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A Dual ADCP-SMS Mooring System Survives Incredible Odds in the Pacific Ocean, an Eight Year Journey

Rick Cole (RDSEA International, USA)

RDSEA International, Inc. (RDSEA) (St. Pete Beach, Florida) was engaged by the seafloor mining community back in 2012 in support of site environmental impact studies (EIS) of a specific region of the deep-ocean for Seafloor Massive Sulfides (SMS) extraction at a later date in time. RDESA is an oceanographic and ocean engineering consulting company that provides physical oceanographic data and support to the national and international oceanographic, engineering, and offshore energy communities worldwide.

Deep-sea mineral explorers, search out submarine hydrothermal vents near plate boundaries long recognized to contain SMS deposits of high-grade copper, zinc, silver, gold, and other trace minerals typically found in water depths exceeding 1000m. In parallel to AUV and ROV efforts, drilling operations, and multibeam bathymetric surveys of the seafloor, RDSEA was contracted to provide complete water column physics of mining tenement areas based on in-situ measurements (Acoustic Doppler Current Profiler [ADCP] deployments), including analysis and description of the variation in currents throughout the record. Collection and analysis of water-column density (conductivity/temperature/depth (CTD) data collected during deployments are included. Geochemistry data is also collected by sediment traps with rotating carousels on moorings. This is the story (quick version) of a dual ADCP mooring that was deployed in 2012 and not recovered until 8-years later with full data sets achieved for as long as power (batteries) provided.

A standard subsurface ADCP mooring with peripheral measurements of density (at the sphere) was designed and deployed. Water depth is in the 1200m range, a system plan of using two 75kHz Teledyne ADCPs mounted at 600m was planned. A higher frequency 600kHz ADCP was used in-line on the mooring just above the anchor to profile as close to the seabed as possible. The "bottom boundary layer" is of high importance for sea-floor mining operations. This region of profiles from mid water-column is lost due to sidelobe reflection (a given function of acoustics) as is nominally 6% of the surface, due to reflection. A 75kHz ADCP has a range of ~ 500m (as long as there are "scatterers" at range for proper Doppler feedback), the 600kHz system, ~ 60m. Therefore, in theory, in 1200m of water, mounting dual 75kHz ADCPs, mounted mid depth (600m) one looking up and one looking down, should profile the full water column. Interpolation is used at the bottom and the surface to complete the dataset.

A Riser and Lifting System (RALS) Concept for a Deep-Sea Polymetallic Nodule Mining

Alex Ran, Xiangdong Chen, Xinxiao Tang, Zhongnian Wang (JinAo Deep Sea Technology, China); Jim Li, Tuanjie Liu, Renjun Wang (OffshoreTech LLC, USA)

A riser and lifting system (RALS) concept is developed for a perspective deep sea mining project in 6000 m water depth. Nodule airlifting and pump lifting methods are investigated at the early stage of concept design. Key performance indices including production rates, energy consumption, riser size requirements, etc., are compared between these two different methods. A lifting riser system concept with axial flow centrifugal pumps is finally selected. The riser system comprises one 16-inch vertical lifting pipe, two 8 inch produced return water pipes, and three sets of lifting pumps installed at various depths. The riser is hung off from the supporting structures located inside the moon pool of the surface production support vessel (PSV). In order to reduce riser loads on the PSV, buoyancy modules are installed on the pipes within 4000 m below the water surface. This paper presents the details about nodule lifting method study, riser global sizing, riser strength analysis, fatigue analysis, as well as considerations for riser axial vibrations, etc.

Please find full paper on Appendix I

Bioextraction as a Method for Processing Polymetallic Nodules - an Economic and Environmental Game Changer

Renee Grogan (Impossible Mining, USA)

Impossible Mining is developing a novel, energy efficient, microbial bioextraction method for the processing of minerals critical to green energy production, that include nickel (Ni), cobalt (Co), copper (Cu) and rare earth elements (REEs). Bioextraction is different to traditional bio-leaching where the bacteria are used to generate acid to allow leaching of metals. By comparison, bioextraction occurs at neutral pH, in a process that is complete within hours.

The bioextraction methodology draws on knowledge gained from basic research on a group of bacteria that can rapidly dissolve various metal oxides, including insoluble iron (Fe) and manganese (Mn) oxides, under anaerobic conditions, thereby reducing the metal oxides to soluble metal salts. This technique will enable low-energy processing of minerals without traditional reagents like arsenic and cyanide, without generating toxic waste and without using freshwater. Furthermore, we will aim to achieve carbon neutrality, and eventually carbon negativity, by utilizing fossil fuel independent carbon and energy sources for the microbes.

Bioextraction has been tested at a small-scale laboratory level on polymetallic manganese nodules and shown to be extremely effective, achieving recovery rates commensurate with existing mineral processing methodologies, and without the generation of a waste stream.

Current work is focused on scaling the process from very small-scale laboratory tests to a pilot-plant scale, over the next ~18 months. It is expected that, if scaling is successful, bioextraction will be extremely cost effective when compared to any other form of mineral processing, for both capex and opex, due to the low energy inputs, lack of reagent inputs and the lack of waste storage infrastructure required.

When proven at scale, we believe this technology will completely disrupt current mineral processing methods, particularly the currently proposed mineral processing methods for polymetallic nodules, delivering a pathway to carbon-neutral, waste free processing for the deep-sea metals industry.

Adaptation of Nodule Mining Technology to Mitigate Environmental Impact

Gopkumar Kuttikrishnan (National Institute of Ocean Technology, India)

Deep Sea Mining (DSM) in its global interpretation refers to harvesting of seabed polymetallic nodules (PMN), seafloor massive sulphides (SMS) and cobalt rich crusts (CRC) from various locations of the world's seas and oceans. Each of these mineral/ores have the collection system different; while the vertical transport to the surface vessel/floater would essentially be similar. The deep sea mining trials of 1974-78 in harvesting PMN has set a working template of the technology to be adopted, especially for PMN – a self-propelled miner on the seabed sucking up the nodules, connected to a long vertical riser system to transport it as sea water slurry to a surface floater/ship, in controlled station keeping. While the engineering design and development of this configuration is in itself an enormous challenge, the impact on the marine environment and its mitigation is a bigger challenge. Despite the engineering concept being inspired by the offshore engineering for oil and gas extraction, the environmental impact characteristics are very different from the inspiration.

The foremost aspect to accept is that every action such as deep sea mining, where the nodules which are millions of years old, are going to be removed from the seabed without any reasonable replacement, it certainly is a permanent change during the lifetime of human kind. Besides, these nodules are believed to provide a solid substrate on the soft sediment soil surface and host a range of fauna. In the absence of these nodules, these fauna would find it difficult to recolonize from the surrounding untouched-undisturbed areas. The yet to start deep sea mining industry is expected to make this economic and engineering activity "sustainable". Apart from the removal of the nodules from the seabed, other prominent environmental impacts caused in disturbance to the tranquil and extremely slow conditions prevailing at these depths during the mining activity are intruding machinery acoustic energy and lights, physical trampling over the soft soil sediments, seabed plume disturbances abnormally smothering the fauna on the seabed, spread of the plume in the water column from the tailings discharge from the surface floater and higher power consumption in transporting wasteful sediments along with the harvested nodules. Having accepted that deep sea mining will have an impact on the immediate marine environment, it does not mean that start of deep sea mining would result in pollution of the deep waters and cause colossal damage across oceans. In fact, deep sea mining could possibly be a better option to mitigate the overall impacts on the environment by enabling the global push towards cheaper green technology adoption.

Much of the impacts in harvesting PMN, brought out above arise as the following:

Seabed sediment plumes and physical trampling over of the seabed - during the locomotion of the miner on the water-saturated soft sediment soil of the abyssal plains and nodule collection by the jet/physical methods.

Low frequency acoustic noise that propagates far – from the heavy gear-based machinery and mechanical moving parts.

Need for disposal of tailings and wastewater, and possible cause for accidents – application of a very long vertical riser system for nodule transport as slurry with over 80% by mass being seawater and the carryover of wasteful sediments.

The presentation in mitigation of the environmental impacts aims to look at the options for improvement and adaptation of the engineering systems and possible alternate and reliable options to the standard configuration of deep-sea mining.

Age Constraints Through Osmium Isotope Stratigraphy and Chemical Compositions of the Ferromanganese Crusts from the Iwaki Seamount at

Katz Suzuki (JAMSTEC, Japan)

Hydrogenetic ferromanganese (Fe-Mn) crusts are chemical sedimentary rock composed of elements from seawater and the detrital material. They grow slowly on the surface of seamounts (Hein et al., 2000) . Due to the slow growth rate (a few to several mm/my.), Fe-Mn crusts have been used as archives for monitoring long-term chemical evolution of ambient and global seawater. For such purposes, dating methods of each layer of the crusts are essential, and the dating methods such as 10Be isotope and Co-accumulation rate have been used. However, one of the most difficult problems of Fe–Mn crust dating is the determination of accurate ages for layers older than 10 Ma. The Os stratigraphic age model allowed for long-term dating by fitting the obtained Os isotope trend of sublayers collected from the Fe-Mn crust with the evolutions curve of seawater Os isotope (e.g., Klemm et al., 2005; Goto et al., 2014, 2017). It has been reported that the growth rate of Fe-Mn crusts varies among the Os age model and other dating methods (Usui et al., 2007). Also, only a few studies have focused on the difference in growth rate with water depth.

Here we provide the Os isotope data and chemical compositions of four Fe-Mn crust samples collected at different depths (5193 m, 3316 m, 1860 m, 1697 m) in the Iwaki seamount located offshore of northeast Japan, and examined the correlation between growth rates and variations in chemical compositions of the four Fe-Mn crust. We found Fe-Mn crusts grow fast with increasing water depth. The average growth rates are 3 mm/My on the flat top of the seamount, while that is 6 mm/My on the base. Furthermore, two samples collected from the flat top of the seamount also showed significant changes in growth rate. The typical elements concentrated in the Fe-Mn crust, such as Co, Ni, Te, REE, were correlated with the growth rate. In particular, Al which is a major component of a detrital component in Fe-Mn crust shows a positive correlation with growth rate. The intake of detrital particles is likely to have a significant role in the growth rate. We also found that there is a difference in the concentration of each element depending on the water depth and sedimentary environment and also on the growth rate of the Fe-Mn crust even in the same seamount.

An Environmental, Social and Governance (ESG) Handbook for Marine Minerals

Marte Rusten (DNV, Norway)

This presentation discusses the development of an Environmental, Social and Governance (ESG) handbook for marine minerals.

Environmental, Social and Governance (ESG) performance shows how a company is addressing sustainability challenges. When combined with financial indicators, this gives a more complete picture of the risk and opportunity profile of a company and a specific project for stakeholders.

There is currently no ESG (Environmental, Social and Governance) framework for marine minerals. With respect to the increasing demands for sustainable mining an ESG framework in the form of a handbook would be a natural requisite for extraction of marine minerals.

It is suggested that the handbook is based on existing protocols that have been developed for similar purposes like land mining and offshore projects. However, it is important to adapt this handbook to the special conditions that apply to extraction of marine minerals.

The handbook should contain assessment protocols and indicators for measuring and reporting the performance in key environmental and social areas of a marine minerals project. By using assessment protocols and indicators the performance of the marine minerals project can be assessed. This can be done by using a rating system. If the rating for the project is not acceptable the issues that have caused this have to be corrected/improved.

The (ESG) performance that has been carried out can be based on a self-assessment by the company responsible for the marine minerals project. But the self-assessment also needs to be verified by an independent third party.

The ESG performance should be reported in a standardized reporting form so that it is easy for an external to read the report and to compare different projects.

By Looking Back Into the Past, We Have Adapted our Approach to Environmental Research Moving Forward

Hans Smit (Moana Minerals Ltd., Cook Islands)

In recent times, consideration of deep-sea mining environmental impact assessment has necessarily focused on the development of guidelines for the minimum required studies and content of Environmental and Social Impact Assessment (ESIA) reports. In practice, the deep-sea mining industry, regulators, and other stakeholders face the challenge of connecting individual studies to an integrated evaluation of environmental and social impacts, and implementation of monitoring indicators, ensuring a sound scientific basis. Furthermore, the industry is challenged by global supply chain issues with respect to specialized equipment, availability of human resources, remoteness of the mineral resource, and the fact that timelines associated with some studies are not conducive to monitoring. Nodule exploration in Cook Islands, a sovereignty with a strong socio-cultural dimension, where there is very little existing information and that is remote from major logistical centers, requires learning from the past to maximize benefits. Moana Minerals aims to employ an ecosystem-based management (EBM) framework which is required to ensure that ESIA information needs drive the requirements of environmental and social studies and that the results of these studies inform monitoring and adaptive management scenarios. Ecosystem models are a tool in the EBM framework that are used to target studies, sequence those studies to the correct project phases and spatial framework, investigate thresholds of significant impact and collect and communicate detailed scientific data and complex ecological interactions to a wide audience. Adapting to the logistical constraints of Cook Islands (e.g. harbour space limitations) and making genuine commitments to capacity building, provides a platform for maximizing environmental information. Moana Minerals aims to complete more frequent, shorter duration campaigns, benefitting from the relatively short distance between Rarotonga and the nodule resource, allowing partnered operations that can generate data at appropriate spatio-temporal scales and at a tempo that allows for progressive assessment and optimization. This approach also maximizes contractor collaborative opportunity and the ability for the regulatory authorities and stakeholders to engage in a phased and progressive way.

Coarse Grain Sediment As a Conduit for the Lateral Flow of Hydrothermal Fluid and the Formation of Distal Metal Sulfide Occurrences in the Escanaba Trough

Jacob Tidwell (University of California, Sant Cruz, USA)

The Escanaba Trough is the southernmost segment of the Gorda Ridge and the only active spreading center in the exclusive economic zone of the United States. The Escanaba Trough is filled with sandy to silty turbidites and hemipelagic sediment between 300 m and 700 m thick. As one of only three known spreading centers dominated by sediment-hosted hydrothermal vent sites, the Escanaba Trough "provides a geological laboratory of grand proportions."

Previous surveys of the Escanaba Trough by the USGS have suggested that steep-sided sediment hills hosting massive sulfide occurrences at their margins are the result of uplift from basaltic sills. Large outcrops of metal sulfide minerals associated with active and inactive chimneys and mounds occur at the base of steep sediment hills throughout the Trough. It has previously been demonstrated that sand layers allow for radial, strata-bound migration of hydrothermal fluids away from sediment hill ring faults and for the formation of smaller distal sulfide occurrences. In late spring of 2022, the USGS returned to the Escanaba Trough and collected push cores up to 1 m in length using an ROV and gravity cores up to 4.5 m in length. Push cores were taken at even intervals moving from sulfide outcrop to pelagic sediment. Grain sizes ranged from silt to sand and sand layers were identified within the returned cores and analyzed for the presence of hydrothermal material. Cores were CT scanned, split, photographed, and logged using X-ray fluorescence. XRD was used to determine the mineralogy of distinct layers and micro-scale mineralogy was determined using a Raman imaging microscope.

We present the results from our analyses of recovered sand layers in both push cores and gravity cores. By identifying the presence of hydrothermal material in sand layers and the preservation of any sulfide minerals, we hope to understand the role of coarse grain sediment as a conduit for hydrothermal fluid flow. Samples recovered during previous USGS expeditions to the Escanaba Trough revealed metal sulfides dominated by pyrrhotite and sphalerite. Our investigation confirms that pyrrhotite is the dominant sulfide mineral present in massive sulfide occurrences.

Communicating Data Quality for Polymetallic Nodules Projects

Sean Aldrich (RSC Consulting Ltd, New Zealand)

Work undertaken by RSC on a variety of seabed mineral resource estimations (MRE) has shown that unknown data quality is a significant risk to the confidence of the estimation, when reporting in accordance with JORC or NI 43-101. The communication of this risk is equally important for all stakeholders. Data quality should be discussed in the context of the objective for which the data are being collected. In the minerals industry, the term 'fit for purpose' is commonly used to convey the principle that data quality should suit the objective (data quality objective, DQO). RSC's approach to data quality is based on establishing a project-specific data quality management system (DQMS). A DQMS comprises three components, quality assurance (QA), quality control (QC) and quality acceptance testing (QT). QA takes place by putting in place standard operating procedures (SOPs), QC takes place by inserting and continuously monitoring checks and balances, ensuring the data collection process remains in control. Once it has been established the data collection process was in control the Qualified Person (QP)/Competent Person (CP) can carry out QT to determine whether the data demonstrate suitable accuracy and precision with respect to the DQO.

A thorough understanding of this terminology is critical for all stakeholders, in particular investors, to be able to better define and communicate the risks associated with data used in MREs, public announcements, and subsequent economic studies. As projects move into a more exploration-intensive phase, the seabed industry stakeholders need to be able to assess the accuracy and precision of sampling methods that will be used to inform MREs and other material technical studies. A better understanding of this also allows for more informed and efficient decision making during the exploration planning, implementation, and development stages.

COMPASS: GSR's Adaptive Management System for the Responsible Commercial-Scale Collection of Polymetallic Nodules

Kris De Bruyne (GSR, Belgium)

Global Sea Mineral Resources NV (GSR) holds an exploration contract with the International Seabed Authority (ISA), to explore for polymetallic nodules on the seafloor of the Clarion Clipperton Zone (CCZ) in the Pacific Ocean. There is much commercial interest in the Pacific Ocean nodules as they contain more nickel, cobalt, and manganese than all land-based reserves combined (Hein et al., 2020).

In the spring of 2021, GSR successfully tested its pre-prototype seafloor nodule collector Patania II at 4,500 m water depth in the CCZ. By driving and collecting nodules, these in situ trials provided valuable information for operational and technological purposes. Simultaneously, the environmental impacts and effects of collecting nodules from the deep seabed were monitored as well. The learnings from Patania II will be taken forward in the next stages of the development.

The trials with Patania II have confirmed that the environmental effects will not only vary with (e.g.) the bathymetry and seafloor currents at a certain location but will also depend on operational choices such as the mining path, including sequence.

In 2017, in parallel with the development of Patania II, GSR initiated the development of COMPASS. COMPASS' main objectives are to (1) define and implement the environmental monitoring strategy during exploitation using Best Available Techniques and (2) develop a system that generates the most optimal mining path taking into consideration the (in)direct impact (e.g., sediment plumes) and the technical and operational limitations with a specific aim to minimize environmental effects to the extent possible.

COMPASS is an adaptive overarching system, integrating different data sources, such as the environmental baseline data with bathymetrical and geotechnical measurements. Subsequently, another layer of information is superimposed, consisting of actual oceanographic and turbidity measurements, as well as the operational data of the mining system itself. COMPASS will not only inform the mining operations, it will also be able provide the information transparently to the governing bodies, as well as have the ability to directly intervene on the controls of the mining system, serve as a tool for operational planning, and provide an early warning system to ensure environmental compliance.

COMPASS will entail an impressive monitoring suite comprised of fixed stations such as moorings and landers equipped with oceanographic instruments, and mobile stations such as AUVs, gliders and ROVs. This interconnected sensor suite will be used for monitoring the operations (visual, turbidity, noise, chemical, light etc.), sampling and lastly, for actual oceanographic measurements that inform the sediment transport numerical model (e.g., currents). This requires (near) real time feedback from these sensors to the Surface Operating Vessel and/or Seabed Nodule Collector, allowing quick and early decisions to be made about the operational proceedings.

Furthermore, a multi-layered algorithm has been developed generating a series of alternative mining paths. These paths are computed on day-to-day level, considering economic (production), bathymetric, and operational parameters. These are subsequently evaluated and compared from an environmental impact perspective, e.g., by means of sediment plume numerical modelling predictions. The best mining path is then executed. The operations are continuously monitored and compared with model predictions to improve the algorithms as well as allow adaptation of the operations as needed (adaptive management).

COMPASS will be tested and validated during GSR's System Integration Test (SIT), planned for 2025. The SIT will encompass a commercial scale Seabed Nodule Collector, Patania III, and a Vertical Transport System (VTS), including all necessary auxiliary (deck) equipment. COMPASS' procedures and sensor suite required for monitoring the environmental impact and effects as envisaged to be implemented for commercial scale operations, will also form an integral part of the SIT.

GSR remains committed to responsible deep-sea research and technology development, one step at a time.

Core-Key to the SMS and OCC Puzzle

Alden Denny (Adepth Minerals, Norway)

The structural style and three-dimensional evolution of seafloor massive sulphide (SMS) deposits related to oceanic core complexes (OCC) is less well understood compared to mafic hosted volcanogenic massive sulfide (VMS) due to the limited subsurface data available in the marine environment. Deep ocean mapping over the last decades has focused on using geophysical methodology, with rock samples collected opportunistically from the seafloor, and infrequent drilling campaigns. Ocean drilling efforts have focused on large resource-intensive platforms that are not suited for resource estimation. Efficient direct sampling of the sub-seabed coupled with geophysical observation has been identified as a critical bottleneck in realizing the three-dimensional understanding of SMS and OCC systems. This study explores the requirements and testing program for a bespoke seafloor coring system suited to SMS and OCC exploration and quantification.

Seabed minerals can occur in thicknesses of up to 100 meters over a variable map extent on the order of 200 m. The subsurface is poorly defined, with only the TAG-type active deposit explored in detail (i.e., Murton et al., 2019) and little exploration of subsurface extinct deposits. Existing equipment for core sampling or sample collection can, to varying degrees, function for SMS and OCC data collection (Sterk, R; Stein, J.K., 2015). Current methods are challenged by sampling depth and operational flexibility to take samples from both unconsolidated sediments (typically cored using weight / piston) and hard rock (typically cored with diamond coring or drilling). The existing equipment that can reach desired depths are either drilling vessels / platforms, which are cost-prohibitive and inefficient, or stationary seabed drilling rigs that are inflexible in terms of mobility and terrain. Current methods have yet to prove commercially viable for evaluation of resource potential and to further understand geological deposition processes.

To better quantify SMS and OCC systems this project is focused on the development and field-testing of a new FlexiCore diamond core drilling solution capable of drilling up to 100 meters / day (dependent on geology) in SMS and OCC environments. Once in operation this system will be more flexible regarding substrate and terrain with the ability to core soft sediment and hard rock and able to operate in steep slopes and at a user-defined angle to the seafloor. The FlexiCore system will be time and cost efficient as it will be able to change drilling bits at the seabed and be able to take core samples from multiple locations in an exploration region without recovery to the surface. We present the results of the initial marinization process of this system and plans for deployment to the Mohns Ridge in early 2023 for a full field test and exploration campaign to quantify OCC related fluid flow in an ultraslow spreading environment.

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Data Needs for Continued Consideration of Ferromanganese Crusts as a Potential Deep Ocean Minerals Resource

Kira Mizell (USGS, USA)

Within the realm of deep ocean minerals, five distinct mineral types have been investigated: manganese nodules, ferromanganese crusts, seafloor massive sulfides, phosphorites, and rare earth element-rich muds. Each of these marine mineral types has experienced varying levels of resource interest through the past several decades. While no mining of these marine minerals has taken place to date, exchange-compliant resource assessments and environmental impact assessments have been completed for manganese nodules, seafloor massive sulfides, and phosphorites. Manganese nodules are currently garnering substantial interest as the International Seabed Authority works to release exploitation regulations by 2023 anticipated by contractors in the Clarion-Clipperton Zone, though many barriers remain before exploitation can proceed. Further progress combined with continued challenges for nodules, sulfides, and phosphorites leaves ferromanganese crusts and rare earth element-rich muds in a state of uncertainty in terms of likelihood and timeline for resource development. Rare earth element-rich muds are the most recently discovered deep ocean mineral occurrence with only preliminary investigation into distribution, compositional variation, and extraction and recovery feasibility. On the other hand, ferromanganese crusts have been scientifically explored for decades and exploration licenses for crusts have been granted by the International Seabed Authority. Therefore, a larger body of information exists regarding crust distribution and formation, yet resource assessment relevant information gaps persist and research and development for extraction technologies remains in its infancy. In this presentation I will summarize the state of knowledge regarding ferromanganese crust occurrences and the progress toward resource estimation. I will discuss the scientific exploration needs to fill data gaps and inform continued consideration of ferromanganese crusts as a potential deep ocean mineral resource.

Deep Sea Minerals on the Norwegian Continental Shelf – Activities and Data

Harald Brekke Bjørnestad, (Norwegian Petroleum Directorate, Norway)

The Norwegian Government has initiated a process to prepare for a possible opening of continental shelf areas for the exploration and exploitation of seabed mineral resources. As part of this process, the Government is currently undertaking an impact assessment study. The Norwegian Petroleum Directorate (NPD) is given the task to explore and map the continental shelf deep-sea mineral resources to make resource assessments and to give input to the impact assessment study. The deep-sea mineral resources of the Norwegian continental shelf consist of deposits of polymetallic sulphides and polymetallic crusts; the area is not favorable for polymetallic nodules. For many years, the NPD has collaborated on a scientific basis with academia in marine research on deep-sea minerals including seabed sampling. However, since 2018, the database has been considerably expanded by the Government's dedicated annual seabed mineral exploration cruises carried out by the NPD. High resolution multi-beam bathymetric, geophysical, electromagnetic, and geochemical data have been acquired by the extensive use of AUVs fitted with relevant sensors. Sampling of sulphides and crusts for geochemistry and characterization has been done by ROV and core drilling. During the years 2018, 2019 and 2020, the cruises concentrated on the Mohn Spreading Ridge and its newly discovered sulphide deposits, while the 2021 cruise was dedicated to the Knipovich Ridge further to the north. The data from the NPD surveys since 2018 and data from collaboration with academia since 2011 was released to the public in June this year. Details on these data and how they may be accessed will be given. We will also present some of our in-house current work in using the database to build geological models of sulphide and crust deposits that may form the basis for resource assessments and further exploration.

Deepsea Minerals Systems Advancements: Applying Oil & Gas Technology to Unlock Deepsea Minerals Resources

Brian Mizell (OSI Minerals, USA)

OSI Minerals™, a part of Oil States, is leading the development of next generation solutions for deep-sea minerals collection by transferring technologies historically applied in offshore oil & gas installations. OSI Minerals has leveraged Oil States' 80-year history and more than 40 years of deep-water experience in oil & gas (O&G) technology to develop an award-winning Merlin™ Deepsea Minerals Riser System which will help to unlock previously inaccessible deep-sea minerals resources at up to 6000 m/ 20,000 ft water depth. In the past three years, the industry has provided very positive feedback, as OSI Minerals has secured several project awards and delivered multiple Deepsea Minerals Riser Systems which have now been deployed offshore. These projects include a Deep-Sea Minerals Riser System for Cosmos Shoji Co Ltd awarded in 2020, an ultra-deep-water system for Allseas in early 2021, and a Front-end Engineering & Design (FEED) Study for Green Minerals AS (Norway) Harsh Environment Deepsea Minerals Gathering System in early 2021. Also in 2021, OSI was awarded the prestigious Offshore Technology Conference ("OTC") Spotlight on Technology® Award for the Merlin™ Deepsea Mineral Riser System. In order to accomplish this, as they have historically done for offshore O&G developments, OSI Minerals carried out Global Engineering & Riser Analysis to design systems that were optimized for the expected field conditions including the ultra-deep-water as well as expected metocean conditions. The team also adapted existing Merlin™ riser and connection technology which allowed for a robust, fast make-up, safer, hands-free, automated system capable of withstanding extreme operating conditions in the remote deep-water regions of the world. The application of these traditional technologies for offshore O&G is not only helping to make deep-sea minerals operations possible, but also safer and more reliable.

Deep-sea Mining Plume Monitoring: Results from the First Deep-sea Trial of the Patania-II Pre-prototype Nodule Collector and Parallel Plume Monitoring with Hydroacoustic and Optic Methods.

Iason-Zois Gazis (GEOMAR Helmholtz Center for Ocean Research Kiel, Germany)

In April 2021, the first deep-sea trial of the Patania-II pre-prototype nodule collector vehicle was conducted by DEMEGSR in the Belgian contract area for polymetallic nodules in the Clarion-Clipperton Zone (CCZ). The European MiningImpact2 research consortium (Joint Programming Initiative Healthy and Productive Seas and Oceans) conducted an independent campaign (IP21) to monitor in high-resolution the evolution and spatiotemporal extent of the sediment plume produced by the collector. A dense monitoring network was deployed with 50 acoustic and optic sensors (ADCP, ADV, AquaScat, PartiCam, and OBS such as JFE, FLNTU, and Seapoint). These sensors provided data from the first 20m above the bottom (mab) in the vertical direction and 50m to 2000m away from the trial site in the horizontal direction. In addition, a deep-sea Autonomous Underwater Vehicle (AUV) was extensively used, running five additional acoustic and optic sensors (MBES, SSS, FLNTU, JFE, Camera) and thus increasing the data coverage to distances up to 5000m away from the source and 50mab. A lab calibration of the optic sensors enabled the precise recording of the sediment concentration (mg/l) and particle size (μm) at different altitudes and successive distances from the source. In brief, the analysis showed that the sediment plume is influenced by the local seabed morphology and bottom currents (development of sediment gravity flows following the morphology and subsequent passive dispersal by bottom currents).

Aggregation of fine-grained sediment into larger, relatively fast-sinking particles likely promoted the settling of most of the mobilized sediment in the vicinity of the trial site. A perfect match between the calibrated turbidity sensors, the seafloor images, and the MBES data confirms the spatiotemporal extent of the plume to distances up to 5 km. The strongly overlapping photos obtained within the trial area were used to construct the so far largest photomosaic from the CCZ. The photomosaic shows in ultra-high-resolution the seafloor before and after the mining operations. The DEM generated to produce the ortho-mosaic depicts the caterpillar and excavator depth in sub-centimeter resolution; it provides valuable insight into the total amount of mobilized sediment and shows the changing fine-scaled morphology with increased sediment deposition. In addition, the images were used to quantify the polymetallic nodule abundance and the deep-sea fauna distribution. The results from this study provided valuable information regarding the fate of deep-sea mining plumes in morphologically complex terrain, and a detailed understanding of the impact deep-sea mining has on the seafloor. A novel 4D visualization tool is used to show the plume evolution of the study site.

Diverse Marine Minerals in a Geologically Diverse Area - the Cook Islands Seabed

John Parianos (Cook Islands Seabed Minerals Authority)

A new seabed geomorphology map for the Cook Islands seabed frames the variety of polymetallic nodules, ferromanganese crusts and rare-earth rich muds so far found within the country's exclusive economic zone.

The seabed comprises different generations and orientations of abyssal plains with widely varying amounts of volcanic knolls, a major volcanic plateau with associated marginal horsts, rifts and fracture zones, and seamount chains and volcanic rises. This map helps domain a habitat management framework and mineral resource estimates.

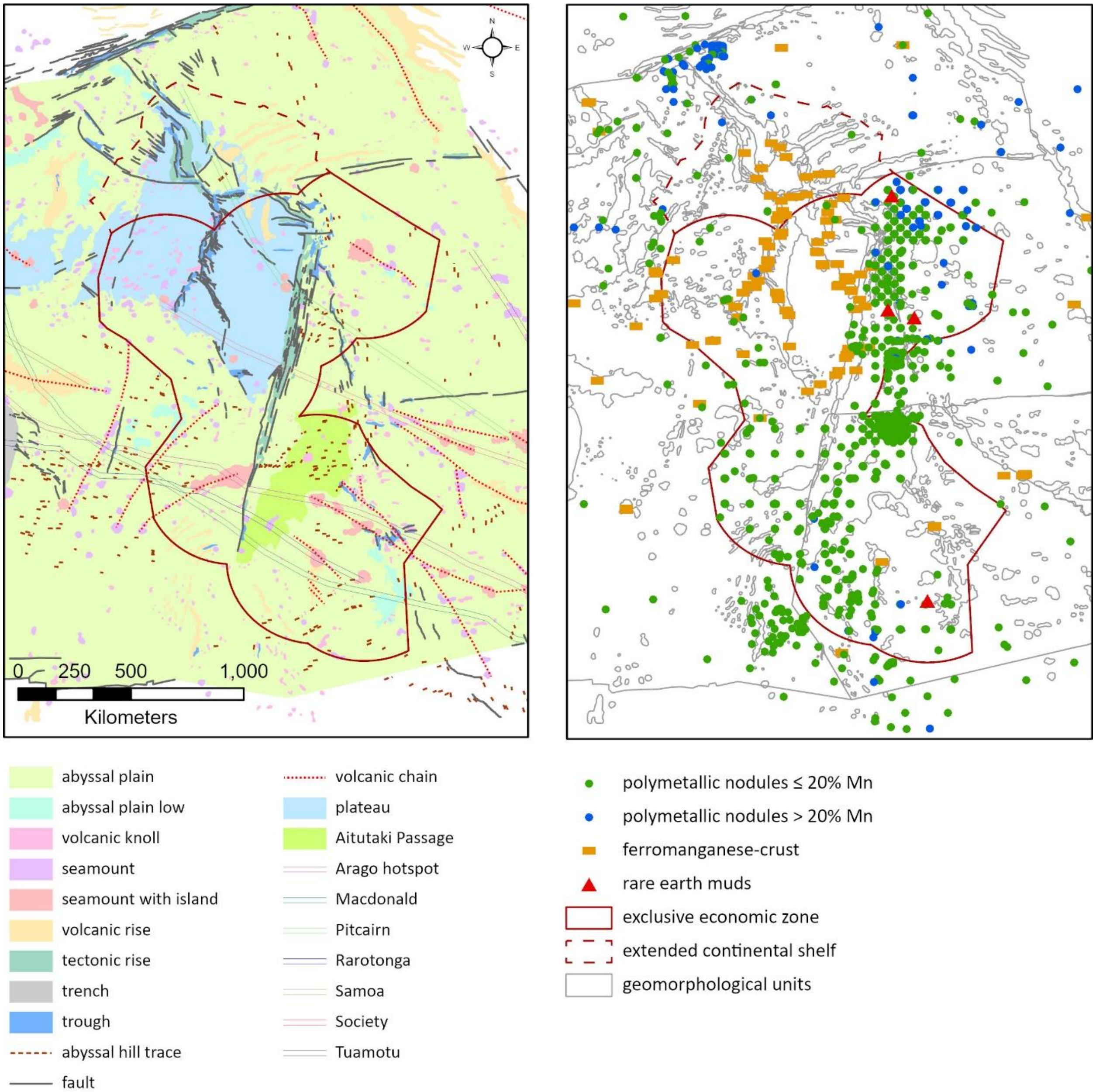
Much of the seabed was formed in relatively ancient times (early-Cretaceous) with formation of a large igneous province and subsequent ocean spreading in several directions. More recent volcanic activity (e.g. mid to late-Cenozoic) is associated with the numerous components of the "hot spot highway". The relatively old age of seafloor means that sediment clay-ooze cover is frequently thick (>100 m) and can incorporate large concentrations of biogenic material.

Three main grade types of polymetallic nodules have been sampled in the Cook Islands. Best known are high Co high Fe:Mn nodules that are often present in high abundance and have been associated with specific bottom water currents. In the north of the Cook Islands high Ni-Cu-Mn:Fe nodules are associated with higher levels of primary productivity, but wide-spaced exploration in the mid 1980s only found these in low abundances. In other parts of the EEZ, low grade nodules are also present in highly variable abundances.

Hydrogen etic ferro-manganese crusts are widespread through the Cook Islands. Best known from the Manihiki Plateau, these can reach several percent of cobalt, but their extent has never been mapped. Hydrogenetic and diagenetic crusts are also found amongst the nodules, most usually on topographic highs.

Rare-earth rich muds are known from several localities, but systematic exploration has never been conducted within the Cook Islands EEZ. Grades of REY can reach several thousand ppm, equivalent to the best reported from elsewhere in the Pacific.

At this stage the Cook Islands is only allowing exploration of its marine minerals. Environmental considerations will be foremost before any development is allowed to proceed further.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Samoa
Society
Tuamotu
polymetallic nodules ≤ 20% Mn
polymetallic nodules > 20% Mn
ferromanganese-crust
rare earth muds
exclusive economic zone
extended continental shelf
geomorphological units

Dynamic Models as Marine Minerals Prospecting Tools

Ebbe Hvidegård Hartz (Aker BP, Norway)

Deep Sea Mining is new in the sense of 'deep sea', but not if one takes the geological perspective of 'oceanic rock mining'. Ophiolites (ocean crust thrust onto continents during plate-collisions) have been a key source of metals since the bronze age. Roughly 2/3 of the Earth is ocean, yet much (not all) of our mining hereunto has come from the tiny chunks of oceanic rocks (ophiolites) on land.

Most of Norway's (historical) mining has been in ophiolites, yet Norway is now turning its attention to its vast areas (1 milllion km^2) of ocean rocks in its exclusive economic zone and its potential as source of critical raw materials with high supply risk. Regulations and fiscal terms are expected to be modeled after Norwegian oil legislation which has proven highly profitable for both industry and nation, and trend-setting in regard ESG. At present, Norway's oceanic crust is not opened for exploration, but multiple companies are preparing for the expected upcoming licensing round.

Given the limited data from the Norwegian oceanic crust, we train our understanding and algorithms in areas with publicly available high-resolution data: The central Atlantic TAG area is probably the best studied SMS swarm in the world, and the data are public. We use it to develop machine-aided prospect-generation and are 100% successful in 'blindly' finding the known deposits. Interestingly, we find more prospects than known deposits. This could represent undiscovered SMS's but also be false positives. False positives are common in exploration and not much of a problem as the method still reduces the areas of sampling and appraisal drastically. In fact, false negatives (not seeing high value resources) would be far more of a problem.

In Norwegian waters, high resolution public data are just starting to emerge, but we are initiating several lines of studies on the available data, discovering new features both in form tectonics and morphology of a slow spreading ridge, and exploration. An important part of this work is geodynamic, hydrothermal and hydrodynamic models. When combined, these models evaluate the potential for metal deposits in hydrothermal vents, and suggest where active SMS's may form, and equally important where they will not form, perhaps teaching us what to look for when exploring for extinct SMS's. Other models evaluate ocean currents near ocean floor structures, relevant both for evaluating crust formation, spread of plumes caused by activity on the seafloor, and deposition of sedimentary cover. These models are fed by available data (regional 2D seismic lines, earthquakes, ocean circulation, and known samples). Machine Learning (neural network algorithms) are used both for prospecting and to recognize macrolife from ROV video material and are expected to guide evaluations of where one can, and should not, mine, and possibly even guide ongoing mining operations. These data are important when we evaluate ecological impact per resource produced, as the health of the ocean is a cornerstone both for both technological development and formal license to operate.

Collectively these bio, ocean and geo-science models are progressing, but they all crave for more of geo-, ocean- and biodata and understanding.

Economically Viable Selective Harvesting of Polymetallic Nodules

Jason Gillham (Impossible Mining, USA)

At Impossible Mining, we are building autonomous underwater robotic vehicles (AUVs) to collect battery metals from the seabed, without destroying the marine ecosystem. Our fleet of AUVs will utilize remote sensing and camera imaging technology to identify nodules, a series robotic arms to pick the nodules up individually, and a dynamic buoyancy system to maintain neutral buoyancy above the seafloor, as the AUV harvests and reaches its payload limit.

The remote sensing system will enable the AUV to identify and avoid nodules that are hosting deep sea fauna, and to algorithmically program the AUV to leave behind a percentage of nodules as habitat corridors to ensure the ecosystem and habitat remains intact.

Our technology is being developed in a manner that avoids the creation of a significant sediment plume that would impact on nodules left behind, or the benthic ecosystem. The operation of the AUVs will avoid contact with the seafloor sediment, and the AUVs themselves are designed to ensure the buoyancy system, the harvesting system and the overall fluid dynamics of the AUV minimize any production of sediment plume.

Conceptual economic modelling indicates that a fleet of 80 AUVs with two support vessels can achieve a 3 Mt production rate with more favorable economic results than a dredge-like approach. This is primarily due to the extremely high utilization rates achievable with a parallel fleet of smaller harvesting machines, the lack of rise and lift pumping system, and the much lower capex required for nonspecialized support vessels.

Impossible Mining is looking forward to pilot testing of the AUVs in the first half of 2023, and to working with existing contract holders to achieve full scale production that is both more environmental and more economic than dredge-like solutions.

Ecosystem Modeling of Chemosynthesis Around Mound Type Methane Hydrate

Tetsuo Yamazaki (Osaka Metropolitan University, Japan)

Potential of natural methane hydrate in seafloor sediment layer for an energy resource was highlighted about 25 years ago in Japan and a national R&D project to explore the deposit locations and to develop the exploitation technologies has been conducted these 20 years. Mound type methane hydrate (MTMH) on the seafloor has been added as the project target these several years. On and around MTMH, a quite unique and large-scale ecosystem community is frequently created. It is a chemosynthesis-base ecosystem depending on methane supply. When methane, which comes up from deeper layer, meets downwards diffusing seawater sulfate, it is oxidized anaerobically by a consortium of microorganisms that use sulfate as an oxidant, producing hydrogen sulfide. Hydrogen sulfide and residual methane are utilized by chemosynthetic communities near the seafloor, such as *Acharax*, *Calyptogena*, *Bathymodiolus*, and the mat-forming bacteria *Beggiatoa*. In case of MTMH exploitation, quite severe damages on the seafloor ecosystem community are expected. In order to minimize and expect the damages and the recovery, an ecosystem model, which numerically calculates the chemical processes and the ecosystem reactions, is created in this study. One of the fundamental processes, the material supply and consumption of *Beggiatoa*, was observed by using a cored seafloor sediment sample under controlled conditions in laboratory. The result is helpful for the understanding of the fundamental process. However, for the completion of the model, it is necessary to monitor the extension of damages by the exploitation and the re-colonization of the ecosystem under a small-scale exploitation experiment of MTMH.

Environmental Impacts & Risks of Deep-Seabed Mining

Ann Vanreusel (Ghent University, Belgium)

The European JPI-Oceans project 'MiningImpact2' (MI2) brought together scientists from 29 European institutes to analyze the environmental impacts and risks of deep-seabed mining. The objectives of the MI2 programme included assessing the environmental impacts of industrial scale, deep-sea mining activities on abyssal ecosystems (composition, traits, functions, connectivity, spatial & temporal scales); investigating potential mitigation measures, such as spatial management plans of mining operations and means to facilitate ecosystem recovery; developing sound methodologies to assess the environmental risks and estimate costs; and exploring how uncertainties in the knowledge of impacts can be implemented into appropriate regulatory frameworks, such as ISA's Mining Code.

Two areas were investigated before, during and immediately after the trials of Patania II in the Clarion Clipperton Zone (CCZ): the Belgian-sponsored (GSR) contract area and the German sponsored (BGR) contract area. The different contract areas offered the ability to study two regions of the CCZ with different surface productivity regimes which is reflected in ecosystem functions such as organic matter remineralization at the seafloor and benthic communities. The two sites also have different seafloor topography, along with different nodule densities and size classes.

This talk will summarize the immediate impact-related changes in environmental conditions (e.g. biogeochemical conditions, benthos/macrofauna and meiofauna densities, endofauna) and will discuss sediment plume dispersal modelling. It will also describe a long-term restoration/rehabilitation experiment that is underway and the use of species distribution models and habitat classification models to assess mining impacts. Indeed, habitat classification models will help in the design of Impact Reference Zones (IRZs) and appropriate Preservation Reference Zones (PRZs), as required by the International Seabed Authority. Set-aside areas need to contain representative habitat characteristics of mined areas to preserve abyssal biodiversity, and minimizing large-scale impacts requires careful and adaptive spatial panning of mining operations and a network of representative conservation areas.

The MI2-BGR-GSR collaboration is an example of a transparent joint effort between contractors and between contractors and the scientific community to obtain knowledge and data needed to allow informed decisions for responsible management. The collaboration is making a significant contribution of global knowledge on deep-sea environments for the benefit of humankind.

Environmental Monitoring in Marine Mineral Resource Management

Steinar L. Ellefmo (Norwegian University of Science and Technology, Norway)

Future demand for mineral and metals appears to be undisputed. No consensus exists however on where the minerals and metals should come from. Following a strict definition of sustainability, extraction of a non-renewable resource is in itself not sustainable. However, mining can be done responsible for a sustainable development. We argue that a holistic approach is needed where urban mining, onshore mining and offshore mining are considered in parallel where all the sources are part of the solution.

Mining the deep sea is controversial, partly due to the challenging conditions with great water depths, far from shore and challenging sea states, and the many unknowns when it comes to the ecosystem and its response to a so far untested and mostly unknown mining system. What is not questioned is the need for a robust, cost effective and complete environmental monitoring system that collects and process the data necessary for a thorough management of the environment and the resource. Such a management system must be multilevel, where the regional environmental management plans (REMPs) set the conditions for the operation and the project specific environmental monitoring and management plans (EMMPs).

In a successful management system, the EMMP will set constraints on the development of the mine plan and the execution of it. (Fig 1) It will thereby affect the definitions of the resource and the reserve given in tonnage and grade using modifying factors, including the ESGs, factors focusing on the environment, social aspects, and governance. Further, the execution of the mine plan will facilitate data collection that are fed back in the reconciliation of both the EMMP, the REMP and the resource model that describes the deposit characteristics.

In land-based mining, a resource is defined solely based on geological data, with the addition that there should be possible to foresee some future mining operation. A reserve is a portion of a resource where the modifying factors have been applied and thorough assessments have shown that this portion can be mined with a sustainable financial outcome while adhering to rules and regulations given in REMP and EMMP equivalents. For this reserve definition no decision must have been made to develop the deposit. In petroleum, this is different. A reserve is the portion that has been decided to be developed and produced.

Experimental Study of Excavation Efficiency of Cobalt Rich Ferromanganese Crusts on the Takuyo No.5 Seamount and Environmental Survey Around the Test Site

Orita Kiyotaka (Japan Oil, Gas and Metals National Corporation, Japan)

Numerous amounts of Cobalt-rich ferromanganese Crusts (CRCs) were discovered on the deep seafloor. They contain valuable metals like cobalt, nickel, and platinum in high concentration. Thus, CRCs have the potential to be a new supply source of these metals. However, mining technologies and knowledge of the impact on the deep-sea ecosystems have not yet advanced enough for starting the commercial development of CRCs. Therefore, the small-scale excavation and dredging test was conducted on Takuyo No.5 seamount in Japan's EEZ by using the mining testing machine to obtain the fundamental information related to the mining technology and the environmental impact.

For improving excavation efficiency, the drum cutter in the machine was designed to change its height and roll automatically depends on the relative topography change. The test results showed that 649 kg of CRCs were successfully excavated and dredged as the first time in the world. However, about half of the predicted excavation area was not excavated due to the unexpected small convex of the rocks and larger pitch of the machine than prediction. These results demonstrated that the performance of the height and the roll adjustment system of the cutter was insufficient for commercial use.

Possibilities for impacts on the surrounding environment, which were caused by excavating seafloor and generating the sediment plume, were studied by comparing temporal observations within 300 m radius of the test site one month before, during and one month after the test. Firstly, the video-transect survey by an ROV showed that the negative impacts on the composition ratio and population of the mega benthos were not observed except the direct removal of cnidarian colonies in the excavation tracts. Secondly, data from the instrument array showed that the re-sedimentation of the coarse particles was observed within 200 m from the test site with the strong influence from the tidal currents. Lastly, the chemical analysis of the collected water showed that the concentration of the suspended solids and particulate organic carbon contents were increased temporally but lowered when sampled after one month. On the other hand, the concentration of dissolved nutrients and heavy metals did not show any anomalies during the test, including samples directly collected from the operational plumes. These results demonstrated that the environmental impact at this small-scale test was limited. Results and lessons learned from the excavation and dredging test of CRCs will contribute to develop mining machines for commercial scale and improve environmental management strategies.

Exploratory Data Analysis/Synthesis in Support of Cook Islands Nodule Exploration

Mark E. Luther (University of South Florida, College of Marine Science, USA)

The University of South Florida College of Marine Science (USF/CMS) is providing support to Odyssey Marine Exploration (OMEX) for exploratory cruises in the Cook Islands to perform data analysis and synthesis of existing data sources to guide mooring design and placement. The overarching goal is to compile baseline environmental data necessary for preliminary test operations in line with standards set out by the Cook Islands National Environmental Service (NES) and applicable laws and regulations, as well as monitoring of environmental conditions and potential impacts of deep sea mineral extraction, for polymetallic nodule exploration efforts. The primary focus is to collect sufficient physical and geochemical data to fully characterize Benthic Boundary Layer (BBL) turbulent processes and water column circulation to inform oceanographic modeling of sediment plume transport and fate, as well as to guide potential future mineral extraction activities. Preliminary results will be presented from a "desktop" analysis of all pertinent existing oceanographic and meteorological data for the Cook Islands region. Results of this study will be used to guide initial exploratory cruises and benthic lander/mooring design and placement. Understanding site conditions, bottom bathymetry, and regional hazards will allow for the proper design and planning of field deployments as well as for potential deep sea polymetallic nodule resource exploration and extraction. Direct in-situ, satellite, recombined data, and output from numerical geophysical models will be extracted from available data sets or taken from the literature to characterize the mean, range, and annual variability of the following variables: Water Column Currents; Wind Speed and Direction; Water Column Temperature; Water Column Salinity; Air Temperature; Precipitation; Surface Waves; Internal Waves. Information will be provided on typical and extreme or hazardous meteorological and oceanic conditions relevant to operations within the Cook Islands region. Additional calculations will be performed for quantities with data sufficient for accurate computation of seasonal to inter-annual variability due to the El-Nino Southern Oscillation (ENSO) that is significant in the region. The 3 to 6-month predictability of ENSO will then permit better operational preparation for likely changes in the risk of hazardous environmental conditions. This area also is influenced by the Indo-Pacific through-flow and the Indian Ocean Dipole oscillation.

Geochemical-Mineralogical Properties of Manganese Nodules in the Subseafloor Sediments in Site U1371, South Pacific Gyre area

Jaewoo Jung (Department of Oceanography, Pusan National University, Korea)

Manganese nodules were collected within the subseafloor sediments (118.22 mbsf) at Site U1371 during International Ocean Discovery Program (IODP) 329 expedition from the South Pacific Gyre (SPG). The manganese nodule was divided into the concentric layer outside the manganese region and the inner part of the phosphatized part consisting of manganese oxide minerals and carbonate fluorapatite (CFA) minerals. The two-dimensional element distribution analysis of Mn, Co, Ni, Sr and Cu, Zn with low Mn/Fe ratio indicated that manganese nodules were formed predominantly by a hydrogenetic process and a biogenic process in certain manganese layers. As a result, the manganese nodule was continuously precipitated in SPG environments of oligotrophic open ocean conditions and rapidly buried with siliceous ooze when the SPG changed to a eutrophic environment. It has been confirmed that manganese nodules found within deep subseafloor sediments could be used as a new indicator for the reconstruction of paleooceanographic environment.

Long-term Monitoring of Ocean Currents in the Tropical North Pacific from the Sea Surface to the Deep Benthic Boundary Layer

Jon D. Wood (Ocean Data Technologies, Inc., USA)

An understanding of the physical oceanographic processes at potential future deep-seabed mining (DSM) sites is advantageous for many reasons. Numerical models predicting the fate and transport of suspended sediments require velocity data for model development and validation. Environmental Impact studies will also benefit from accurate, long-term data collection. Operational planning will rely on favorable conditions to perform various works, avoiding time periods where conditions may impede or otherwise affect operations.

In 2021, a GSR cruise recovered successfully four (4) long-term oceanographic moorings deployed in their contract areas since 2017 and 2018. Overall data capture was outstanding. Of the 21 instruments deployed collectively on these moorings – including Acoustic Doppler Current Profilers (ADCPs), single point current meters, multi-parameter probes, sediment traps - 19 instruments operated properly and recorded years-long, high-quality data sets.

All the moorings were instrumented to measure ocean currents and water properties in the near-bottom boundary layer; vertical current profiles were obtained from 2.5 m above the seabed to as high as 20-to-100 m above the seabed with fine spatial and temporal resolution. Water properties such as temperature, salinity, pressure, and turbidity were monitored as close as 5m above the seabed. These time series ranged from 2 years to 3+ years in duration.

One mooring was designed to measure currents throughout the entire water column, including continuous vertical profiles in the upper 1000 m of the ocean. More than 3 years of high-resolution observations of the upper ocean circulation were recorded. Additional single-point measurements were obtained also at 1500 m, 2500, 3500, and 4000 m depths, along with current profiles within the near bottom boundary layer.

The data showed variability modes consisted of semi-diurnal tides, inertial oscillations, and other lower frequency circulations with time scales of ~months. Several major hurricanes passed over the study area – ocean responses to these events were captured in high resolution. Comparisons of velocity between adjacent sites provide evidence of large-scale eddies impacting the region, as well as a sense of flow steering along bathymetric features.

Novel LISST-RTSSV for In-situ Particle Size Characterization of Deep-sea Mining Sediment Plumes: Instrument Capabilities, Mining Trials Deployments and Preliminary Insights

Souha El Mousadik (Massachusetts Institute of Technology, USA)

Increased insight into the physics of the sediment plumes produced by deep-seabed mining operations is critical. In particular, accurate in-situ measurements of size and settling velocity distributions of suspended sediments are necessary to understand plume behavior and to better inform models of sediment transport. However, measurements of these particles in-situ with sufficient resolution are yet to be realized. To address the capability and knowledge gaps, the LISST-RTSSV (Real-Time Size and Settling Velocity) instrument is under development as part of an ARPA-E funded SBIR collaboration between MIT, Sequoia Scientific, Inc., and Scripps Institution of Oceanography. The LISST-RTSSV measures the size and settling velocity distributions of suspended sediments in-situ, down to 6000 m.

An instrument prototype was successfully deployed, in spring 2021, during the Global Sea Mineral Resources NV (GSR) pilot monitoring of a pre-prototype nodule collection vehicle, in the Clarion Clipperton Zone (CCZ). A follow up deployment of the advanced prototype of the LISST-RTSSV, with an integrated settling column for settling velocity measurement, is scheduled for the NORI-D Monitoring Campaign of The Metals Company (TMC) in 2022. The capabilities of this new instrument system and initial insights drawn from measurements performed during these deployments will be presented.

Numerical Analysis of Dual-Bore Riser System for Polymetallic Nodules Exploitation

Marcio Yamamoto (National Maritime Research Institute, Japan)

Exploiting polymetallic nodules located in a water depth of about 4,000 m shall require a dual-bore riser system. One bore shall convey the slurry, two phase fluid composed of seawater and ore, while the second bore shall return the water to the seafloor. The slurry is included in the simulation as a homogenous fluid with a density of 1220 kg/m3 and a mass rate of 53.8 kg/s.

For the simulation, both pipes have an external diameter of 177.8 mm. These pipes were arranged in a tandem configuration. The drag coefficient for this tandem configuration was obtained in the literature. The floating platform is an actual drillship; its first-order response in irregular waves was calculated using its Response Amplitude Operator. Besides, we had to assume the added mass coefficient for the dual-bore riser and the subsea slurry pump attached to the bottom end of the riser. This pump had a mass of 300 tons and had the shape of a cylinder with 2 m in diameter and 12 m long. It is necessary to highlight that it is required to have a weight attached to the riser's bottom end. Otherwise, the riser can have extreme bending moments caused by the Mathieu Instability.

It is also assumed that the platform moves forward at a constant velocity of 0.5 m/s. The irregular waves are calculated using the JONSWAP spectrum with a significant height of 2 m and a peak period of 10 s. The current profile was obtained in the literature, which is typical for the Clarion-Clipperton Zone.

Despite the external pipe diameter being constant along the riser, we tried to optimize the structure by reducing the wall thickness at the lower portion to reduce the whole riser mass and, consequently, reduce the effective tension at the riser's top part. The simulation was calculated twice for a constant thickness riser and a riser with reduced wall thickness at the bottom end. The numerical results confirmed that reducing the wall thickness reduces the effective tension on the top portion, while the riser displacement was almost the same.

In the next step, we will evolve the slurry model, assuming it is a two-phase fluid, to consider the pressure drop distribution along the pipe.

Numerical Simulation of Deep-sea Sediment Dispersion Induced by a Pre-prototype Nodule Collector Vehicle in the Northeast Tropical Pacific Ocean

Kaveh Purkiani (GEOMAR Helmholtz Center for Ocean Research Kiel, Germany)

Deep-sea mining may be a profitable option to satisfy the future metal demand of humankind, but it has raised major concerns regarding its environmental impacts on deep-sea ecosystems. In the framework of the Joint Programming Initiative for Healthy and Productive Seas and Oceans, the 'MiningImpact' project aims to assess the long-term impacts of polymetallic nodule mining in the deep sea. In the context of the first industrial trial of the pre-prototype collector vehicle Patania-II by the Belgian company Global Sea Mineral Resources in the Clarion Clipperton Zone in April-May 2021, MiningImpact researchers in parallel conducted an independent scientific environmental monitoring campaign.

To understand the dynamics of sediment transport and spatiotemporal dispersion of the sediment plume in the deep ocean, a numerical simulation study was conducted using observations from the high-resolution monitoring survey in the German and Belgian contract areas for polymetallic nodule exploration. For this purpose, a 3-D sediment transport module coupled to the MIT general circulation model (MITgcm) was applied using local ocean hydrodynamic conditions to simulate sediment plume characteristics generated by the Patania-II activity at the seafloor. A statistically significant agreement between model results and observations of deep-sea current properties and sediment concentrations at different sensor locations around the trial sites was obtained.

Consistent with the prevailing deep-sea currents during the trials, sediment deposition indicates a northwesterly and southeasterly settling pattern at the respective trial sites. The sediment deposit shows a maximum thickness between 30 and 50 mm in the vicinity of the mining tracks and decreases with increasing distance from the mining tracks, reaching about 0.1 mm at a distance of 2500 m from the tracks. Analysis showed that most of D50 and D75 class particles settled immediately within the first day after the mining test was completed, while 5-6% of the D25 material remained suspended in the bottom water for several days. Sediment plume dilution through mixing with the bottom water was very limited.

Offshore Environmental-Resource Exploration in the U.S. Exclusive Economic Zone

Paul O. Knorr (Bureau of Ocean Energy Management-BOEM, USA)

The Bureau of Ocean Energy Management (BOEM), part of the United States Department of the Interior, is the steward of mineral resources on the U.S. Exclusive Economic Zone adjacent to coastal states. The United States defines critical minerals as minerals essential to U.S. economic and national security, that serve a vital function in manufacturing, and that have supply chains vulnerable to disruption.

Approximately half of the designated U.S.-listed critical minerals may occur in offshore deposits. BOEM's Marine Minerals Program , comprised of diverse technical and policy experts, engages in partnerships with federal and state agencies, academic institutions, and other entities to develop and implement multidisciplinary research program to characterize the baseline environment of the U.S. seabed that may contain critical minerals, to analyze the potential effects and impacts of future activities on the chemical, physical, biological, and human environment, and to locate and identify critical minerals. Research projects are underway in the Pacific, Atlantic, and western Aleutian Island regions in 2022, 2023, and 2024. In the Pacific, a 2022 research expedition gathered environmental and resource data associated with hydrothermal sulfide deposits found in the Escanaba Trough spreading center offshore northern California. On the U.S. Atlantic shelf, a planned 2022 ship and autonomous underwater vehicle expedition to the Blake Plateau will gather further data about the environments of known nodule and crust deposits. The study area has been visited several times since historic test mining in the early 1970s and provides an excellent opportunity to document long-term impacts and the recovery of disturbed seabed. Finally, in the western Aleutian Arc of Alaska, a three-phase research program beginning in 2022 will: 1) collect bathymetric and oceanographic data using an autonomous surface vehicle; 2) explore and sample specific sites that show evidence of hydrothermal activity; and 3) perform in-depth analytical environmental characterization of selected sites that could contain critical minerals. Initial bathymetry collection in the Aleutians will commence in Summer 2022, with follow-on projects planned in 2023 and 2024. These projects, all located within the U.S. EEZ, are designed to gather data about both mineral resources and associated environments, providing researchers and BOEM analysts with the types of data and information needed for responsible stewardship.

Patania II Trial: Leveraging Independent International Scientific Engagement towards the Responsible Management of Deep Seabed Resources

Dr. Samantha Smith (Blue Globe Solutions / GSR, Canada)

The world's demand for metal is rising and solutions must be explored to meet the needs of population growth, increasing urbanization, along with clean energy and circular economy goals. Seafloor mineral production could help diversify the world's supply of responsibly sourced minerals and metals. For this industry to happen responsibly, though, we need to take a precautionary approach as we carry out the science, engineering, and impact analysis necessary to extract and process metals with the least environmental impact possible. We need to be committed to the highest standards in environmental science, engineering, and transparent communication. We need partnerships to achieve the goals and we need science to help us make informed decisions.

This presentation will provide an overview of the trial of GSR's pre-prototype seafloor polymetallic nodule collector that occurred in the Clarion Clipperton Zone in April/May 2021, 4.5 km below the ocean's surface. It will also provide an overview of the environmental monitoring that was conducted from the GSR vessel, initial findings, and an overview of next steps.

Progress on Deep Sea Mining Plume Mitigation

John Halkyard (Deep Reach Technology, Inc., USA)

Sediment plumes have been and remain a key topic in evaluation of seabed mining environmental effects. Deep Reach Technology has been developing methods to mitigate plumes with the support of the US DOE Advanced Research Projects Agency – Energy (ARPA-E). The effort involved two innovations: design of a nodule concentrator which prevents sediment collected with the nodules from entering the riser and lift system and using electrocoagulation (EC) to flocculate the sediment on the collector so that it will settle quickly. Preliminary results of this effort were reported at UMC 2020. The UMC 2022 presentation will provide an update and propose a way forward. As a result of a techno- economic evaluation, we have concluded it is probably uneconomic to incorporate EC on the collector. However, we have discovered an innovative method for removing the nodules from the concentrator which should be able to exclude all the sediment from the riser. The method has been demonstrated in CFD calculations and plans are underway to perform experiments to validate these results and to optimize the system, which appears to be economically feasible. Meetings with plume modelers from our industry participants have been encouraging. Plans are to seek additional funds through a Joint Industry Program to carry out the experiments.

Recent Experiences in the Commissioning of a Full-Scale Pilot Mining System in the CCZ

Jon Machin (The Metals Company, Canada)

In early 2019 the formation of a partnership was announced by The Metals Company (TMC) and Allseas Engineering SA (Allseas) for the purpose of the design, build, commissioning and operation of a fully integrated Pilot Test Mining System. The selected test site for operation of the system was NORI-D which is part of the polymetallic nodule contract area held in the Clarion Clipperton Zone (CCZ), under the regulations of the International Seabed Authority (ISA), by Nauru Offshore Resources Inc (NORI).

NORI itself is sponsored by the government of the Republic of Nauru, and it is a wholly owned subsidiary of TMC.

A formal contract between NORI and Allseas for test mining was subsequently announced with the stated objectives;

1) demonstrate technical feasibility of a polymetallic nodule collector system;
2) assess technical performance of prototype collection system, incorporating learnings into full-scale commercial system designs,
3) assist in predicting potential environmental impacts of full-scale operations.

The paper describes the course of this major project which has then followed over the last 3 years. It describes an initial technology evaluation phase which drew on the learnings of previous integrated pilot test mining projects in the CCZ during the 1970's. It describes the eventual concept selection of an approximately 1/5th production scale prototype system for the pilot test. It also describes how advances in deep water subsea engineering and vessel technology from other sectors such as oil & gas, telecoms, and defense, as well as pioneering undersea component test work by other contractors in the CCZ areas, have all contributed to the design, build and eventual successful commissioning by Allseas of the NORI system.

The Pilot Test Mining System is shown to be fully integrated with the following main components:

Surface Support Vessel (SSV). The is capable of supporting PTMS operations and launching and recovering all subsea equipment including the riser. Dynamic positioning (DP) enable the vessel to hold position and follow the subsea equipment as it moves along the seafloor. The vessel selected is a re-purposed and converted oilfield drill ship acquired by Allseas in early 2020 and named *Hidden Gem*. It is a mono-hull vessel with a carrying capacity of about

61,000Te, an overall length of 228m and a width of 42m.

Prototype collector vehicle (PCV). The PCV is a remote control tracked vehicle that uses "Coanda Effect" water jet flow technology to collect nodules from the seafloor with the maximum possible efficiency. It is controlled from the surface vessel via an umbilical.

Riser and Return. The riser system transports nodules collected at the seabed to the SSV using an air lift system. A return pipe discharges entrained water and sediment separated from nodules at the surface to a carefully selected water depth.

The system fabrication, assembly and integration has taken place in 2020 and 2021. It has been completed in Europe in early 2022. Sea trials have subsequently been completed in the North Sea (shallow water commissioning tests) and in the Atlantic Ocean (deep water commissioning tests). Findings and observations from the sea trials are discussed in the paper.

Looking ahead, at the time of Conference it is expected that the system will be operational as the key part of the first fully integrated polymetallic nodule pilot mining system test to have occurred in the CCZ since the 1970's. This should represent a truly historical event for NORI, Allseas, the ISA, and the entire global underwater minerals community.

Responsible Approach Towards a Sustainable Deep-sea Minerals Extraction Future

Guido Van Den Bos (NOV, The Netherlands)

The Deep-sea Mineral Extraction industry will have the opportunity to adopt a widespread experience on offshore vessel - & equipment engineering, sub-sea operations, various levels automation (incl robotics and data analytics) and more recently offshore carbon footprint reductions (CFR) within the marine- & upstream business.

This presentation will cover the development process for a sustainable deep-sea mining process, while looking at the wide range of operational challenges with a pragmatic and system integrational approach.

Not only looking at the vessel operational requirements, but also from all safety aspects in order to keep people and environment out of harm's way. With the various surface equipment developments, sub-sea experience, supply chain overview (offloading) and offshore experience combination to allow operators to perform repeatable, predictable outcomes in remote- and/or harsh environments.

So, adding value through specific product development engineering, technology, and partnerships.

Risk Management Techniques and Application to Deep-Sea Mineral Harvesting

Aaron Barr (Transocean, USA)

On the sea floor of specific deep ocean environments lie prolific amounts of nodules that contain the minerals that are critical to meet the future demands of a developing and growing worldwide population. Polymetallic nodules rich in manganese, nickel, and cobalt spread over millions of square kilometers of abyssal seabed contain the minerals needed for future energy storage demands of the electric energy expansion and other applications. Transocean seeks to participate in the electric energy expansion by leveraging its deepwater experience for the harvesting of these abyssal resources. The knowledge and wisdom gained from decades of offshore experience provides significant insight into the development and implementation of the technology needed to address the challenges of deep-sea nodule harvesting. Specifically, the authors describe herein a risk identification and mitigation methodology developed and refined by the oil and gas industry and apply it to the similar challenges of developing and implementing the technology for harvesting the nodules that contain these precious minerals needed to fuel the electric energy expansion. The methodology includes tools, such as HAZID, HAZOP, and FMEA, techniques, processes and procedures learned by experience from work in complex technological and high-risk deep-sea operations in remote areas.

The risk identification and mitigation study could support a Definitive Feasibility Study as part of an application for commercial operations. The study should address several topics important to the system design and operational function. The scope includes subsea and surface operations and offers insights into the type of risks to be considered during the system design process. While other sources have dealt with risks of subsea and surface operations, this work takes a holistic approach, applying the risk identification process to the development and implementation of the technology needed to access these minerals from the seabed. A short discussion accompanies each major risk and describes its significance to the project. These topics include: • International, Domestic, and Maritime Regulations

- Subsea Collector and Auxiliary Systems
- Vertical Transport System
- Processing, Storage and Offloading System
- Station Keeping Philosophy
- Power Management System
- Hull Structural Design
- Environmental Monitoring
- Emergency Response
- Logistical Support

Seafloor Massive Sulphide Exploration in the German ISA License Area

Udo Barckhausen (BGR Federal Institute for Geosciences and Natural Resources, Germany)

The identification and evaluation of seafloor massive sulphide ore-deposits in the deep ocean is a needle-in-a-haystack problem. The deposits are relatively small (size of a soccer field) and form in complex terrain at mid-ocean ridges, island arcs, and back-arc spreading centres. The plume of active hydrothermal systems can be traced in the water column; however, active hydrothermal vents have no mining potential. Inactive and extinct vent sites are generally missing characteristic seafloor expressions such as black smokers and distinct vent fauna and may be hidden under a thin layer of sediments.

Since 2015, BGR carries out annual research cruises on behalf of the German government to the German license areas for polymetallic sulphides located along the Central and Southeast Indian ridges (INDEX project). The 15-year project has been approved by the International Seabed Authority (ISA) with the aim to find prospective mineral deposits and to establish environmental baseline studies. A number of so far unknown hydrothermal systems have been identified using a systematic approach including ship-based and deep-tow high-resolution bathymetry, mapping of water column tracers, video observations, petrophysical analysis of rock samples, and biological sampling.

An important aspect in mineral resource assessment is the inner structure and spatial extent of the deposits, in particular their dimensions in depth, which can be addressed by geophysical methods. In addition to magnetic and bathymetric surveying, we apply electromagnetic and self-potential methods using different sensor platforms such as the Golden Eye Profiler and Vulcan deep-towed 3-axial electric field receivers. We can clearly relate electrical conductivity and self-potential anomalies to previously identified sulphide sightings of both active and inactive hydrothermal areas. The combination of electrical properties, self-potential, magnetic anomalies, and geological constraints allows for 3D-inversion and modelling of massive sulphide ore bodies and hydrothermally altered rocks. However, deriving spatial constraints is still one of the most challenging and vital disciplines of geophysical exploration in this context.

Figure 1. Left: Golden Eye recovery on RV Pelagia. Right: Vulcan E-field receiver being deployed at the aft deck.

Selective Mining of The Seabed Using Telerobotic Mining Techniques

Greg Baiden (Penguin Automated Systems Inc., Canada)

Mining of the seafloor has had limited success to date with mining companies using dredging and mass cutting techniques. While these methods can be applied successfully and have been in current surface mining applications. The key to successful seafloor mining will be the ability to work in a selective fashion limiting the disturbance to the marine wildlife and the habitat of the area.

In the early 1980's Inco Limited began a strategic thrust to fundamentally change underground mining by using surface controlled remote (teleremote) mining techniques. These techniques were undertaken to improve safety, productivity, and reserves. This initiative saw advances in worker safety while improving the mining fundamentals, increasing throughput, quality and profitability while allowing selective (surgical) mining techniques. Demonstration of the techniques and methodology occurred with a robotic mining pilot plant located at the 175 Orebody in Copper Cliff, Ontario, Canada. This Pilot Plant tested the concepts and proved the expected outcomes. This pilot proved selectivity of the mining results, reduced travel time into the mine, improved the quality of the unit processes and subsequently reduced consumables and capital costs. Key technologies demonstrated were advanced wireless networking using advanced communication, GPS denied positioning, virtual robotic control of machines and AI swarming control of robot systems. This new telerobotic concept of operations (CONOPS) is gradually being implemented globally today albeit in a piecemeal fashion.

While this strategic shift to telerobotic mining is quietly revolutionizing land based operations on 29% of the planet, the remaining 71% (underwater) of the planet is a potential new frontier for safe, responsible exploitation of underwater resources. The key question is do we have the technologies to support this style of mining underwater? This paper explores progress made towards this goal. Recent developments in wireless underwater optical communications with the bandwidth to teleoperate fleets of underwater mining robots, GPS denied positioning for the control of those robots and the interface with the mining area, solid state robots for deep underwater operations and AI based fleet control to build systems for underwater mining will be discussed in this paper.

Ship to Ship Transfer of Polymetallic Nodules in the Deep and Open Oceans

Tyson Breedlove (ABS, USA)

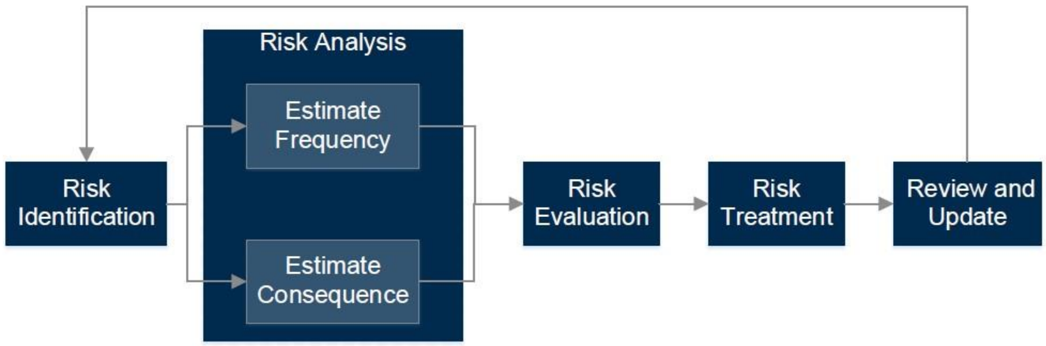
OBJECTIVES/SCOPE:

Many companies with a history of innovation and achievement in the offshore industry are working on new solutions to making deep sea mining safe, responsible, and commercially viable. As the level of maturity of related systems and vessels mature, Class Societies are working with Flags and Regulators to lay down frameworks for Rules and Regulations that add confidence to the operation and provide assurance to key stakeholders. The goal is to have industry standards and regulations to develop at nearly the same pace as technology. This process relies heavily on current use cases throughout the industry, lessons learned from previous experiences, as well as risk assessments and engineering evaluations. This paper will discuss one aspect of a deep sea mining operation that will require Class and Flag approval: ship to ship transfer of polymetallic nodules extracted from the abyssal plains in the deep and open oceans.

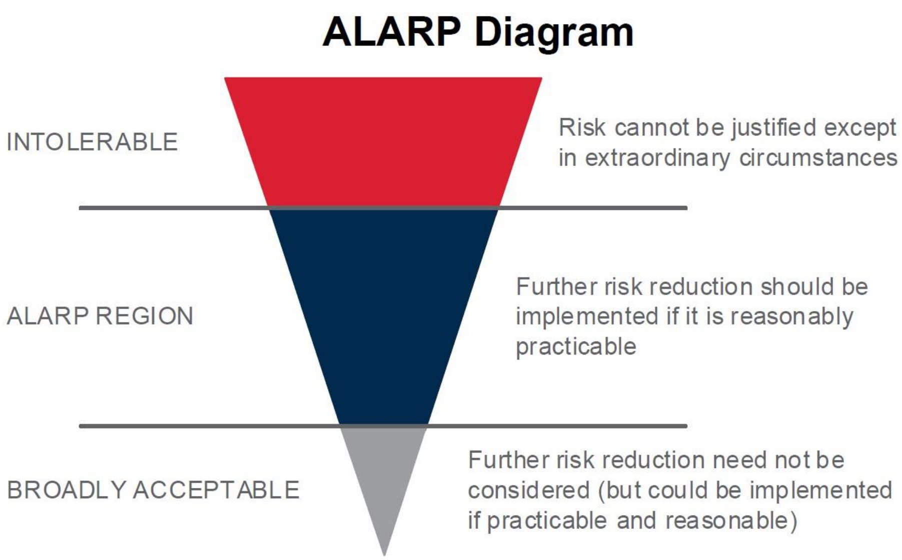
METHODS, PROCEDURES, PROCESS

Ship to ship transfer of polymetallic nodules in the deep and open oceans is a novel concept that is yet to be done on a commercial scale. When Class Societies evaluate novel concepts, they look to risk assessments and engineering evaluations to demonstrate equivalency and acceptability for a proposed design. The goal of these evaluations is to ensure that the novel design provides acceptable levels of safety in line with current offshore industry practice.[i]

Risk assessment techniques can identify, mitigate, and manage the unique risks that arise from such an activity. The process of a risk assessment consists of four basic steps visualized below, Risk Identification, Risk Analysis, Risk Evaluation and finally Risk Treatment.



The *ABS Guide for Subsea Mining* requires, at a minimum, a Hazard Identification (HAZID) workshop to be conducted. **HAZIDs are effective at not only identifying risks, but also analysis and evaluation of the risks.** It is expected that such risks will be reduced to the As Low As Reasonably Practicable (ALARP) Level. ALARP is a level of risk that is neither negligibly low nor intolerably high, for which further investment of resources for risk reduction is not justifiable. Risk should be reduced to ALARP level considering the cost effectiveness of the risk control options.



RESULTS, OBSERVATIONS, CONCLUSIONS

There are several service cases that can be applied to help us to learn what the associated challenges will be. The two concepts for ship to ship transfer of nodules at sea are dry transfer or wet (slurry) transfer. Each transfer mode offers a different set of challenges and benefits. The purpose of this paper is to go into the relevant requirements associated with each transfer mode based on comparisons with current industry use cases and lessons learned.

Wet Transfer:

For example, wet transfer near shore has been ongoing in New Zealand for several decades, and much has been learned about managing the associated risks. At the Port of Taharoa, wet iron sands (Titanomagnetite) are piped from an onshore mine to a single buoy mooring in and exposed offshore location about 2 km from land. A bulk carrier is moored to the buoy for wet transfer of the iron sands into cargo tanks. Once settled into the bulk carrier holds, the water is decanted into the open sea. Afterwards the vessel departs the single buoy mooring. It should be noted that this operation was performed without a tug, but with assistance of a pilot.

For some years, this operation took place with off the shelf Cape-max bulk carriers. However, after more than a few safety incidents involving cargo instability, three purpose built carriers were specifically designed for this service. Some design improvements included a raised forecastle deck to protect crew from the sea, a Schilling Rudder to improve maneuverability at slow speeds and an improved dewatering system.

Figure 1 - Schilling Rudder Profile

This operation is similar to SBM operations in the hydrocarbon industry, where there is a need to safeguard the integrity of the buoy. Yet a deep-sea mining operation will have notable differences, namely the material being transferred. Iron sands is classified as Category C in the International Maritime Solid Bulk Cargoes (IMSBC) Code, which means it is not subject to liquefaction. Even so, during the Taharoa operation the voyage was not to be commenced until the free water has been discharged, however the iron sands did not need to undergo drying. Bulk polymetallic nodules are yet to be classified. There is a risk that their behavior under loading conditions is more susceptible to liquefaction and cargo shifting than iron-sands. The exact behavior of polymetallic ore and the appropriate precautions needed to be taken cannot be determined until the properties of the ore have been thoroughly tested.

Dry Transfer:

Dry transfer of bulk occurs worldwide, particularly in transshipment and lightering services, and much has been learned from this service history.

For deep sea mining the environmental loadings on the mining installation and transport vessel have the potential to be higher than in nearshore service, and much higher than port loading. These arise from the bending and shear effects caused by waves as well as motion induced loads from vessel movement. Transfer of bulk cargoes in such cases require preplanning of the loading sequence and a full understanding of the limitations which need to be applied to the transfer operation envelope.

Evaluation of the planned operations will involve defining the location(s), frequency of transfer, vessel types and sizes, and the properties of the cargo.

A wide range of machinery and equipment is available for dry transfer operations and optimum selection depends on the inputs above: these may include cranes, buckets, conveyors, hoppers, hatch covers, and other associated items.

The high density of solid cargoes requires attention to the hulls of both the shipping and receiving vessel. Particular attention is paid to hull strength and fatigue based on the loading patterns and the resulting bending moments and shear force on the overall structure. Local strength in the holds is also a consideration. Allowable loadings will set limits on the environmental conditions for the transfer operations in terms of observed wind, wave and current as well as vessel motions. Motions need to be considered for the multiple vessels since they are essentially connected to each other as a combined system.

Stability of the vessels is also important not only before and after transfer, but also for temporary conditions during transfer when equipment is not in its stowed position and while the weight and center of gravity are changing throughout the loading sequence.

An additional challenge is the nature of coordinating multiple vessels when approaching each other, engaging fendering and mooring, undertaking the cargo transfer, and disengaging after completion.

All of the foregoing lead to a need for a robust safety management system that covers the operations, and encompasses:

- Crew training;
- Procedures (normal and emergency);
- Equipment maintenance;
- Hull inspection planning;
- Safety of vessel approach/departure
- Combined operations safety, operational limitations, and chain of command.

Conclusion:

In conclusion, ship to ship transfer of dry or wet bulk or polymetallic nodules at sea is a novel operation requiring thorough risk assessments and mitigations in order to be done safely. Lessons learned from current operations worldwide provide a wide array or considerations, most notably cargo stability, hull fatigue and cracking, weather limitations and the importance of an approved loading plan.

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State-of-the-art, Integrated Monitoring and Modeling of Nodule Mining Sediment Plumes

Tomas Peacock (Massachusetts Institute of Technology & Scripps Institution of Oceanography, USA)

The evolution of sediment plumes associated with deep-seabed nodule mining activities involves a combination of fluid mechanics processes that span a wide range of temporal and spatial scales, resulting in complex behavior. We are developing an integrated approach to sediment plume modeling and monitoring that combines fundamental fluid mechanics, state-of-the-art computational science, laboratory experiments, instrument development and physics-informed monitoring of field studies to produce breakthrough advances in how sediment plumes should be modeled and monitored for deep seabed mining.

In this presentation we give an overview of some of the latest advances. This includes: (i) the first direct observations of collector plumes in the turbidity current phase from the 2021 GSR collector trials in the Clarion Clipperton Zone, which confirmed our modeling predictions, (ii). the outcomes of some cutting-edge GPU-powered 3D direct numerical simulations of the sediment plume produced in the vicinity of a complex test-mining pattern, using the specific pattern conducted during the 2021 GSR collector trials, and (iii) in-situ turbulence measurements.

A key take-away from these advances in physics-informed monitoring and modeling is that failing to properly consider the fundamental fluid mechanics processes that control plumes, particularly in the early phase of their evolution, leads to misconceptions in interpreting field data and substantial errors when predicting their scale and fate. Our methods provide solutions that can be incorporated and custom-tailored to any modeling and monitoring campaign, in order to thoroughly assess the scale and fate of sediment plumes produced by any seabed mining activity.

Taking the First Industrial Steps into the Deep Sea in Norway

Ståle Monstad (Green Minerals AS, Norway)

The Norwegian authorities are currently conducting a comprehensive impact assessment within the Norwegian Exclusive Economic Zone (EEZ) in preparation for the Norwegian Parliament and their scheduled “Opening Decision” session in Q3/2023 (figure 1). The area decided for the assessment covers more than 600 000 km^2 and comprise several proven active, inactive and extinct seafloor massive sulphide (SMS) occurrences, within more than 1000 km of ultraslow-spreading Atlantic Mid Ocean Ridge (Mohn-Knipovitch ridge) with several proven SMS. In addition, the assessment areas include settings favourable for deposition of polymetallic Crust (e.g The Greenland Basin and the Vøring Spur). No significant accumulations of polymetallic nodules are proven or expected within the Norwegian EEZ.

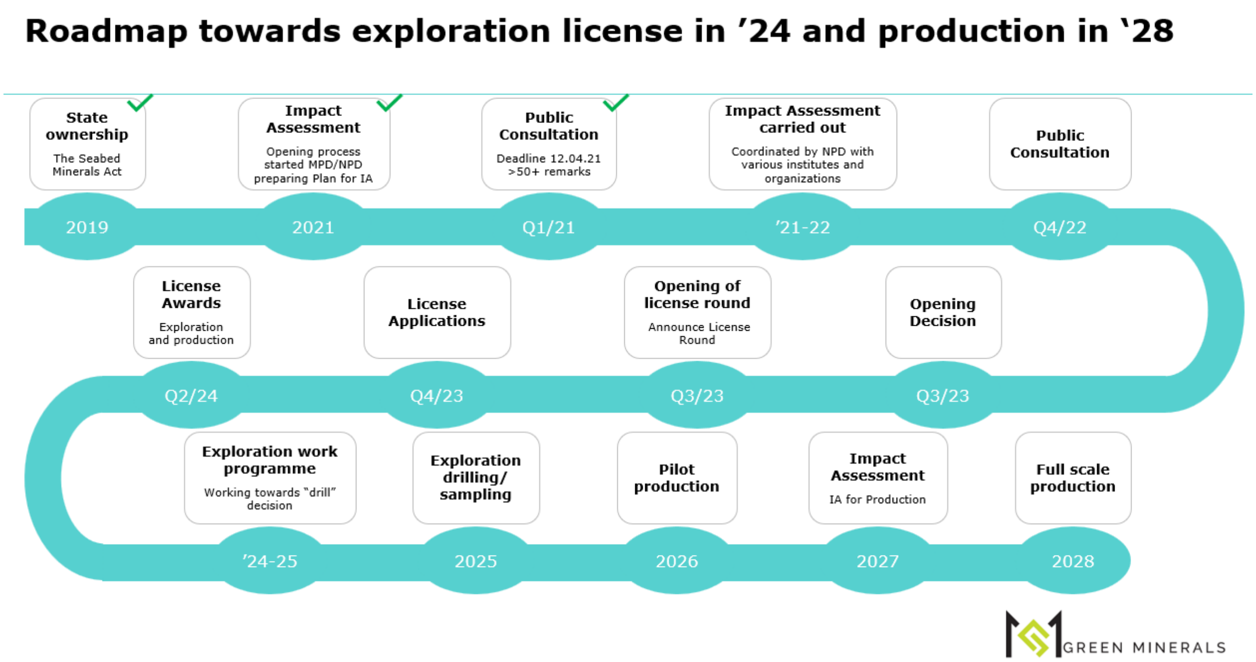

Figure 1, Roadmap for Deep Sea Minerals activity in Norway’s EEZ

According to several recent reports (i.e., IEA, 2021), the Green Shift will require a significant increase in metal supply. An ambition that may be challenging to satisfy.

The deep-sea minerals in Norway may represent an important metal resource that could contribute to this increasing future metals demand. Green Mineral's initially focuses on the SMS resources in the Norwegian sector where preliminary analyses indicate very interesting copper concentrations (up to 14 %) and potentially commercial concentrations of cobalt and zinc (up to 0,7% and 3,2% respectively) , Ref NPD, Faavne discovery, 2022.

Globally, existing onshore mining operations must accommodate with ever-decreasing copper grades. The Average copper ore grade in Chile, the world's largest copper producer, is currently below 0,8 % and new onshore projects in Scandinavia (re-opening of previous mining areas, I.e., brown fields) exhibit similar ore grades. During the last decade, the onshore copper-exploration success has been low and led to few greenfield developments. In addition, greenfield developments are also faced with considerable environmental challenges. We firmly believe that the potential SMS resources offshore Norway offers an attractive alternative to some onshore greenfield developments - and could significant supplement the existing onshore copper production.

As a preparation to discussions with onshore mineral processing facilities in the Nordic countries, Green Minerals has initiated a comprehensive characterisation study of SMS material from a slow spreading ridge. This characterisation study is the necessary step before a processing study to investigate if and how SMS ore can be processed together with the onshore ore through a blending strategy. Blending SMS high grade copper ore into lower ore grade ore from an existing mine may have several positive impacts including, an increased Life-Of-Mine for the existing operations, a decrease in waste production and a decrease in energy requirements per tonne of produced metal. Finally, such a blending strategy may enable the use of existing mineral processing facilities which would significantly decrease the CAPEX of deep-sea mining operations and prove itself as a key-enable for this new industry.

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Target-driven Approach to Deep-Sea Minerals Exploration with AUV's

Anna Lim (Argeo, Norway)

Decades of research studies and offshore campaigns have established a solid knowledgebase about different types of deep-sea minerals (DSM). Active hydrothermal vent fields have been most systematically studied across the global mid-ocean ridge, in large due to their geological and biological significance and not least due to the relative simplicity of their identification through hydrothermal plume tracing in water column. Seafloor massive sulfides (SMS) associated with hydrothermal venting also benefit from their three-dimensionality, typically reaching a few hundreds of meters horizontally and a couple of hundred meters vertically, which affects their detectability with remote geophysical sensing. This is not the case for polymetallic crusts that can extend for a few kilometers horizontally but rarely exceed 0.5 m in thickness.

Similarly, polymetallic nodules can spread even wider, hundreds of kilometers, but practically present 2D-fields of disconnected nodules of around 0.15 m diameter. With such a range in dimensions and very limited vertical extent of the deposits compared to water depth they are typically found at (3,500 m on average), water sampling and other sea-surface measurements become no longer efficient in identifying nor resolving these deposits, especially the inactive or buried deposits. In recent years, best-practice exploration methodology has shaped to include the use of various high-frequency sonars together with magnetometers and passive electric field sensors mounted on autonomous underwater vehicles (AUV's).

Such setup allows for more confident identification of the deposits, and provides insight into deposit's subsurface extent. However, confident delineation and characterization of the ore bodies in the subsurface has not been fulfilled with these passive methods. To further improve both horizontal and vertical delineation of polymetallic crusts and SMS, as well as to improve nodule fields exploration in green areas and provide a reliable and efficient method for inactive sites mapping, Argeo have developed a new controlled-source electromagnetic system that can be mounted on one or several AUV's considerably improving exploration efficiency and data quality. Our modeling results suggest that near-seafloor controlled source electromagnetics (CSEM) specifically developed for DSM exploration combined with advanced EM data processing techniques allows delineation and characterization of polymetallic crusts as thin as a few cm.

Considering the environmental impact of any marine operation to be carried out in deep sea and the economic requirement for efficiency of marine mineral exploration, finding both the most informative combination of methods and a balance between spatial resolution and areal coverage will be key to ensuring successful and sustainable development of the industry. An exploration survey must provide relevant data of high quality (informative methods for a given geological context, sufficient data resolution and density) at an optimal areal coverage rate with as minimum impact on the environment as possible (choice of equipment, time spent at the seafloor, disturbance of the seabed and water column). In our presentation, we will discuss how AUV's can be used to address these challenges and provide ultrahigh-quality data with applications across the DSM value chain.

Techno-economic Assessment of Deep-sea Mining

Rahul Sharma (National Institute of Oceanography, Goa, India)

Deep-sea minerals such as polymetallic nodules, ferromanganese crusts and hydrothermal sulfides, are emerging as potential sources of metals such as Cu, Ni, Co, Mn, Fe, and other rare earth elements that could be mined in future and contribute towards green energy alternatives. As many of these mineral deposits lie in the international waters in the oceans of the world, the International Seabed Authority (established as per the provisions of UNCLOS) that regulates all activities related to seabed resources has signed exploration contracts with several entities. Mapping of these resources has been underway for several decades using sophisticated sounding, sampling and imaging techniques leading to resource evaluation of these minerals that are found in millions of tones and estimates show that these contain strategic metals worth billions of dollars.

Key points of this presentation are follows:

1. Besides an increase in metal demands due to industrial growth and rising living standards, there is a need to transition the energy, transport and industrial infrastructure from fossil fuel to green and renewable energy options.
2. There is a projected demand for millions of tones of metals (including Mn, Ni, Cu and Co) to meet these requirements.
3. Mean production rate of different metals has been rising in the last 20 years (eg. Co = 8.3% per year, Cu = 3.1%, Ni = 3.7%, Mn = 4.3%, Pb = 2.6%, Zn = 2.9%).
4. Estimates have shown that the available reserves of some of the metals such as Mn, Cu, Ni, Co would last for just over two decades whereas Pb and Zn would last over one decade.
5. Polymetallic nodules mined at different mining rates (1-3 MT/y) would yield ores between 3000 and 10,000 tones per day and the area (size) of the mine site would range between 4267 sq.km and 12,800 sq.km.
6. The area of contact that would be actually scraped would vary between 200-600 km^2 per year for mining rates between 1.0-3.0 million tones per year, which is 0.66-2.0 Km^2 per day and works out to 5-16% of the Contract area (75,000 sq.km).
7. In a typical nodule contract area of 75000 sq km with a cutoff abundance of 5 kg/m^2, the total available resource would be 375 MMT (wet) or/ 281.25 MMT (dry), containing total metal resource of at least 67.53 MMT (@Mn=22%, Ni=1%, Cu=0.78%, Co=0.23%).
8. At the metal prices of 2021, the gross in place value of these four metals would be $ 21.15 billion at the mining rate of 1.5 Mt/y, whereas the CAPEX and OPEX for mining of 1.5 Mt/y for 20 years, including the cost of mining system, ore transfer and processing plant currently works out to $ 14.64 billion, implying that metals worth $ 21.15 billion can be extracted for an investment of $ 14.64 billion from a single nodule area.

The Vertical Approach: Sustainable Exploration of Mineral Resources in the Deep Sea

Semel Matthias (Bauer Maschinen GmbH, Germany)

The Vertical Approach is an innovative new concept for minimal invasive deep sea sampling. This exploration method focuses on the extraction of large volumes from massive sulfide deposits. The Bauer Maschinen company started the concept design and development of this vertical sampling technique based on their long experience and history within the area of trench cutters. At first the Bauer cutter technology originated from special foundation projects. On construction sites trench cutters are mainly used to create impermeable diaphragm walls. In the past Bauer already successfully transferred their cutter knowledge to offshore applications. For bulk sampling campaigns in shallow coastal waters trench cutting proved its capability. To further investigate the technical feasibility of the Vertical Approach concept and its readiness for deep sea applications, a research project was launched in 2021. Jointly together with four German university institutes and one industry partner, Bauer is evaluating and enhancing their system for minimal invasive bulk sampling of massive sulfides. The major objective is to minimize and monitor the environmental impact of the exploration operation whilst providing an efficient and economical way of retrieving large amounts of sample materials from the seabed. The research project will be ongoing for two more years and will be finalized with conclusion regarding prove of concept.

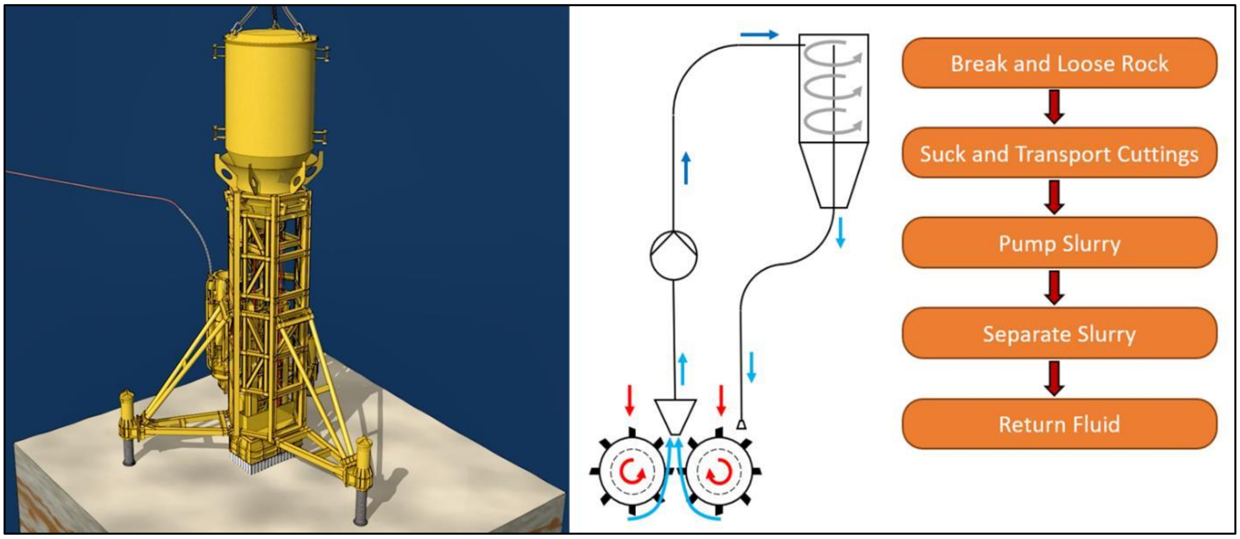

Figure 1. Vertical Approach concept and operation sequence for massive sulfide bulk sampling

The sampling method of massive sulfides through a trench cutting system is suitable to perform exploration activities whit lowest impact on the surrounding environment. The Vertical Approach System consists of a landing template, cutter unit including suction pump and a collector bucket attached on top. After lowering the complete unit down to seabed via vessel crane, the template levels the system. Then cutting and sizing of the seabed massive sulfide ores with the trench cutter can commence. Two cutter wheels are breaking and loosening the solid rock formation. The crushed material is removed from the trench and adjacent pumped into the collector bucket. Separation process of cuttings and process water will take place within the collector bucket in-situ at seabed level. The treated process water will be reused and pumped back into the cutting zone. As the trench is enclosed and shielded against the ambient seawater environment, a closed mud circuit is established. At the end of the process sequence, once the separation bucket is filled up, only the container with the sampling material will be disconnected from the template and lifted back up to the vessel. This discontinuous conveying method substitutes a costly and energy intensive riser system. The ore is already separated on the seabed and transported mechanically via crane winch to the ocean surface. On vessel deck the collector bucket is emptied, remaining process water gets treated and material is stored. Afterwards the collector bucket will be lowered back to seabed and connect to the template again. The sampling unit can then be positioned on the next location.

The research project “Deep Sea Sampling”, subsidized by the German Federal Ministry for Economic Affairs and Climate Action, will contribute to solve and tackle the challenges of deep sea exploration.

Turning the Resource into a Commodity

Espen Simonstad (Green Minerals AS, Norway)

The Norwegian authorities are currently conducting a comprehensive impact assessment within the Norwegian Exclusive Economic Zone (EEZ) in preparation for the Norwegian Parliament and their scheduled "Opening Decision" session in Q3/2023. The area decided for the assessment covers more than 600 000 km^2 and comprise several proven active, inactive, and extinct seafloor massive sulphide (SMS) occurrences, within more than 1000 km of ultraslow-spreading Atlantic Mid Ocean Ridge (MohnKnipovich ridge).

Before an opening decision is taken, only Norwegian public bodies or academic institutions are allowed to acquire data on the Mohn-Knipovich ridge and other area under Norwegian jurisdiction. Green Minerals have through academic partners secured two rock samples from the Mid Atlantic Ridge, Figure 1, in the TAG area. The samples, one massive sulphide sample and one sample from a layered sulphide exhibiting significant weathering, show the variety of SMS ore types. we believe these sample are representative for a Norwegian study due to similar geological settings between the Mid-Atlantic Ridge and the Mohns-Knipovich Ridge.

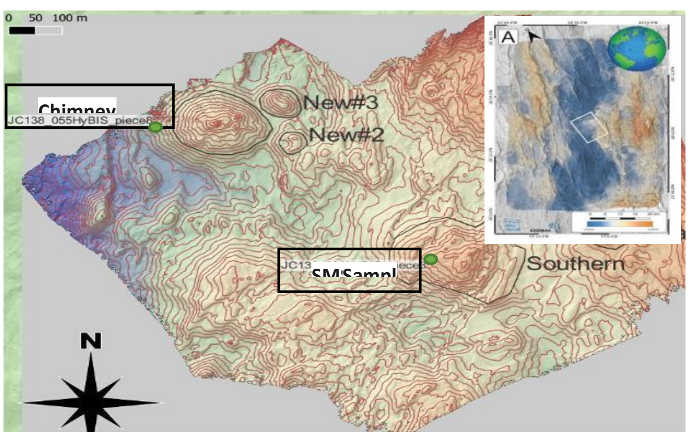

Figure 1. Location of samples from The Mid Atlantic Ridge

Designing the value chain of SMS ores and exploring the potential scenarios for their production requires an in-depth understanding of how these SMS ores can be processed and refined. This can be done through a predictive geo-metallurgical approach Figure 2 that allows to evaluate potential processing options for a given ore based on key ore properties (mineralogy, textures, etc.) and their variability within the deposit. To progress with the geo-metallurgical study, Green Minerals has started a characterization study of the aforementioned SMS samples together with the Geological Survey of Finland (GTK). This characterization study is the necessary first step towards a mineral processing study where options for recovering target minerals and metals from SMS ores can be developed further. This characterization study is also the necessary step before investigating if and how SMS ore can be processed together with an onshore ore presenting similar characteristics through a blending strategy. Blending SMS high grade copper ore into lower ore grade ore from an existing mine may have several positive impacts including, an increased Life-Of-Mine for the existing operations, a decrease in net waste production and a decrease in energy requirements per ton of produced metal. Finally, such a blending strategy may enable the use of existing mineral processing facilities which would significantly decrease the CAPEX of deep-sea mining operations and prove itself as a key-enable for this new industry.

The objectives for the geo-metallurgical characterization study in phase 1 are:

- To quantify the chemical and mineralogical composition of the SMS ores, to support the identification and definition of target metals and potential by-/co-products or penalty elements,
- To define the main mineralogical and geo-metallurgical properties of SMS ores in terms of:

  o Elemental deportment of target metals (*e.g.*, Cu, Zn) in specific minerals, o Target minerals grains size distribution, o Target mineral liberation and associations,

- To formulate preliminary considerations on mineral processing based on the above.

To achieve these objectives a comprehensive testing schedule has been established as shown on Figure 2

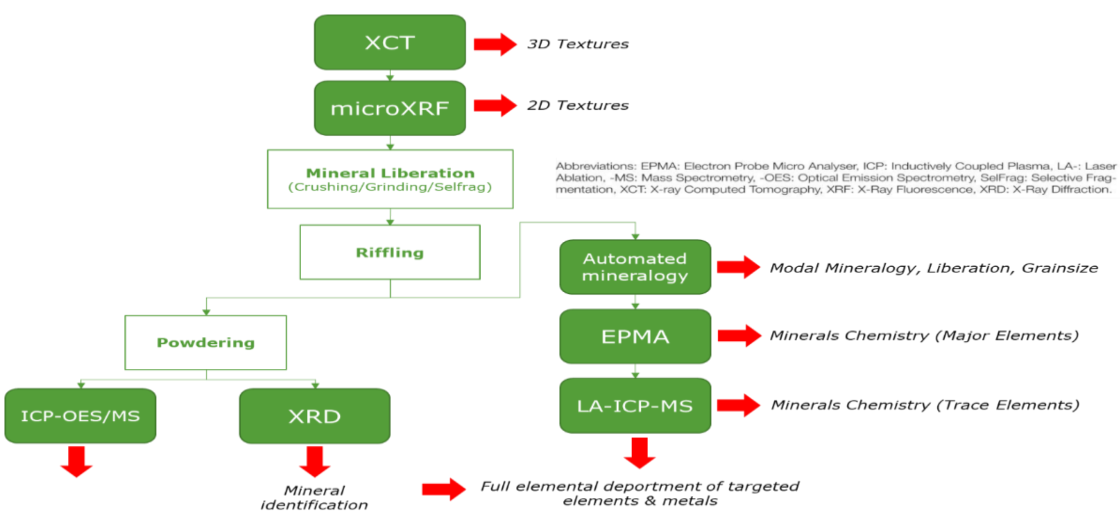

Figure 2. Testing flowchart for characterisation study.

When the characterization study results will confirm the possibility of a performing a mineral processing study on the aforementioned samples, the objectives of this study will be:

- The preliminary definition of processing methods and technologies suitable for SMS ore based on the characterizations study outcomes,
- To perform a liberation analysis through crushing and grinding tests, particle size distribution and optimal grind size definition and to perform lab-scale scoping mineral processing tests (flotation, gravity, etc.) on SMS samples.
- To perform tests on a blend of SMS ore and equivalent available onshore ore (*e.g.,* VMS ore) with similar characteristics.

We will share preliminary results from the characterization study, discuss the importance of the results and share our thoughts on future work.

Volumetric Acoustic Measurements on Polymetallic Nodules using a 3D Sonar System for Surface Density Estimation on the Seafloor

Michael Ehrhardt (Fraunhofer-Institute for Biomedical Engineering, Germany)

Motivation

A reliable economic assessment of vast polymetallic nodule deposits in the deep sea requires a fast and accurate estimate of the amount and mass of nodules. Up to now, the quantitative remote in-situ acquisition of nodules for estimating the surface density is predominantly performed via the analysis of optical images from deep-towed video sledges. With this method, the nodule abundance (kg/m²) can only be estimated if the nodules lie on top of the sediment surface, their sizes vary little and the nodules are largely free of sediment cover. In areas where the nodules are partly or completely covered with sediment and the size distribution varies significantly, this optical image-based method fails due to insufficient accuracy. For such occasions, acoustical imaging techniques provide advantages since the acoustic waves can penetrate the covering sediment layer and detect the top side of the nodules. The intended contribution describes and discusses novel volumetric acoustic measurements of polymetallic nodules that were performed in an artificial environment with ambient conditions similar to those on the sea floor. The purpose of these measurements was to detect the cumulative volume of the nodules with an accuracy better than ±20 % in order to reliably estimate the surface density.

Materials and methods

An innovative proprietary 3D sonar system [1] has been used for the acquisition and analysis of the acoustic data. This sonar system is an experimental prototype system consisting of a 1024 element matrix antenna together with a research beamformer [2] as well as a customized reconstruction and evaluation software. The aim of the work was to investigate and evaluate the system's suitability for the application in surface density estimations of polymetallic nodules on the sea floor. For performing the acoustic measurements, an appropriate measuring site (pool with diameter of 3 m, water height of 1 m over 20 cm of sediment) with a high-precision antenna positioning system (accuracy of one millimeter in all three directions, accuracy of one degree for two tilt angles) was designed and realized. The environmental parameters within the measuring site have been copied from nature as far as possible in order to receive comparable results for the later on application in the deep sea (artificial seawater with salinity of 3.5 %, natural sediment from the deep sea).

Measurements on different sizes and arrangements of nodules in accordance with their natural occurrences have been performed using image compounding techniques from various antenna perspectives. Here, the nodule arrangements have been captured also under covering sediment layers of different thicknesses. For the correct superposition of the acoustical data sets obtained from the single perspectives, the antenna position was continuously tracked with the aid of a high-precision optical tracking device (Polaris Spectra from NDI Medical). For an evaluation of the system's measurement accuracy, the point cloud volumes derived from the acoustic measurements have been compared to those from a micrometer-resolution laser scanning system, serving as reference model.

Results

A comparison between the point cloud representations was performed via a spatial deviation analysis. Here, the deviations between corresponding points from both point clouds were calculated and displayed color-coded. The analysis showed that the spatial deviations are within a range below 7 mm, which implies a very high level of spatial accuracy in the acoustic measurements.

In order to quantitatively evaluate the actual nodules' volumes from the acoustical measurements, single nodules have been segmented from the data set followed by a numerical volume calculation based on geometric approximation. This work was performed by Pagoda Systems, Germany. The volumes of these nodules also have been determined using the Archimedes' principle (water displacement). As a result, we found an averaged volume deviation of 19 % for the nodules. Overall, the results of the acoustical measurements with the novel 3D sonar system show convincing point cloud representations of the polymetallic nodules with the potential of a subsequent automated volume extraction. Comparisons to the results of reference measurements show an appropriate accuracy of the acoustical volume determination. Even under higher water turbidity and moderate sedimentation layers, the nodules' volumes could be determined within the given accuracy tolerance. Hence, it can be stated that the proposed acoustical measurement system is basically suited for the application of volumetric acquisition of polymetallic nodules for surface density estimation.

Acknowledgement

The work has been conducted on behalf of the Federal Institute for Geosciences and Natural Resources BGR in Hannover, Germany. The volumetric analyses of the point cloud representations have been performed by Pagoda Systems, Germany.

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(Poster) Characterizing sedimentary phytodetritus utilizing chlorophyll-a and phaeophytin pigments in NORI-D, Clarion Clipperton Zone

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Polymetallic nodule fields in the Clarion Clipperton Zone (CCZ) have been identified as a viable source of metals to aid in the global transition to renewable energy use. In order to gauge the potential impact harvesting these nodules would have on the benthic ecosystem of the CCZ, it is necessary to characterize sedimentary phytodetritus compositions utilizing labile chlorophyll-a and degraded phaeophytin pigment concentrations. These values reflect the availability of organic matter as a food source for benthic organisms and represent the degree of organic matter deposition to the seafloor. This study focuses on the southeasternmost exploration area of the CCZ contracted to Nauru Ocean Resources Inc. (NORI). Multicores were collected aboard the Maersk Launcher in October-November 2020 and again in May-June 2021 from three primary areas in the exploration zone; test mining, affected areas, and preservation sites. Sediment cores from 0-5 centimeters in depth were collected and separated into 1 centimeter increment subsamples. Acetone extracts were taken from each subsample for spectrofluorometric analysis. Measurements concluded that preservation sites for both campaigns had the highest average phyto pigment concentrations (0.040 +/- 0.003 ug/g chl-a; 0.072 +/- 0.013 ug/g phaeo) in comparison to test sites (0.027 +/- 0.004 ug/g chl-a; 0.049 +/- 0.005 ug/g phaeo). A type 1 ANOVA test revealed that there was limited significant variability between phyto pigment concentrations among campaigns, suggesting the possibility of minimal seasonal change in phyto-detritus deposition. In addition, a type 1 ANOVA test revealed minimal variation in spatial distribution of phyto pigments between preservation and test sites for both campaigns. This suggests that the preservation zone within NORI-D is a valid representation of habitat type based on sedimentary phytodetritus. These findings are in support of and will be incorporated into a larger research effort to establish a pre-test mining environmental baseline in the CCZ.

(Poster) Nicholas for Deep-sea Mining? Developing a Multi-criteria Decision Framework for the Selection of Ecologically Favorable Exploitation Techniques for Deep-sea Mineral Deposits

Raoul Schmitt (Norwegian University of Science and Technology, Norway)

Selecting a suitable exploitation method for land-based mines is an early and pivotal step in evaluating a mining project's overall feasibility. The chosen mining method is decisive for subsequent stages of the mining value chain, including mine design and production scheduling. Generally, the most suitable mining method achieves the safest, most environmentally considerate, and economical operation while maintaining high productivity. Traditional numerical approaches that help to match the attributes of specific mining methods to the orebody characteristics comprise the well-known Nicholas method and its modified version, the UBC method, amongst others. The evaluation criteria, or system input parameters, considered in mining method selection (MMS) encompass but are not limited to spatial, geologic, geotechnical, geo-metallurgical, technological, economic, and environmental factors.

Is it possible to approach the extraction of mineral deposits from the deep sea correspondingly? Increasing interest in the subject matter from academia, government, industry, and the public sparked by the 'green transition' requires a framework for selecting the most suitable exploitation techniques from the currently existing Best Available Technologies (BAT) and technological concepts for deep-sea mining (DSM). The deep sea is a host to ecologically sensitive and largely unknown habitats (e.g., inactive seafloor massive sulfide (SMS) deposits), which are likely to be adversely affected by DSM activities. Thus, this investigation aims at integrating ecologic uncertainty into a selection framework for DSM methods.

Given the different deep-sea deposits known to date, a global perspective on DSM is necessary. Therefore, SMS and cobalt-rich ferromanganese crust deposits on the Norwegian extended continental shelf, as well as manganese nodule deposits of the Clarion Clipperton Zone (CCZ) and rare earth element (REE) rich muds found within the Japanese exclusive economic zone (EEZ) are considered. In a first step, BAT in DSM and their applicability to different mineral deposits is reviewed, and possible environmental stressors (e.g., noise, light, vibration, substrate removal rate, sediment compaction, sediment plume generation, discharge of pollutants) are identified and quantified. Presently there are numerous concepts and techniques for vertical and horizontal DSM available. Many of these solutions are adaptations from the oil & gas industry. However, the Technological Readiness Levels (TRL) tend to be low (< 5).

Subsequently, the following specific criteria within different categories are reviewed and quantified for each type of deep-sea mineral deposit:

- Location: distance from shore, depth below water, weather conditions
- Geometry: depth below the seabed, orebody shape, dip, strike, thickness
- Geotechnics: rock mass rating, universal compressive strength, joint spacing
- Geometallurgy: mineralogy, mineral grades, grade distribution, mineral recovery, grindability, acidmine drainage potential
- Technology: ore recovery, dilution, ore loss, mining selectivity
- Economy: reserves, production rate, CAPEX, OPEX, commodity prices, cost of energy, labor cost,life of mine
- Environment: number and type of specialist fauna, number and type of background fauna, faunaldistribution, faunal density, biomass per disturbed area, species connectivity, sediment plume generation, and dispersion, sedimentation rate

The multitude of available input parameters and the uncertainty regarding deep-sea ecosystems lead to a complex decision process. Thus, it becomes evident that a multi-criteria decision analysis (MCDM) such as the Analytical Hierarchy Process (AHP) is required. This process enables the efficient matching of the specific deposit criteria with the available mining technologies for DSM. A frequently criticized shortcoming of the Nicholas technique is that all input parameters are assigned equal weights. Conversely, the AHP allows for the calculation of weighting factors to express each parameter's importance based on expert opinions (e.g., mining engineers and marine ecologists from academia and industry), therefore providing a way to deal with the uncertainties inherent to this investigation. Although deposit-specific criteria are expressed numerically (e.g., dip) or linguistically (e.g., 'uniform grade distribution'), the latter can easily be quantified numerically. Alternatively, fuzzy logic decision-making can be applied to represent indistinct linguistic criteria.

As the final stage of the process, a numerical ranking of DSM techniques according to their suitability for the established boundary conditions and deposit-specific parameters is presented to the decisionmaker. Analogous to the Nicholas approach, the final ranking indicates the most suitable DSM methods and provides the decision-maker with the knowledge of which mining techniques should proceed to further and more detailed evaluations.

This investigation is part of the TripleDeep project (TripleDeep – The Deep Dilemmas: Deep Sea Mining for the new Deep Transition) financed by NTNU through its call for interdisciplinary research collaboration in sustainability. TripleDeep comprises a multidisciplinary team of PhD candidates and experienced researchers with educational backgrounds in history, marine biology, economy, and (mining) engineering and aims at addressing and resolving issues and

dilemmas associated with the potential extraction of minerals from the deep sea. The presentation of this investigation will expound on why a selection framework for DSM is required, the necessary initial assessments regarding the identification of deposit-specific criteria, and the structure and preliminary development of a multicriteria decision model.

Keywords: mining method selection, multi-criteria decision making, biodiversity loss, ecosystem uncertainty, best available technologies

(Poster) Preliminary Analysis of Epilithic Foraminifera from the NORI-D Polymetallic Nodule Lease Area in the Southeastern Clarion-Clipperton Zone

Adam Elkin (Eckerd College, USA)

The Clarion-Clipperton Zone (CCZ) in the equatorial Pacific Ocean is home to a diverse community of undescribed foraminifera and foraminifera-like lifeforms that rely on polymetallic nodules for habitat. Encrusting and attached foraminifera are dominant components of all biological size classes (meio-, macro-, mega-) amongst nodule fields, so it is necessary to characterize this ecosystem to understand these epilithic communities. Epilithic organisms, such as encrusting foraminifera, komokiacea, and xenophyophorea, are especially susceptible to deep sea mining (DSM) impacts like direct removal of hard substrate and subsequent burial from ambient sediment plumes. Nodule assemblages from two multicore sites in the NORI-D region were analyzed using photography, microscopy, and morphological taxonomy. A serialized photograph and taxonomic description system were used to keep track of undescribed species and to maintain taxonomic consistency. Greater than 95 distinct species of attached foraminifera have been identified. Foraminifera were the primary inhabitants of the polymetallic nodules examined. Certain species preferred hydrogenetic, diagenetic, or cracked surfaces. This study addresses and contributes to the understanding of an enigmatic abyssal plain community that will be affected by nodule mining.

(Poster) Establishing benthic foraminiferal baselines in the Southeastern Clarion-Clipperton Zone, NORI-D

Bryan Omalley (Eckerd College, USA)

The Clarion-Clipperton Zone (CCZ) in the eastern equatorial Pacific is a target of commercial deep-sea mining (DSM) due to the extensive deposits of high-grade polymetallic nodules. Effects of DSM on the environment include the generation of sediment plumes, the redeposition of sediment and organic matter, as well as the loss of hard substrate as a unique habitat in the abyssal plain. Benthic foraminifera (BF) are single-celled protists that comprise a large portion of abyssal meiofauna and play a significant role in carbon cycling and ecosystem function. On account of their low trophic level, species-specific ecological requirements, size and abundance (valid for statistical analysis with low sample volumes), and widespread distribution, BF are reliable bioindicators of environmental change. This study aims to establish baseline patterns and understand the effects of seasonality on BF biodiversity and density/abundance from the top 5 centimeters of multi-cores collected at 44 sites from a test mining region and a preservation region in the NORI-D contract area. This study also compares BF biodiversity and density/abundance to total organic matter, type of organic matter (chlorophyll-a vs. phaeophytin), and grain-size as a means to discern how certain environmental parameters, that coincide with DSM effects, drive BF distribution. Setting BF baselines and continued monitoring throughout the exploration and test-mining phases will allow us to understand the effects of DSM by implementing an ecosystem-based approach to the management of polymetallic nodules.

(Poster) Topographical Characteristics of Seafloor Preading and Ocean Core Complexes (OCCs) at the Middle Part of the Central Indian Ridge

Gyuha Hwang (Korea Institute of Ocean Science and Technology – KIOST, Korea)

The middle portion of the Central Indian Ridge (MCIR) is located between 8°S and 18°S and consists of six first order segments that are offset by transform faults. The ocean core complexes (OCCs) occur at nearly all segment ends. OCC is an exposed mantle rocks uplifted through long-lived detachment fault processes which can also lead to extensive hydrothermal circulation. We analyzed seafloor morphology of OCCs in MCIR using high-resolution bathymetry and backscattered data recorded on the Deep-Tow Side-Scan Sonar system (IMI-30 and IMI-120, UH). Because new oceanic crust generated by spreading center has a complex morphology, we calculated the slope-gradient variations from the high-resolution bathymetry to examine the topographic change near the spreading zone. In slopes greater than 30° areas, the normal faults including the detachment faults were observed generally with high backscattered intensities that reflect more topographic effects than acoustic medium variation, while the gentle slopes less than 10° areas tend to show the relative low backscatter intensities reflecting the acoustic medium variation. To estimate the initial angle of the OCC detachments, we reveal the outward and inward dips of a breakaway zone and show 60° of initial dip, suggesting that the detachment faults exposing the OCCs are initiated with high-angle normal faults. In order to examine the variations in magma supply of OCC in MCIR, we calculated map-view M factor (MVM), which is defined as the fraction of total seafloor spreading accommodated by magma accretion, using the slope-gradient and down-slope direction variations. Currently, we are preparing to compare the MVM with other geophysical anomalies (e.g., gravity anomaly and magnetic anomaly). Although further study on the MVM should be carried out, other results provide that the topographical characteristics of seafloor spreading and OCC structures. Thus, we expect that the combination of the results (after M factor study) indicates a strong link among cold mantle sources, limited magma supply, and development of OCCs in MCIR.

(Poster) Variations in Elemental Concentration Between Diagenetic and Hydrogenous Hemispheres of Manganese Nodules

Daniel Rivera (Eckerd College, USA)

Manganese nodule mining is poised to become the future source of compounds required for the transition from fossil fuels. These concretions of oxide layers form over extremely long-time frames in undisturbed ocean basins through hydrogenous and diagenetic processes. To further our understanding of manganese nodules as an elemental resource, this study seeks to determine if there is any variation between the hydrogenous formed and diagenetically formed hemispheres. Nodules from three regions of mining interest will be split and separately analyzed by x-ray fluorescence and x-ray diffraction to determine elemental concentration and crystal phases.