. A gondola design includes the launch of a towed system as well. Larger USVs can carry more complex systems for remote surveys, and larger USV offer better survey equipment than existing smaller platforms. The endurance and the seakeeping capabilities required to work in the Area still pose a challenge to USV solutions. Larger USVs and longer endurance require adaptation of classification schemes.

- *Sensors and Data Access*

Physical constraints may limit technical innovation or the use of deep-sea technologies for specific tasks (e.g., imaging from great distances, shipboard multibeam echosounding). For example, active sonars require higher energy to be produced but for the benefit of better sensitivity, data quality, and processing. Modifying sensors, such as enhancing receivers and beam imprint, lead to smaller environmental imprints and better quality of imaging. Similar benefits arise from modifications in electronics, processing, and beamforming.

Sensor-based sampling and analyses require appropriate laboratory set ups, which are established in onshore labs but may be challenging on vessels or in situ after sampling. Autonomous sampling and (in situ) analyses offer important information and add significant value to vessel-based analysis (e.g., filter collection, DNA extraction, sequencing) but might be challenged by contamination, reliability of sampling and analyses, and acceptance by scientists. Analyses must meet analytical standards, monitoring requirements, and the needs of the operator, regulator and public.

ISA contractors generate huge amounts of data that need to be analysed, interpreted, and used to ensure efficient activities with lowest possible impact. Serious data analyses and data science are required, as well as standardisation of data storage and reporting. The public use of environmental data, nonconfidential and disclosed to the public, is openly promoted by the ISA secretariat and its DeepData data base. However, the secretariat is also using the contractors' data for regulatory management purposes, namely the development and preparation of Regional Environmental Management Plans (REMPs), which are obligatory before any exploitation activities can start. Contractors' oceanographic data are of key importance for any assessment of the marine biodiversity in the contract areas and will also inform environmental threshold discussions and standardisation.

The wealth and complexity of data, along with the anticipated information and final products needed for effective marine environmental protection, require a sound understanding of data and its modelling for conclusive management, monitoring, and inspection tools and standard operations. A standardised data base (DeepData) is used for machine learning and artificial intelligence. It has the potential to model and predict various aspects of oceanography, geology, mineral resources, biodiversity, and the environmental effects of human activities. AI-based modelling has the capacity not only in environmental assessment but also in forecasting consequences to inform management and monitoring plans. The ISA's DeepData development in the coming years includes easier access and better visualization. DeepData is interoperable in sharing data with other databases including OBIS for biodiversity data, and IOC/UNESCO for oceanographic data.

Data reporting from production, monitoring and inspection will demand further development of a data-base capable of storing, reporting, and disclosing data from individual contractors. Reporting to the regulator and a future mining register will still be mandatory. The ISA is developing and acquiring a mining registry, which will be a key module for contractors' activities and reporting during exploitation, like national registries for land-based mining activities. Environmental information will be accessible to stakeholders and the public, comparable to the current DeepData.

- *Technology Market*

The potential marine mineral and monitoring market is very small, even when considering world-wide marine research activities. Currently, only 22 contractors with 31 contracts may mature from exploration to exploitation. Even with the entry of new contractors, the number remains limited, constraining potential investments. Overlap exists with activities in national jurisdiction and with other markets (e.g., blue economy developments and interests, ecosystem services for aquaculture, pollution, geohazards) presenting opportunities for joint and highly specialized developments.

Specialized companies sell limited numbers of highly specialized tools over long time periods to a non-linear market. The market includes a variety of users and addresses various marine aspects. Specialized products and companies are likely driven by specific needs of a developing industry (e.g., Norway's petroleum industry for the assessment of installations and monitoring of production) offering opportunities to lead technical developments in emerging markets and industries. It is critical to design products and tools with the potential for diversity to enter broader markets.

- *Regulation*

Regulators ask for the best available technology (BAT) and a related approval process. In the offshore oil and gas industry, new equipment must comply with defined standards (American Petroleum Institute (API) Standards) and standards compliance usually provide the frame for best available technological solutions. ISA as the regulatory body oversees proposals for exploration, potential exploitation, monitoring, and inspection technologies, and checks the systems against approved standards, including material selection, and the equivalent of the electrohydraulic system. Respective regulations must be in place. As technology evolves rapidly, standards must be flexible enough to capture modifications or regular updates for improved technologies or processes.

Best available technologies and corresponding standards may also require definitions for favourable processes, such as resource recovery and mitigating potential environmental impacts. A step forward for regulators could be the introduction of a warning scheme (e.g., green-yellow-red) and the definition of standards for different grades (e.g., particle density in the water column). For actual mining and monitoring technologies, the definition of objective standards (e.g., material selection, welding process, hydraulic connection) might be better handled by experienced third parties.

The development and standardization of best available technologies are constrained by companies' and contractors' reticence regarding intellectual property. The industry is interested in progressing the development of instrumentation and beginning the regulation process for agreed standardisation. Expert and regulator participation in an organization will be required for plume monitoring, modelling approaches establishing baseline standards acceptable to all stakeholders.

While regulation and standards for deep-sea mining are under negotiation and preparation, the industry requires guiding principles to proceed. Those are set by the regulator (ISA) which provides information. Contractors, according to their contracts with the ISA, are requested to invest in the development of mining technology and need to show the capacity to recover marine minerals off the seabed in a responsible way while avoiding harmful effects on the marine environment. Experts in the ISA Legal and Technical Commission test and check potential mining solution and the entire process supports defining future seabed mining standards. Five contractors have tested mining equipment in their contract areas or national waters, influencing standard definitions. Activities in national jurisdictions are outside of ISA regulation but certainly inform the definition of standards. Timely standards, such as Integrated Services Methodology, are particularly important for smaller companies in the subsea industry to ensure their equipment and systems meet these standards and to form possible consortia.

The multilateral process for regulations aims to strike the right balance. The level of tolerance is a political decision, informed by scientists and experts, tailored to the comfort and trust of individual countries. This is a requirement to answer constituents about accepted tolerance levels.

Innovation towards a comprehensive monitoring scheme

It is a requirement that the regulatory authority and its contractors keep up with technological innovation and development. The industry looks to scientific and regulatory bodies to define potential commercial applications. Regulations need to match technological innovation, and non-conformity limits the application of new technological developments. Developing state-of-the art regulations that are continuously updated offers opportunities for enhanced innovation and application.

The stocktaking of existing technologies and their opportunities for ocean observation, communication and monitoring highlights possible future developments for effective monitoring. The wide availability and technical readiness of sensors is obvious; however, the precision of these sensor measurements needs to be tested against the requirements set by the ISA. Working groups on monitoring thresholds were established, and the compilation of natural variability in particular components is ongoing to better define thresholds for regions of future mining interest (e.g., CCZ, CIOB, MAR). The threshold definition will inform the required standards for sensor precision. Open solutions are related to aspects of ocean communication, which has physical restrictions and demands smart solutions for data transmission on the seabed. Once collected and transferred to a cabled system, transmission to land in almost real-time is standard operation.

Aspects of best technological availability are constrained by the quick advancement of technologies by multiple contractors and stakeholder industries potentially following different concepts and designs. Activities should encourage competition for the most successful technological solution. Defining minimum standards for mining and monitoring technologies by the regulator can allow for safety and efficiency, support synergies, and promote further competitive development for longer time periods without defining strict short-lived provisions of best available technology.

Technologies for exploration, exploitation and monitoring activities are available on the market. Their availability is critical for future industry developments. As seen in examples from the marine industries or wind farm construction, the availability of new technology always leads to the potential for upgrades. The use of these technologies promotes innovation and advanced solutions. Defining best available technologies too rigidly might limit the potential for upgrades during mining and monitoring.

Remote monitoring technologies – including monitoring equipment, data transfer and data analysis – are rapidly developing. Remote monitoring ensures effective inspection and enforcement activities by the ISA. Special emphasis is laid on recent developments towards the application of artificial intelligence, the use of drones for remote monitoring, and data communication through the water column at very large water depths. Artificial intelligence is essential for processing and modelling vast volumes of data from remote monitoring. Data patterns can inform decision making and forecast environmental hazards, such as meteorological phenomena and ocean conditions, which are important for operations. AI could also forecast expected environmental impacts. Drones will play a major role in all types of monitoring activities on the seabed, in the water column and on surface. Batteries are still a limiting factor for the range. Combustion engines in drones, fuelled by kerosene, methanol, ethanol or propane, can increase the range substantially, and can be combined with an onboard battery pack.

Monitoring demands include boundary layers (i.e., the surface, the water column and the bottom) within a 3D environment. A combination of methods will be needed for extensive remote monitoring. These activities will require numerous and multipurpose sensors for the entire water column, with a sophisticated architecture to ensure a sufficient and reliable monitoring coverage with best-possible resolution and accuracy. The tools under consideration still have their potential limitations, i.e., data storage capacity, sensors payload, limited coverage. Satellite coverages, necessary for an overview and surface observation, can be extended by planes with autonomous monitoring systems. Satellites have shortcomings, and the required sensors are not yet ready for constant and reliable use at the required resolution.

- *Conclusion*

The readiness level concerning monitoring and contractors' preparation of mandatory baseline studies for the environmental assessment and potential prediction of impacts is critical for any future seabed activity. Scientists and contractors collected expertise to predict the potential plume development during PMN collection at high confidence levels, even considering possible seasonal changes. The readiness level is controlled by the availability of sensors, monitoring infrastructure, and autonomous and robotic systems. Cooperation between the industry, contractors, and regulators is required for designing and operating a comprehensive monitoring framework and system.

Contractors are comfortable with the current availability and capability levels of sensors, robotics and automation technologies in the industry. They have contributed large investments in technological developments in recent years. Offshore testing has offered the opportunity for in situ development, testing, and improvement of monitoring technologies, demonstrating the technology readiness level. These efforts need to be synchronized with the regulator's approach to technical risk and monitoring design. Reference can be made to the oil and gas industry having established a successful trusting and common-sense relationship with its regulatory bodies, proven to work over the last 30 years.

Mining and monitoring activities might offer the opportunity for an iterative approach. The natural environment in the Area is far from defined laboratory conditions. Any activities require a best- and baseline-informed modelling approach, which is then tested and continuously improved based on test results and experiences. Measurements and monitoring have physical and technical limitations; an iterative approach with tested and improved models is suggested for the formulating standards as well.

It is agreed that ongoing science resulting from exploration, test mining and technology testing and monitoring activities provide credence to the validity and the neutrality to the results from observation, measurements and monitoring. Scientific publication is a notoriously slow process though, and the definition of standards and the regulations require agreed-upon data to base defined thresholds on. Since the principles of scientific publication are time-consuming and unlikely to change quickly, an iterative, model-based approach and intense interaction and cooperation between academia and companies are logical steps ahead. This approach has been demonstrated in recent collector and mining tests.

Most existing monitoring exercises to date have been driven and created by scientists primarily, for science purposes, and not necessarily for commercial-scale monitoring operations. Therefore, upscaling ocean observation and monitoring trials is required to properly inform monitoring standards and regulations. Defining the scientifically acceptable tolerance to deviations from natural conditions for critical environmental parameters in a certain region will impact real-time monitoring standards. Cooperation between the operator and the regulator, as well as well-informed clear communication with the public, is essential.

The preparation for seabed mining requires significant investment by the mining industry to develop, test, and approve their mining technology. Production requirements may change with market conditions and demand, having consequences for the actual mining design, such as necessitating upscaling with multiple collectors. The effect of upscaling on mining and its monitoring has not yet been tested. A standardised set of thresholds, based on data collected during extensive exploration activities and supporting research projects, are currently under scientific discussion, will allow for monitoring and provide objective measures to ensure compliance with regulations. Standardising thresholds and the generalisation through modelling must consider scales and local to regional variations to prevent data bias.

The ISA and the scientific community will define objective criteria for the authorized responsible recovery of marine minerals and mining operations. Standardising data requires defining key aspects and information at different scales, from single contract areas to wider regions. Mandatory templates for providing information to DeepData support this standardisation of information across various areas and different contractors. The contract areas are connected to the wider region, e.g., the CCZ or the northwest Pacific. Oceanographic and biodiversity data span larger areas describing ocean-wide phenomena. Enhanced cooperation between contractors regarding environmental data was initiated. Increased collaboration with the scientific community, such as through the European JPIO and INESC TEC programmes, could significantly improve data quality, potential outputs, and the knowledge created for comprehensive, responsible, unbiased and transparent physical and environmental monitoring of seabed activities.

Expectations for technological development from the perspective of the rule-making process

– by Tomohiko Fukushima (Legal and Technical Commission)

The Legal Technical Commission (LTC) in International Seabed Authority (ISA) is consisted of 41 members with expertise in law, geology, engineering and the environment. Its main tasks include providing advice and recommendations on exploration and development regulations, preparing documents related to various guidelines and standards, reviewing and advising on reports submitted by contractors, and holding related workshops. In carrying out these tasks, LTC members always take feasibility into consideration. Feasibility can be broadly divided into economics and technology, and technological development, the theme of today's workshop, is an important topic that determines technical feasibility. Rule-making and technological development are complementary. Sometimes technological development sides are undertaken to accommodate existing rules, but other times technological advances can change the rules. LTC members respect technology and want to work hard to create rules as technology advances. In that sense, today's workshop is worthy of attention.

Theme Presentations and Abstracts

Agenda item 3: Marine Monitoring – Setting the Scene (requirements, examples)

(i) **Pedro Madureira (University of Évora and Eduardo Silva (INESC-TEC):** ***Marine Mineral Resources in the Area – Current Regulatory Approaches for Comprehensive and Responsible Environmental Monitoring.***

The International Seabed Authority (ISA) is the organization through which the current 169 States Parties (plus the European Union) to UNCLOS organize and control all mineral-resources-related activities in the Area for the benefit of humankind as a whole. In so doing, article 145 of UNCLOS provides that ISA has also the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from those activities. Therefore, monitoring of the programmes established by contractors to explore and exploit minerals from the Area is in the core of the ISA's mandate. This abstract gives some content on the current existent regulatory framework (exploration) for responsible environmental monitoring and on what may be necessary to implement in the exploitation regulations.

Monitoring the marine environment to protect it from harmful effects that may arise from activities in the Area is a highly demanding task that is part of the contractors' obligations. As defined in the regulations on exploration for minerals resources in the Area, marine environment "*includes the physical, chemical, geological and biological components, conditions and factors which interact and determine the productivity, state, condition and quality of the marine ecosystem, the waters of the seas and oceans and the airspace above those waters, as well as the seabed and ocean floor and subsoil thereof*". Therefore, while the Area refer to the spatial domain of the deep-seabed and subsoil thereof, the activities in the Area depend on the deployment of equipment and machinery from vessels that may impact not only the Area, but also the water column (e.g. pollution), the migratory routes of marine mammals or birds, and even the airspace from vessels CO_2 emissions. In accordance with Article 165, paragraph 2(h), of UNCLOS, the Legal and Technical Commission (LTC) "*shall make recommendations to the Council regarding the establishment of a monitoring programme to observe, measure, evaluate and analyse, by recognized scientific methods, on a regular basis, the risks or effects of pollution of the marine environment resulting from activities in the Area* […]". While this is yet to be developed, the LTC has been responsible for developing (Regional) Environmental Management Plans ((R)EMPs) that consider mechanisms for monitoring the achievement of the conservation objectives for the areas identified as Areas of Particular Environmental Interest (APEIs) (e.g. ISBA/17/LTC/7).

The current regulations for exploration include a Part V, which is related with the protection and preservation of the marine environment. Regulation 31 (in the case of polymetallic nodules) and 33 (in the case of polymetallic sulphides and cobalt-rich ferromanganese crusts) state that "*Contractors, sponsoring States and other interested States or entities shall cooperate with the Authority in the establishment and implementation of programmes for monitoring and evaluating the impacts of deep seabed mining on the marine environment* […]". Regulation 32 (in the case of polymetallic nodules) and 34 (in the case of polymetallic sulphides and cobalt-rich ferromanganese crusts) give a specific obligation to contractors to establish environmental baselines against which future effects in the marine environment may be assessed and a programme to monitor and report on such effects. In this context, it is considered that the LTC may issue recommendations to list the exploration activities that may be considered to have no potential for causing harmful effects on the marine environment. In fact, the LTC recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration (ISBA/LTC/6/Rev.3) do list the type of activities that may have an impact and that require an Environmental Impact Assessment (EIA) and a monitoring programme to be implemented during and after these activities, which need to be approved by the LTC. In its recommendations the LTC also points that the testing of mining components or test-mining may be conducted by contractors collaboratively. Tests need to be monitored intensively to allow the prediction of changes to be expected from the development and use of larger-scale commercial systems. Moreover, when test-mining has already been carried out, even if by another contractor, the knowledge gained through those tests should be made available and applied, where appropriate, to ensure that unanswered questions are resolved by new investigations.

The regulatory framework for future exploitation for mineral resources in the Area is still under discussion in the ISA Council. Knowledge gaps are still existent, namely on the impacts of noise and light, as well as of benthic and/or mid-water plumes on the increase of turbidity and potential toxicity in the water column and in areas beyond the mining impacted sites. All these deliverables are being targeted by the LTC and a group of experts nominated to develop the appropriate thresholds that will allow the implementation of a precautionary approach particularly significant in the initial stages of deep-seabed mining. Monitoring will be crucial to assess contractors' activities, which impacts needs to stay within the previously accepted Environmental Impact Statement (EIS) and below the environmental thresholds that may be defined by the ISA. The current exploitation Draft Regulations require an assessment of applications also based on the technology that will be used to comply with the Environmental Monitoring and Management Plan (EMMP) and the Closure Plan. Thus, technology will play a central role in making sure that monitoring of mining activities may be effective and transparent, ensuring that the principle of Common Heritage of (Hu)mankind is pursued by the ISA.

(ii) **Mengyao Zhu (Ocean Policy Research Institute/The Sasakawa Peace Foundation, Japan):** ***Bridging Science, Policy, and Society through the "Ocean Shot" Initiative: Innovations in Monitoring for Ocean Discoveries.***

Ocean Shot is an international research-grant initiative launched by the Ocean Policy Research Institute (OPRI) of the Sasakawa Peace Foundation, designed to catalyze fundamental ocean discoveries and address global sustainability challenges in the ocean. The program supports transformative research from two key perspectives:

(1) the discovery of new marine ecosystems, species, and ecological functions, and

(2) the development of innovative technologies and data science approaches that enable such discoveries.

Since its launch in 2023, Ocean Shot has funded 6 research projects around the world, some of which directly contribute to seafloor mapping and deep-sea biodiversity monitoring. These projects encompass pioneering work in eDNA-based biodiversity exploration, AI-assisted monitoring of seafloor, novel imaging technology and video analytics for real-time monitoring, etc. While OPRI itself does not conduct monitoring activities, these supported projects exemplify how targeted scientific investment can advance monitoring capabilities in previously inaccessible marine environments.

OPRI's role goes beyond scientific funding. As a policy think tank, we actively promote the Science-Policy-Society interface, working to ensure that cutting-edge marine research informs decision-making processes and leads to tangible societal benefits. In the context of the ISA framework, this integrated approach can offer valuable insights for the design of future monitoring strategies that are scientifically sound, policy-relevant, and socially inclusive.

This presentation aims to share our experience in connecting science with policy and practice, and to contribute to the ongoing dialogue on innovative and collaborative approaches to deep-sea monitoring.

(iii) **Muhammad Zarar (Geo-Tech Consultancy Services, Pakistan):** ***Technologies and Approaches towards Environmental and Technical Monitoring***

Nowadays military and civil technologies complement each other and the same is true about technical and environmental monitoring of the Oceans and Ocean's beds. Unfortunately, our lack of knowledge and customized technologies hinder our approaches to this vast field of great economic importance and sustainable peace building efforts. Among different approaches, digitalization of the Oceans is the key to all other methodologies. It is the use of digital technologies whether these are geo-spatial, terrestrial or underwater to change a research model and provide new avenues and value producing opportunities. It is the process of moving towards digital research approaches and adopting practically more useful business models. KOBEC already have different approaches which doesn't cover well, different aspects of the Deep Ocean due to vast expanse of the oceans and different technological barriers. This is the reason our understanding about the deep oceans are lagging behind and we urgently need transformation to digital technologies in this context, such as Digital Twins of the Oceans, Geo-machines, Marine Spatial Planning are few venues to be named here. Hence, this paper from me with the title "Technologies and Approaches towards Environmental and Technical Monitoring" is an approach, which can support all other approaches and activate other science interventions and impacts to enhance the applicability of databases and authenticity of the digital simulations.

Most of the data available now is also in different forms and it needs to be organized/harmonized in digital formats to utilize for further research works related to Blue Economy, R & D and Real-time Monitoring. Organizations working in this context can get the benefits of this approach hence it can generate great commercial values for the communities, countries and global stakeholders. As far as environmental concerns are taken into account, we may predict impacts of deep-sea mining, ocean warming and other invasive activities such as mCDR, shipping, fishing, solarization, floating wind turbines and land-wastes dumping in the oceans. To cut short, this approach is not only an addition to our endeavors towards better understanding of the Blue World but a necessity to accelerate our research process with the applications of digital transformation resources.

Digital Twins of the Ocean

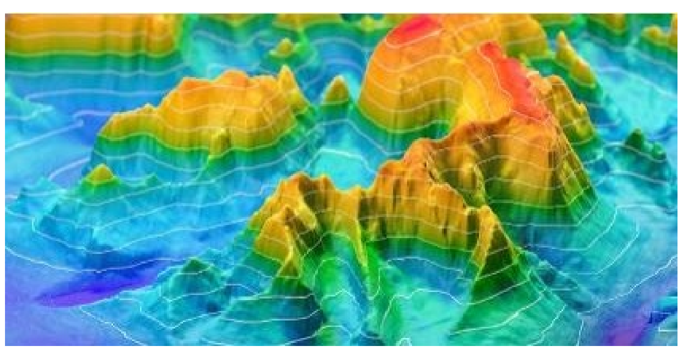

Figure 1. Courtesy, ILIAD Digital Twins of the Ocean Marketplace

(iv) **Musa Animashaun (Hydrographic Science Research Center, University of Southern Mississippi, USA/Nigeria):** ***Hydrography in the Deep Sea: Enabling Transparent, Scalable Monitoring of the International Seabed Area***

Effective monitoring of seabed activities within the International Seabed Area requires a robust understanding of the ocean floor and its surrounding environment. Hydrography, through precise bathymetric and geophysical data acquisition, plays a foundational role in establishing environmental baselines, detecting anthropogenic impacts, and supporting long-term, transparent monitoring frameworks. This presentation will explore the core contributions of hydrographic science to deep-sea monitoring, including the deployment of multibeam echosounders, sub-bottom profilers, and autonomous platforms in ultra-deep environments. Emphasis will be placed on integrating hydrographic outputs with environmental and oceanographic data streams to support the ISA's Regional Environmental Management Plans (REMPs) and Areas of Particular Environmental Interest (APEIs). The talk will also highlight best practices in data quality assurance, capacity development for developing states, and the importance of standardized geospatial data for regulatory compliance. By positioning hydrography as both a scientific and operational pillar, this presentation proposes strategic pathways for enhancing the efficiency, inclusivity, and credibility of monitoring efforts across the Area.

(v) **José Miguel Almeida, Alfredo Martins, Betina Neves, Eduardo Silva (INESCTEC):** ***TRIDENT: Project, Updates and Tech Insights for Long-Term Deep-Sea Monitoring***

This presentation will focus on the technology details of TRIDENT's Blackbox and Smart Low-power Data Logger, highlighting the characteristics, modularity and "smart" features within. It will proceed to address the seabed nodes (robotic and relocatable) and prepare the way for NOC's sharing of sensors and adaptive plume sampling with AUVs. It will finalize the presentation, with the communication, navigation and positioning aspects of the TRIDENT architecture and the autonomy and energy charging features of the project.

(vi) **Matthieu Straub, Sylvain Pascaud (NineNorth, USA, France):** ***The Visualization of Environmental Data and the Possible Outreach Solutions***

1. Introduction

Environmental data, particularly in the fields of oceanography, is vast and often fragmented in terms of sources and formats. Advances in sensing technologies and autonomous vehicles have greatly increased our ability to collect such data, whether from detailed bathymetric surveys, satellite observations, real-time sensor feeds or long-term archives. However, this proliferation of data paradoxically creates a new challenge: the challenge is not just to aggregate data, but to transform it into coherent, usable information that enables scientists and stakeholders to better understand and analyze the data they have collected. At Nine North, we've made this challenge our mission. Our approach is based on our experience of the deep sea and our knowledge of computer engineering in the service of science.

Our Approach: From Data to Ocean Intelligence

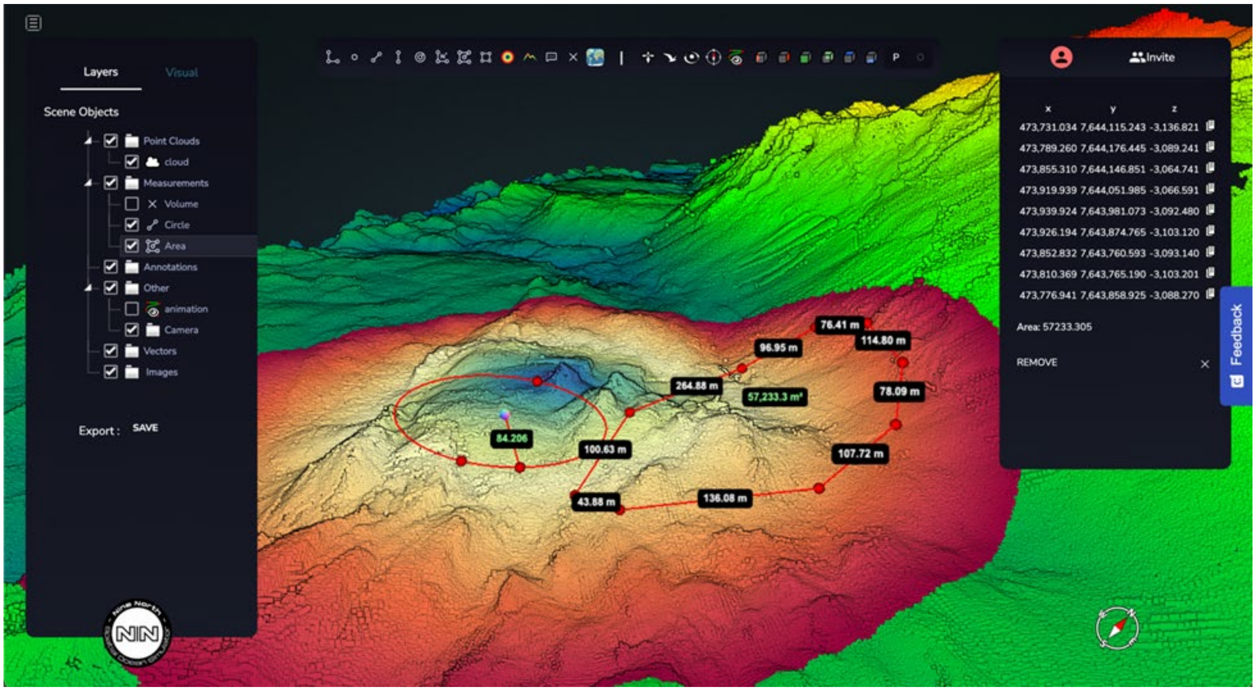

Figure 1: DeepMap, an example of 3D surface measurement.

In response to these challenges, Nine North has developed DeepMap, a web-based platform that lays the foundations for Ocean Intelligence. This approach enables the visualization of ocean data, highlighting patterns, behaviors and relationships within complex systems. Our focus is not only on data visualization, but also on how environmental processes evolve and interact over time and space. Our first iterations focus on importing and processing oceanographic data and visualizing them via our collaborative platform. We are also providing advanced 3D tools to quantify and measure key features of these datasets. This enables multi-disciplinary teams to work and to engage with each other, facilitating timely decision-making. On this basis, our current development plans include numerous evolutions both in Big Data management and in quantification, 3D segmentation, and the contribution of artificial intelligence for very precise fields such as visual detection.

Shared Exploration: Bridging Science and Public Engagement

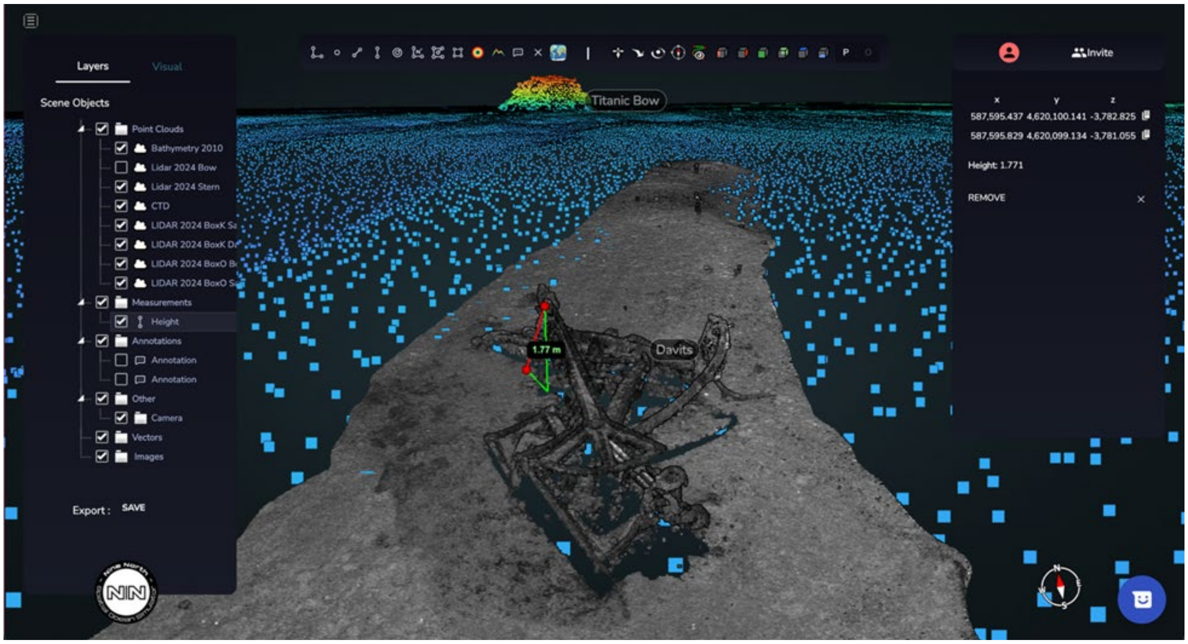

Figure 2: DeepMap, displaying a high-resolution Lidar made in 2024 on the bathymetry from 2010.

Beyond its core technical capabilities, our web platform also serves as a powerful tool for scientific outreach and public engagement. A compelling example of this is our work on the 2024 RMS Titanic expedition, where the same interactive 3D environment used by scientists to document and analyze the wreck site was also made accessible to the wider public. Researchers could collaboratively examine high-resolution scans, annotate features of interest, and exchange insights in real time. Simultaneously, the broader public could explore the site within the very same environment by navigating through detailed models, discovering contextual information, and gaining a richer understanding of the wreck's historical and environmental significance.

Figure 3: Set-up of the Nine north team in the vessel Dino Chouest during the RMS Titanic 2024 expedition.

This shared experience illustrates how the platform seamlessly supports both technical analysis and public storytelling, without distinction between expert and non-expert users. Everyone interacts with the same content, the same tools, and the same data, each drawing from it what they need, whether it's scientific insight or emotional connection. The Titanic project demonstrated how a unified interface can foster both collaboration and engagement, encouraging deeper involvement across communities.

2. Connecting DeepData: A First Step Toward Integrated Exploration

As part of our collaboration with the International Seabed Authority (ISA), we conducted a feasibility study to explore how official deep-sea environmental datasets, specifically those hosted on the ISA's DeepData platform, could be made more interactive and accessible through our web-based 3D visualization environment. This effort marked an important first step toward building a seamless bridge between structured marine data and intuitive, spatial exploration tools. Our aim was not to replicate DeepData's functionality, but rather to extend its reach by offering a more visual and contextualized interface. In this initial iteration, we focused on extracting relevant metadata and geospatial references from publicly available datasets, such as exploration contracts, sampling stations, and environmental measurements, and mapped them into our collaborative 3D platform. Users could, for the first time, browse data spatially, click on a sampling station, and instantly view its associated entries, such as CTD or ADCP, displayed alongside seafloor topography and other contextual layers. This pilot integration proved that it is technically feasible to link structured ISA datasets with immersive, web-based visualization tools. It also highlighted the potential for such platform to foster new forms of interaction between policymakers, researchers, and civil society. It enables users to ask better questions and make better-informed decisions. This initial success opens the door to a deeper integration with ISA's data infrastructure. It provides a working example of how structured regulatory data can be made more discoverable, usable, and impactful when viewed not as static records, but as part of a larger narrative of place, activity, and environmental change.

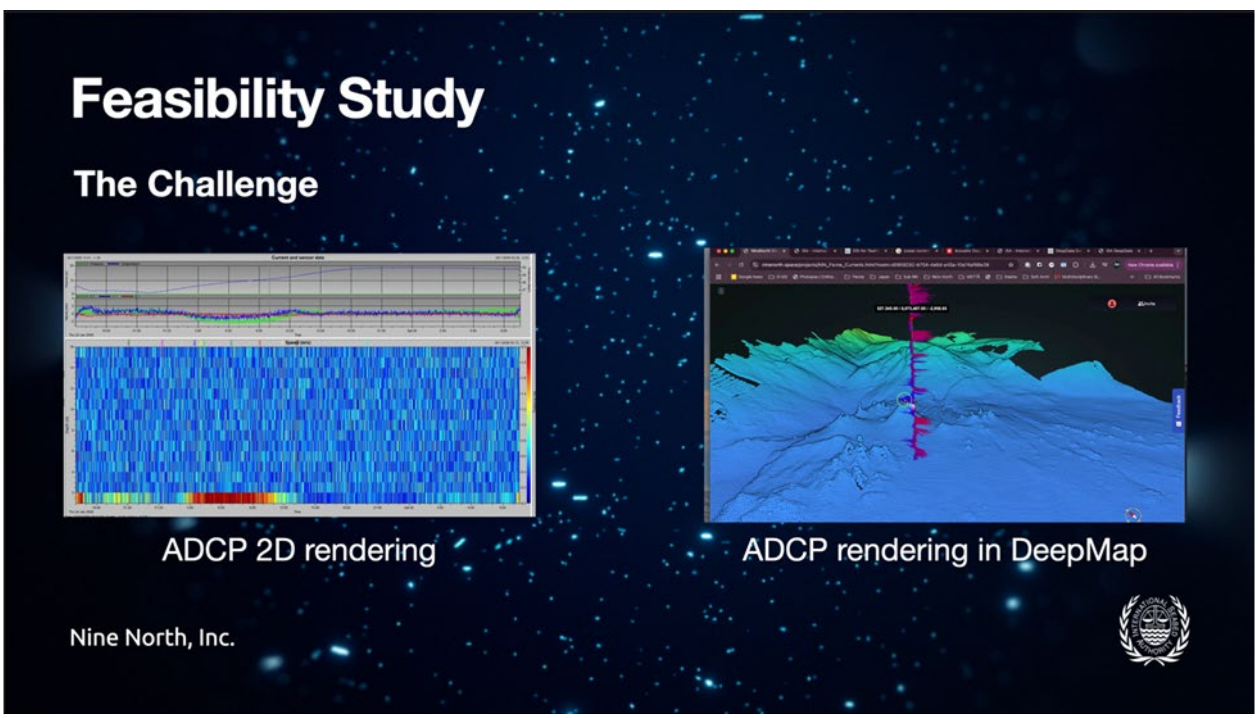

Figure 4: Extract from the ISA 2025 feasibility study. Same data, rendered in 2D and 3D in DeepMap.

3. Conclusion: From Data to engaging stories

Our vision is to transform environmental data from an overwhelming mass into a coherent, compelling story that connects stakeholders, motivates action, and informs sustainable management of our planet's oceans. Through human-centered design, advanced visualization, contextual integration, and collaborative sharing via our web-based platform, Nine North is illuminating the unseen and empowering action. During our presentation, we will delve into these principles, showcase real-world applications including our work with the International Seabed Authority and the Titanic wrecksite, and invite participants to engage with our vision of Ocean Intelligence. Time permitting, we also propose demonstrating these tools during workshop breaks, offering participants a hands-on glimpse into how collaborative data visualization is transforming our understanding of complex marine environments.

(iv) Haiyan Yang (BPHTDC, China): *Monitoring Program under Low-Disturbance Polymetallic Nodule Collecting Condition*.

The Beijing Pioneer High-tech Development Co., Ltd. (hereinafter referred to as "Beijing Pioneer Company (BPC)") signed a fifteen-year polymetallic nodule exploration contract with the International Seabed Authority (hereinafter referred to as the "ISA") in 2019. The contract area is located in the western Pacific and consists of four blocks totaling 74,052 km2 (Figure 1). According to the contract, BPC is required to complete the verification test and environmental monitoring of key mining technologies in the contract area during the first five-year period of the exploration stage, and assess the environmental impact based on the test and environmental monitoring data.

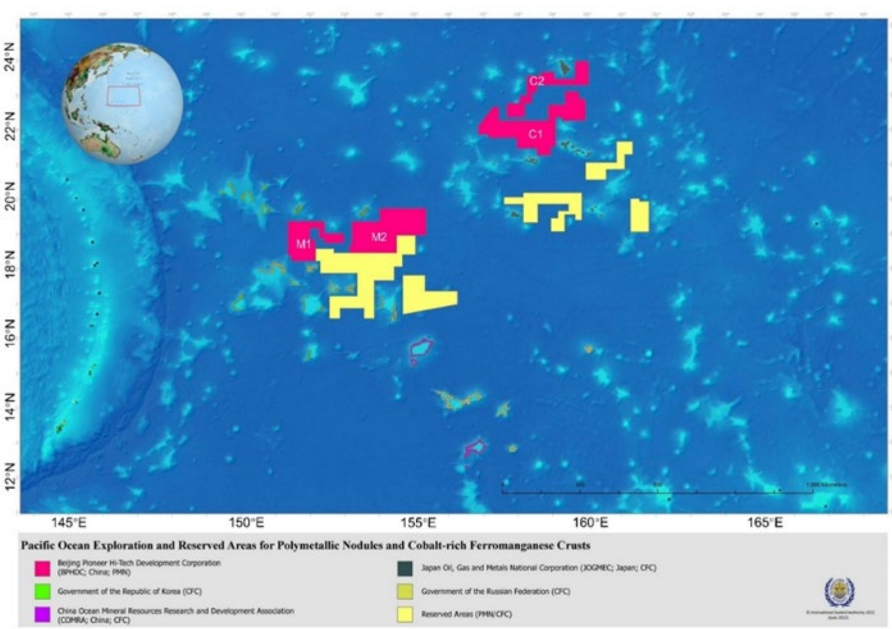

Figure 1 Location of the polymetallic nodule contract area of the BPC
(Source: https://www.isa.org.jm/maps/clarion-clipperton-fracture-zone-2/)

According to the concept of "research-oriented exploitation", this project plans to conduct a 1:5 scale polymetallic nodule deep-sea collection with buffer station joint test in a 500 m × 500 m area in 2025 to verify the reliability of the suspended collection method with the buffer station joint, while carrying out long-term environmental impact monitoring and assessment.

BPC has carried out five cruises about resource and environmental surveys in blocks M1 and M2 since 2021, and prepared the Environmental Impact Statement – Joint Test of Deep-sea Miner and Buffer Station in Beijing Pioneer Polymetallic Nodule Contract Area, Western Pacific in accordance with the Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area (ISBA/25/LTC/6/Rev.3).

Based on the environmental baseline data collected previously and the environmental monitoring data collected before, during, and after the test, the environmental impact assessment of the test will be carried out. Relying on the field observational data and results of high-resolution regional plume model.

When carrying out the practice of deep-sea collection and buffer station joint test, taking into account the low disturbance of the collector and the complex changes in the bottom current in the test area, the monitoring equipment faces many challenges in the monitoring program, and BPC has adopted a series of specific measures to solve the problem:

(1) According to the collection mode and the characteristics of the sensor, the plume generated by the low-disturbance collection is relatively weak. The monitoring stations should be deployed as close as possible to the center of the test area, in order to accurately capture the plume spreading caused by the nodule collection.

(2) The bottom current in the test area appears to be complex and variable, and the uncertainty of the current direction and current speed poses a serious challenge to the spatial layout of the monitoring equipment. BPC set up turbidimeter monitoring nodes in multiple directions 100~500 meters away from the center of test area, and at the same time, determine the deployment of fan-shaped monitoring system to adapt to the changes in bottom current direction, and build up an all-round and multi-angle monitoring program.

(3) The monitoring equipments deployed in the test area are in close proximity to each other, and the accurate positioning of the underwater monitoring equipments has become an important part. Within the near-field of the operation area, there are many different types of observation nodes and monitoring stations, up to more than 20, including turbidity / current meter / ADCP monitoring stations, 20m/50m submersible buoys, benthic plume redeposition and biological observation nodes, and other types of monitoring equipment. The "Manta I" ROV will be used for efficient deployment of small monitoring equipment. Meanwhile, BPC has designed a frame-based heavy-load deployment system (Figure 2). The system is able to meet the needs for deploying different types of monitoring stations and improve efficiency that multiple sets of monitoring stations can be deployed in one launch.

(4) Traditional fixed-point monitoring of the benthic communities in the test area and the surrounding areas may result in sampling bias. BPC plans to conduct near-bottom optical surveys in the test area and plume-affected areas before and after the test by using the "DONGCHA" AUV. The high-resolution seabed images obtained will be used to assess the changes in diversity and abundance of megabenthos as well as changes in substrate before and after test mining.

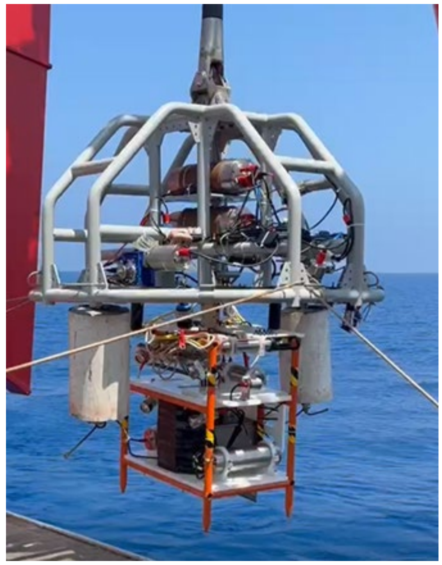

Figure 2 Heavy-load deployment system

Agenda Item 4: Data Handling and Communication

(i) Susumu Takatsuka (Sony, Japan): ***High-Precision Direct Observation of Particles on the Seafloor Using an Event-based Vision Sensor (EVS)***

We propose a novel technique for the direct observation of marine particles using an industrial sensor, the Event-based Vision Sensor (EVS), originally developed as a "visual system" for factory automation robots. With an ultra-high temporal resolution equivalent to 10,000 frames per second, EVS enables precise measurement of the number, size, and motion of particles drifting in seawater. By distinguishing between biological particles such as plankton and non-biological particles such as sand and detritus, the system allows for the spatial estimation of biomass.

This technology enables in situ monitoring without the need for water sampling and is expected to serve as an efficient tool for environmental impact assessments. Leveraging the compact and low-power nature of EVS, we envision future integration into floating drones, seafloor observatories, and ICT-enabled buoys.

(ii) Hina Muranaka (NEC Networks & System Integration Corp., Japan): ***Seafloor earthquake and tsunami observation system for issuing Earthquake Early Warnings and clarifying earthquake mechanisms.***

The Japanese islands have suffered devastating damage from earthquakes and tsunamis over their history. We have developed cable-type earthquake and tsunami observation systems to address these phenomena. These systems, which consists of multiple sensors such as seismometers and tsunami gauges, have made it possible to improve the accuracy of earthquake observation, provides early warning to prevent expected damage, and enables the continuous study of earthquake mechanisms. The 20 systems we developed have never broken down throughout their lifetime and are still in operation today. In this workshop presentation, we will introduce an overview of these systems and the technology behind them.

Earthquakes are frequent in Japan for long time ago because Japan is located on the border of 4 major tectonic plates. Although the land area of Japan is just 0.3% of the entire world, about 20% of earthquakes over magnitude 6 has occurred in Japan. Small earthquakes do not have a heavy impact, however large earthquakes cause a lot of damage such as buildings collapsing and tsunamis. The Great East Japan

Earthquake in 2011 and the Noto Peninsula Earthquake in 2024 caused extensive damage particularly in Japan.

1. Cable-type Observation Systems

We have developed cable-type observation systems for earthquakes and tsunamis since 1979 to prevent damage from these disasters (Fig.1). The strength of these systems is they stably operate over a long period of time. Some of these systems have been in operation for over 40 years.

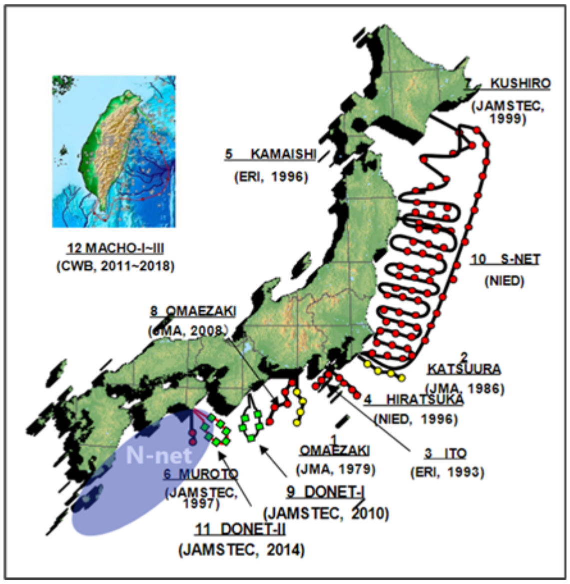

Fig.1 Cable-type observation systems locations

Observation systems in the ocean are generally configured using one of three methods (Fig.2). The inline type is used in S-net, the installation can be completed all at once by connecting the observation devices in a daisy chain. The node type is used in DONET, it has excellent scalability by utilizing nodes. There is also a hybrid type that combines these characteristics, which was first used for N-net in March 2025. Each type has been in operation since its construction without any interruptions.

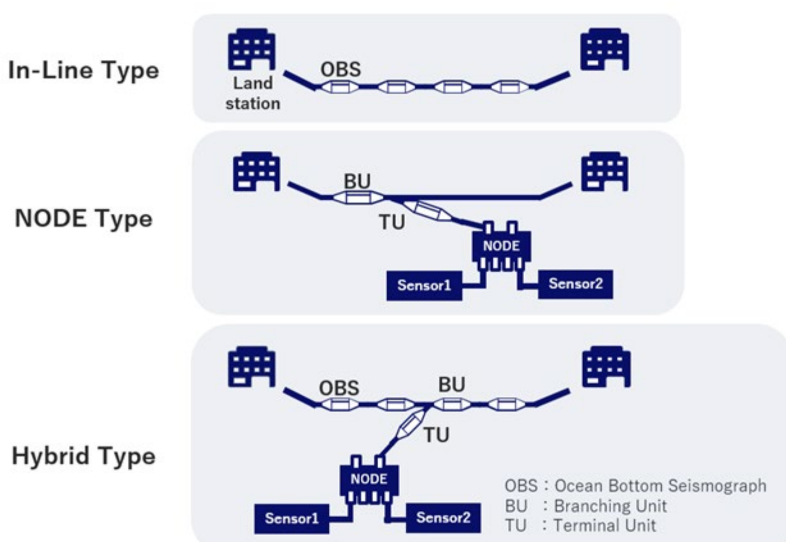

Fig.2 Three methods of the system

The observed data has been sending to several ministries and research institutes. The data is used for issuing "Earthquake Early Warning" and analyzing the mechanism of earthquake occurrence. Therefore, observation systems are very important systems for keeping us safe.

2. Conclusion

Observation systems for earthquakes and tsunamis will continue to be a part of social infrastructure around Japan. It's also thought the system will be necessary in areas around the world where large earthquakes are expected. It will be possible to detect and predict earthquakes and tsunamis more quickly by elucidating the mechanisms of earthquakes through observation data. Consequently, we expect to mitigate the damage caused by these disasters. We remain committed to contributing to the development and maintenance of observation systems.

(iii) Curtis Lee (QYSEA Technology, China): *Intelligent Underwater Drones for Seabed Monitoring, Water Quality Assessment, and Infrastructure Inspection*

QYSEA Technology is pioneering next-generation intelligent underwater robotics with its FIFISH ROVs, engineered for diverse marine operations including seabed monitoring, water quality assessment, and infrastructure inspection. Powered by advanced AI-driven path planning and autonomous routines, FIFISH Underwater Robots enable precise navigation and station keeping in complex underwater environments — even within cluttered or high-risk subsea zones.

The compact ROV's real-time multi-sensor data collection capabilities provide comprehensive environmental and structural insights. Modular integration of tools such as smart measurement systems, water samplers, and robotic arm manipulators allows operators to perform specialized tasks with accuracy and efficiency. Designed with a compact footprint, FIFISH ROVs offer flexibility in deployment from a variety of platforms, from small vessels to fixed structures, while minimizing the challenges of umbilical management during operations.

Ideal for servicing subsea infrastructure such as moorings, landers, pipelines, and mining units, QYSEA's solutions combine intelligent control with rugged adaptability — minimizing human risks while delivering safer, faster, and more data-rich outcomes across ocean industries.

Agenda Item 5: Compilation of Thematic Discussion for Relevance and Priorities in Marine Monitoring, Data Handling and Communication

(To be compiled during the workshop based on participants' discussion.)

Agenda Item 6: Introduction of KOBEC Research Activities

(i) Hiroko Sugioka, Tokihiro Katsui, Jun-ichiro Ishibashi (Kobe Ocean-Bottom Exploration Center, Japan): *Introduction of activities of KOBEC*

Kobe Ocean-bottom Exploration Center (KOBEC) was established in October 2015 as the fundamental research promotion organization, aiming at forming of marine education and research base located in international port city, Kobe. Our present main activities include advanced sea bottom explorations using our T/V Kaijin Maru, promotion of international ocean science programs such as The International Ocean

Drilling Programme (IODP3), and joint researches with other institutions such as JOGMEC, JAMSTEC, AIST, Univ Tokyo.

KOBEC has six divisions to cover various fields related to marine education and research. Ship Operation and Exploration Management Group engages in planning and implementation of shipping schedule of sea area exploration by using T/V Kaijin Maru, and conducts of ocean-bottom exploration practical program including basic observation methods. As one of recent activities, the source region of Noto-Hanto earthquake was investigated.

Marine Engineering Group contributes to develop fundamental technologies for underwater vehicles and sea bottom drilling. As one of on-going developments, application of the bilateral control technologies to the ROV's manipulator is undertaken.

Marine Geophysics Group conducts research and education on the ocean floor and the underlying crust and mantle, through investigating the Earth's interior by collaborative research project with other institutions, and in parallel with developing new instruments and methods.

Submarine Volcanology Group aims to understand mechanisms of magmatic and volcanic activities in submarine volcanoes applying geological, petrological, and geochemical methods. As the on-going research project targeted at Kikai submarine caldera volcano located in southwest Japan, aspects of submarine gigantic volcanic activities have been revealed, such as recognition of submarine giant lava dome, an evolution model of magma plumbing system and analysis of transportation and deposition of pyroclastic flows.

Active Structural Geology Group performs research and education in geology and engineering related to geohazards along the subduction zone. Especially, participation in ocean drilling expeditions has promoted the achievements.

Marine Economic Geology Group aims for implementation of education and research regarding marine mineral resources. Discussion on favorable geologic environment for ore genesis of hydrothermal deposits has contributed to design of effective geophysical exploration.

Agenda Item 7: Technical Requirements for Plume Detection and Measurements

(i) Thomas Peacock & Souha El Mousadik (MIT, United States): ***Monitoring and Modeling Deep-Sea Nodule Mining: Lessons from Recent Collector Trials in the CCZ***

Recent pre-prototype nodule collector trials in the Clarion-Clipperton Zone have provided unprecedented insights into the complex dynamics of deep-sea mining sediment plumes, revealing the need for advanced monitoring and modeling approaches. Our comprehensive field studies demonstrate that plume evolution involves multiple phases - from initial turbidity current formation to far-field passive transport - each governed by distinct physical processes operating across vastly different scales.

Key findings from these trials highlight critical technological advances essential for accurate plume assessment: (1) the LISST-RTSSV sensor's capability for real-time, in-situ measurement of particle size distributions and settling velocities, eliminating artifacts from conventional ex-situ sampling; (2) the importance of high-resolution turbulence measurements for properly parameterizing vertical mixing processes controlling sediment suspension and deposition patterns; and (3) multi-scale simulations capable of resolving turbulence and non-hydrostatic processes in the near field, from collector-wake dynamics to gravity current propagation over hundreds of meters.

These scientific breakthroughs are being translated into operational tools through next-generation Ocean Digital Twin platforms that integrate monitoring and modeling frameworks validated against field observations. This research-to-implementation approach enables adaptive management strategies that can respond to real-time plume dynamics, directly supporting the International Seabed Authority's development of science-based regulatory frameworks for commercial-scale operations with robust environmental oversight and quantitative risk assessment capabilities.

(ii) Yasuo Furushima (JAMSTEC, Japan), Masayuki Nagao (Geological Survey of Japan), Mamoru Tanaka (Tokyo University): ***In-situ Measurements and Estimation Method for Turbulence Intensity (Turbulent Kinetic Energy Dissipation Rate) Near the Deep-Sea Floor.***

In deep-sea mining, turbid water (plume) generated during the drilling and ore lifting processes causes diffusion and re-sedimentation of suspended particles. These phenomena are feared to have negative effects on the environment around the development area. To evaluate these impacts, it is important to understand the mixing environment near the deep seafloor. Therefore, it is essential not only to grasp the average flow near the seafloor using flow meters such as ADCP (Acoustic Doppler Current Profiler), but also to understand the dynamics of vertical mixing (turbulent mixing).

The environmental impact assessment guidelines for deep-sea mining published by the International Seabed Authority (ISA) in 2013 recommend conducting baseline surveys covering physical, chemical, biological, and geological observations. In addition, a review published in 2020 pointed out the need to quantify turbulence and vertical eddy diffusivity throughout the entire water column.

In recent years, the Expendable Vertical Microstructure Profiler (VMP-X), capable of measuring turbulence from the ocean surface to just above the deep-sea floor, was developed by Rockland Scientific International Inc. and JFE Advantech Co., Ltd. The VMP-X has enabled direct measurements of turbulence (turbulent kinetic energy dissipation rate = turbulence intensity) near the seafloor, which had previously been difficult to obtain.

We have been continuously acquiring baseline data on turbulence near the deep-sea floor using the VMP-X and have obtained interesting results. However, vertical mixing near the seafloor fluctuates with significant variability due to ocean currents and complex bottom topography, and a single turbulence observation is generally not representative over time. Therefore, multiple observations at the same location are recommended, however, there remain issues, as turbulence measurements impose substantial operational and financial burdens.

To address this issue, we developed a method for estimating turbulence intensity near the deep-sea floor using turbulence data obtained from the VMP-X and flow measurements from a high-resolution Acoustic Doppler Velocimeter (ADV, NORTEK AS). This method enables us to capture temporal variations in turbulence intensity that were previously only available from single-point measurements. The method has been patented in Japan (Patent Application No. 2021-140907).

This workshop presents in-situ measurements of turbulence using VMP-X, as well as the temporal characteristics of turbulence intensity near the seafloor based on an estimation method.

(iii) Scott Loranger (Kongsberg, Norway): ***Acoustic Measurements of Suspended Sediment to Assess Potential Environmental Impacts from Deep Sea Mineral Extraction***

One of the chief concerns of deep-sea mineral extraction is the impact that the extraction process will have on marine ecosystems, especially abyssal plain and mesopelagic communities. These ecosystems have been difficult to access for most of human history, and our lack of understanding comes from a paucity of information about species themselves, their interconnections, and the resilience of these communities to disturbance and change. To fully realize the potential environmental impacts of deep sea mineral extraction, and to develop methods that mitigate those potential impacts, it is necessary to harness emerging technologies that are deployable to abyssal depths.

One potentially significant environmental impact will be from the suspension of seafloor sediment into the water column. Extraction methods have been proposed that would release sediment both at the extraction site as well as in the midwater water column. This movement of sediment may disrupt abyssal benthic and mesopelagic communities. The degree of disturbance is likely to be directly related to the density of sediment released in those communities, as well as the area over which the sediment is released. To assess how sediment flux influences these environments, it is essential to obtain accurate and reliable data on the sediment's density and particle size across large areas.

The most common methods for detecting and quantifying sediment in the marine environment are point measurements, such as turbidity meters and laser transmissometers. These methods work well to determine the sediment concentrations at the measurement site, but extending those measurements to cover wider regions requires considerable interpolation, which in turn leads to considerable uncertainty. Broadband acoustic backscatter has proven effective in detecting marine sediment, distinguishing marine sediment from other scatterers in the water column, and quantifying sediment density. To quantify marine sediment acoustically it is imperative to understand how sound interacts with sediment particles. Broadband acoustic quantification depends on high-resolution backscatter data combined with validated, physics-based models of sediment scattering. Acoustic methods, unlike point measurements, can cover extensive areas in a single sample, including covering the entire water column at specific frequencies.

Deep sea mineral extraction is a rapidly developing technology, and the environmental monitoring solutions for this technology need to be easily adopted, and ready to evolve as extraction technology evolves. Identification and quantification of targets with broadband acoustic backscatter is an established methodology, with readily available off-the-shelf instrumentation. Broadband backscatter is an established methodology for identifying and quantifying fish, plankton, bubbles, oil droplets, physical oceanographic processes, and seafloor morphology. The expansive application of this technology lends itself to easy adoption in new environments, such as deep-sea mineral extraction.

This presentation will explore the current state of acoustic methods for identifying and quantifying marine sediment and will discuss how broadband acoustic backscatter can assess the environmental impacts of seabed critical mineral extraction. Accurate and dependable sediment flux measurements from these extraction activities can guide the development of extraction methods that minimize environmental impacts. Understanding the characteristics of the sediment introduced into the water column will enable sea floor extraction methods to evolve to limit the potential negative impacts of sediment suspension.

Agenda Item 7: Technical Requirements (Stationary, Mobile)

(iv) **José Miguel Almeida, Alfredo Martins, Betina Neves, Eduardo Silva, Carlos Almeida (INESCTEC, Portugal):** ***PETRA: Innovative Robotics for Deploy/Recover and Monitoring in the Deep Sea for "Shipless" Operations***

This presentation will share, for the first time, the innovative new robot that is underway. How will PETRA address the problems around monitoring infrastructure, and how different and new is this approach in terms of deep-sea monitoring? It will not unveil the pending patents but still lift part of the veil so carefully placed on the ongoing work. The presentation will explain the operations in the deep sea with PETRA, the data mulling, the energy charging and, most of all, deployment and recovery of assets.

It will progress with seabed nodes and underwater base station elements, highlighting the unique, distinctive characteristics and low environmental impact operations, sharing some more on operations' modes and phases.

Finally, a short provocation (or not) on extra services that can be provided in terms of support for mining operations.

(v) Berit Floor Lund (Kongsberg, Norway): ***Machine Learning for Interpretation of Hydroacoustic Data Streams, Real-Time and Post Processing***

Kongsberg Discovery is a technology company within the Kongsberg Group developing and delivering advanced sensors, positioning and communication technologies applied for underwater exploration and deep-sea operations. Multibeam echo sounders for seabed mapping are delivered for all ocean depths. Also, scientific echo sounders are delivered for water column monitoring and fish stock assessment. Kongsberg Discovery produces several types of HUGIN Autonomous Underwater Vehicles (AUVs) with depth rating from 1000m to 6000m, and with endurance from 24 hours to 15 days, depending on battery capacity. The HUGIN AUVs are first and foremost sensor carriers for detailed seabed mapping and water column monitoring.

The presentation will give a brief overview of the sensor technologies, the AUVs and their integrated sensors. The focus of the presentation will however mainly be on the processing of seabed data, and challenges and approaches to data harvesting, and interpretation of these seabed data both real-time and post mission. Interpretation of seabed data involves a wide range of signal processing, machine learning techniques and AI methods, but domain expertise is crucial in all parts of the data harvesting, processing and interpretation chain. Relevant examples will be presented.

KONGSBERG

Kongsberg Discovery AS
kongsberg.com/discovery

(vi) Hiroyuki Yamamoto, Tetsuya Miwa (JAMSTEC, Japan): ***Monitoring System and Technical Story of Edokko Mark-I.*** **<u>(Poster Presentation)</u>**

Agenda Item 8: Monitoring of Activities on Different Marine Minerals (Polymetallic Nodules, Polymetallic Sulphides and Cobalt-rich Ferromanganese Crusts: Surface, Mid-Water and Seabed)

(i) Dhugal Lindsay (Deep Ocean Stewardship Initiative [DOSI], JAMSTEC), Mehul Sangekar (University of Tokyo, JAMSTEC), Ariell Friedman (Greybits Engineering): ***Leveraging AI for Image-Based Monitoring of Pelagic Communities***

Pelagic communities are comprised of a bewildering diversity of taxa, many of which are gelatinous and unable to be sampled using nets. Image-based surveys using remotely operated vehicles (ROVs) outfitted with "plankton cameras" can capture data on both the larger fauna, using the ROV's video camera, and the larval stages and other smaller plankton that can be very abundant but are not resolvable with the camera resolution and illumination regime of the ROV. In largely unknown and understudied regions such as the Clarion-Clipperton Zone (CCZ), baseline surveys are necessarily discovery-based, with labour-intensive, manual analyses of the images to identify, count and characterize the fauna. Annotation of videos and other images using an online tool linked to a database allows exemplar images of each taxon to be harvested for machine learning training data. AI-based systems that can both help and force-standardize human annotations are a pre-requisite for any monitoring activities, especially if the images used for monitoring will be analyzed in (near) real time to react to pertubations so mitigating action can be taken, enabling stewardship. A seamless and integrated workflow that incorporates quantitative in situ imaging systems and post-deployment analysis tools will be introduced.

(ii) Akira Tsune (DORD, Japan): ***Application of monitoring technologies to polymetallic nodules' exploration activities and the technical transfer***

The technologies used by contractors in environmental baseline surveys are expected to be applicable to future environmental monitoring efforts as well. However, contractors are not developers but rather users of monitoring technologies, and they depend heavily on external partners for the necessary equipment and technical expertise. Conducting such surveys requires collaboration with multiple organizations, making technology transfer a complex process. In addition, the unique characteristics of the survey environment, such as deep-sea conditions and remote offshore locations, further complicate technology transfer efforts. On the other hand, contractors may be able to contribute in ways that do not rely on equipment, such as by sharing practical knowledge gained in the field or providing training in data analysis. Furthermore, once we are in the exploitation phase, monitoring is expected to become more routine, establishing a more stable and practical foundation for sustained technology transfer.

(iii)* Hiroko Kamoshida (JOGMEC, Japan):** ***Environmental Monitoring and Simulation: Knowledge-Gap and Assignments

JOGMEC, an ISA contractor, is focusing on the potential value of mineral resources in the area not only cobalt-rich ferromanganese crust seamounts in the Northwest Pacific Ocean, but also seabed mineral resources within the EEZ. The organization is working to achieve both resource development and environmental conservation, and has been conducting ongoing surveys, including environmental baseline surveys. However, there are various challenges, such as the fact that the information obtained from a single survey is geographically localized, questions about the representativeness of the data, and gaps between our limited knowledge and the desired broad understanding of the environment.
Given those backgrounds, the present author introduces one of the results of larval network for the conservation of habitat of sessile organisms on seamounts. We conducted larval dispersal simulations for 18 seamounts around the exploration block and found that all seamounts are interconnected through a network. Furthermore, these networks was generally consistent with physical verification based on the trajectories of ARGO floats.
However, there are also several assignments. The measures considered to solve these problems are listed below. Regarding the challenge that the complexity of flow conditions due to changes in terrain is not fully reflected in particle behavior model, would the use of larval-sized tracers help advance our understanding? Regarding the issue that particle movement calculations between seamounts are two-

dimensional, could this be resolved by using three-dimensional data? Furthermore, regarding the issue of insufficient information on larvae in the target area, could data be collected through high-resolution camera observations or larval traps? We look forward to discussions at this workshop and further advancements in environmental observation technology in the future.

(iv) Fadhili Malesa (BAS Cambridge, UK): ***Modelling of Sediment Plumes from Deep Sea Mining: Current Approach and Future Direction***

The modelling of sediment plumes has evolved over time to quantify the degree of dispersion, and their impacts associated with deep-sea mining activities. Recent studies and reports show that it is possible to measure and monitor sediment plumes in deep sea, both benthic and mid water plumes.

This research offers a preliminary observation to address the critical need for precise monitoring and predictive tools. We developed and applied a sediment plume model that incorporates real-world bathymetry, ocean current data, and sediment characteristics from ISA contractors' datasets in the CCZ to model and understand the plumes dispersion in the area. This simple model would help to deepen our understanding of how sediment plumes interact with the ocean floor for more accurate predictions of plume dispersion, which is crucial for monitoring and the management intervention.

1. Objectives and Methodological Approach

The overall aim is to improve the current understanding of sediment plume dispersions from deep-sea mining operations through the integration of high-resolution bathymetric data, ADCP-derived current profiles, and particle size-dependent settling behavior.

Specific objectives were:

(i) To map and analyze how seabed topography influences sediment plume dispersion; to simulate both benthic plumes using an advection-diffusion-settling framework; and

(ii) To assess the sensitivity of plume dispersion to particle size, initial concentration, and current variability.

61. Key Findings

Bathymetric features were found to significantly constrain plume elevation and direction. In flat terrain areas (NORI bathymetry), plumes remained within 10–15 m of the seabed and dispersed horizontally <3 km. In contrast, rough terrain (BGR data) influenced both plume elevation and confinement, leading to localized accumulation or deflection by ridges and valleys.

Large particles (>100 µm, settling velocity ~ 0.5 mm/s) settled rapidly within 1-2 km from the source, confirming near-field deposition. Fine particles (<10 µm, settling velocity ~ 0.01 mm/s) were transported over far-field distances, especially under variable current conditions. This suggests far-reaching ecological impacts for vulnerable benthic and midwater ecosystems.

Current directions derived from ADCP moorings revealed bidirectional flows and mesoscale eddy influence. The model simulations showed that even in relatively flat topography, minor bathymetric gradients created directional biases, leading to plumes accumulation in some areas and shielding in others. These interactions can potentially affect long-term sedimentation footprints.

Implications for Monitoring and Regulation

(i) The study revealed significant uncertainties in understanding the far-field effects of sediment plumes, particularly their travel distance and concentration. This is due to poorly characterized initial conditions and the need for long-term monitoring of plume evolution.

(ii) In the far field, sediment plumes act as passive tracers, carried by ocean currents, dispersed by turbulence, and settling under gravity. Due to low turbulent mixing in the deep ocean, plumes can stay narrow and travel long distances.

(iii) Design a monitoring program that quantifies and models the plume impact footprint for robust assessment of full-scale polymetallic nodule extraction is required. This program should include real-time current measurements or long-term data to forecast plume patterns.

(iv) Advanced modeling and technologies should support targeted mitigation strategies, such as controlling sediment particle size, optimizing discharge locations, and implementing robust monitoring systems for near-field and far-field plume behavior. These measures are crucial for minimizing the ecological footprint of deep-sea mining and protecting vulnerable marine biodiversity.

62. Future Directions

There is a need for coordinated, long-term monitoring programs to validate plume models and account for seasonal and interannual variability. Future research should include experimental validation of flocculation and settling under different plume concentrations. Moreover, deployment of real-time sensor arrays across bathymetric gradients; and asses the biological impact thresholds in sedimented zones are crucial.

(v) **Georgios Salavasidis (NOC, UK):** ***Novel Sensing and Autonomous Platforms for Deep-Sea Mining Impact Monitoring***

The National Oceanography Centre (NOC) in the UK is advancing environmental monitoring of deep-sea mining through the development of cutting-edge autonomous platforms and novel sensing technologies. Building on decades of expertise, NOC's Marine Autonomous and Robotic Systems (MARS) team has developed a large and versatile fleet of Autonomous Underwater Vehicles (AUVs), including the ultra-endurance Autosub Long Range (ALR) series. These vehicles are capable of operating at depths of up to 6000 metres for multi-month deployments with minimal to no human supervision. Recent trials with the ALR demonstrated shore-based deployment and multi-week, over-the-horizon piloting, offering new opportunities for remote data collection and impact monitoring in challenging environments.

Complementing these platforms, NOC's Ocean Technology and Engineering (OTE) group is developing novel ocean sensors tailored for deep-sea impact studies. Key new technologies include high-precision, low-drift pH sensors based on microfluidic lab-on-chip systems, Eh sensors for monitoring redox potential, and sensors to measure sediment deposition rates. The pH and Eh sensors are deployable on mobile platforms such as ALRs, while the sediment deposition sensors can be fixed to the seabed or integrated into lander systems for longer-term monitoring.

These innovations are being advanced as part of NOC's participation in the Horizon Europe TRIDENT project, which aims to establish a comprehensive environmental impact assessment framework for deep-sea exploration and mining. Within TRIDENT, NOC is developing intelligent, multi-AUV adaptive sampling strategies for real-time sediment plume detection and monitoring, enhanced by developed chemical and physical sensing technology. These capabilities are further augmented by static sensing infrastructure in the far-field of the affected area, such as the sediment deposition plates, supporting a persistent and high-resolution underwater monitoring network.

This presentation will outline NOC's research and developments around deep-sea sediment plume characterisation using adaptive sampling on ALRs and advanced sensing.

Agenda Item 9: Compilation of Thematic Discussion for Technical Requirements for the Monitoring of Activities on Different Marine Minerals

(To be compiled during the workshop based on participants' discussion.)

Agenda Item 10: Monitoring Schemes & Data Reporting

(i) Kanae Komaki (Chowa Giken Cooperation, Japan): ***AI-Supported Structural Review of Deep-Sea Environmental Monitoring Reports: A Conceptual Framework***

This presentation introduces a conceptual framework for applying structure-aware AI to assist institutional review processes in deep-sea environmental monitoring under the ISA framework.

In the context of environmental governance by the International Seabed Authority (ISA), contractor reports and monitoring data play a critical role in regulatory decisions. However, the increasing volume and complexity of these reports pose growing challenges to the consistency, transparency, and traceability of institutional evaluation.

To address this, the proposed framework explores the use of structure-aware generative AI—particularly autonomous agents—to support the structural review of contractor reports. The goal is not to replace human reviewers, but to assist reviewers in identifying missing elements, inconsistencies, and structural deficiencies within monitoring submissions.

Drawing from over a decade of experience in deep-sea observation and recent work in applied AI, this conceptual framework proposes the use of large language models (LLMs) in combination with scientific data processing scripts to explore how monitoring documents might be parsed, raw data compared with descriptive claims, and structured evaluations generated. Hypothetically, such a pre-evaluation step could help identify potentially omitted or underreported regulatory parameters, vague or contradictory statements, and generate traceable summaries that may support internal review workflows within ISA. It may also assist in assessing inconsistencies in scientific deep-sea data.

While still in a proof-of-concept phase, this presentation outlines how such a framework can conceptually be applied to deep-sea datasets, and how AI might support a more transparent evaluation process. Ultimately, this presentation aims to open discussion on the potential of AI as a structural assessment tool—not as a definitive solution, but as an exploratory contribution toward improving accountability and reproducibility in the review process.

(ii) Matthias Haeckel (GEOMAR, Germany): ***Mining Impact, DISCOL, Monitoring of the Patania-II Trials, and the Ongoing Threshold Discussions***

My presentation will give an overview on the monitoring programme conducted by the MiningImpact project in connection with the Patania-II trials, including main results and how this can be transferred into a monitoring plan for industrial mining operations considering the safeguarding of threshold values to prevent serious harm to the environment.

(iii) Timoteo Badalotti (ABS, United States): ***MRV (Monitoring, Reporting, and Verification) – The Role of Class Society.***

In marine and offshore applications, Regulatory Agencies are moving towards real or near real time data collection from operators to ensure compliance. The older systems of on-site monitoring, random spot checks and annual auditing still have their place in a regulatory regime, however the trend is to back up these traditional methods with remote monitoring.

With that said, how can the regulators ensure that the streamed data they are receiving from the operators are accurate, reliable, and verifiable?

As the leading offshore classification society, ABS has been in the forefront of this issue for more than a decade. With the publication of Rules and Guides such as Guidance Notes on Verification and Validation of Models, Simulations, and Digital Twins; we offer both contactors and regulators the assurance that the data that is used for regulatory compliance is solid and accurate. Now with DSM (deepsea mining) as the focus, the systems and methodologies we currently employ in the marine and offshore fields, can and will be used to bolster a safe and compliant new industry.

(iv) Jens Laugesen (DNV, Norway): ***Environmental Monitoring of Seabed Activities – how can this be done correctly and at the same time within acceptable economic constraints*?**

Seabed activities related to deep sea minerals will normally take place at large distances from land. Such large distances make remote monitoring systems suitable for monitoring deep sea minerals activities.
In 2021 ISA published the technical study no. 29, "Remote monitoring systems in support of inspection and compliance in the Area" authored by DNV. In this publication several types of remote monitoring are suggested, such as satellites, drones, sensors and lander systems.

Important questions are: what is needed to be able to do an efficient and correct environmental remote monitoring, while at the same time operating within acceptable economic constraints?
DNV has recommended to ISA that:

- Environmental data should be collected by the Contractor, the Contractor would be operating the various sensors, and transmit the required data to ISA by satellite.
- For regular checks of the Contractor or upon suspicion of irregularities, ISA could use satellite imagery to provide information on oil spills and may also provide information on particle spills on the sea surface.
- Raw data collected by the Contractor is processed at the mining site before it is transmitted to ISA. This would reduce the amount of data transmitted to ISA. The Contractor should be required to store key raw data in agreement with ISA, to allow for assessment of the data by ISA inspectors.
- The data collection, processing, transmission and storage would be protected/encrypted to avoid tampering.

The suggested solution leaves most of the work and costs to the Contractor while ISA still will have the possibility to remotely monitor the activities and control the monitoring data. The alternative would be that ISA will have more of the responsibility for performing the environmental monitoring, but that would result in much higher costs for ISA.

(v) João Carvalho (Deep Focus, Portugal): *Application of Machine Learning for Deep-Sea Mineral Resource Assessment and Habitat Mapping and Monitoring: Challenges and Opportunities.*

AI-powered technological solutions and the proliferation of easily accessible machine learning (ML) algorithms and tools are changing all daily aspects of our lives. Ocean research and monitoring is no exception. In recent years, with the recent developments in satellite remote sensing and advanced robotics, existing AI and ML tools are being applied to visualize and process marine life and environment information, monitor marine biodiversity, detect changes in the oceans' health, model ocean parameters, and map and assess seabed mineral resources.

However, despite the huge potential the use of ML in ocean research and monitoring applications is challenging and runs the risk of developing models based on limited training datasets, with sparse geographical and temporal sampling and or with an incomplete representation of the real data dimensionality, thereby constructing over-fitted or non-generalized algorithms. These models may perform poorly in new regimes or on new, anomalous phenomena that emerge due to changing conditions. One way to mitigate these issues is to define the problem to be solved and implement a strategy and methodology that integrates data from multiple sources and a ML workflow that enables the use, combination, and evaluation of different ML techniques. ML models evaluation and uncertainty quantification are challenging, especially in ocean environments and geo and bioscience applications.

We will share some of the challenges and strategies for mitigating these issues by presenting ML application examples related to seafloor mineral resource assessment, habitat mapping, and ocean monitoring, and provide some considerations in terms of understanding and evaluating ML models' robustness.

Agenda Item 11: Monitoring Assessment – Workshop Summary

(To be compiled during the workshop based on participants' discussion)

Agenda Item 12: Plenary Session: Open Discussion and Consolidation of Future Steps Towards Technical and Environmental Monitoring

(To be compiled during the workshop based on participants' discussion)

Agenda Item 13: Closure of the Workshop

Agenda Item 14: Port of Kobe Cruise, Kobe Maritime Museum: A Journey Through Kobe's Maritime History and Future