UNDERWATER MINERALS CONFERENCE

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UNIVERSITY OF SOUTH FLORIDA
College of MARINE SCIENCE

Abstract Booklet

ODYSSEY MARINE EXPLORATION

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Vertical Transport System: Ready to Launch

Wiebe Boomsma (Royal IHC)

Development of sustainable technology increases the pressure on raw material resources and deep-sea mining is becoming more and more a viable alternative for terrestrial mining. Royal IHC has been at the forefront of this development for many years, leading the research consortia Blue Mining and Blue Nodules, which has resulted in technology for harvesting and vertical transport of polymetallic nodules. In this paper the science and technology involved in the vertical transport system will be discussed in detail. Fundamental knowledge about the transport processes and nodule degradation including methods for validations on different scales will be addressed. This fundamental knowledge is used to develop the hardware for the vertical transport system. The paper will focus on the development of the booster station, an innovation using proven pumping technology for use in ultra-deep waters, including the booster station placement along the vertical transport system with focus on redundancy. A special open permanent magnet motor, called the deep-sea special motor has been developed and thoroughly tested to be able to reliability drive the centrifugal pomp. Finally, the monitoring and control system for efficient clog free nodule transport will be addressed. This development has been a process of continuous testing and learning and finally resulted in a vertical transport system that is ready to launch.

A Free-Standing Deep-Sea Mining Vertical Transport System

Frank Lim (2H Offshore)

Deep sea mining vertical transport systems (VTS), either in design or concept, usually involve a riser string installed and hanging from the surface production vessel. This is necessary, for example in the Clarion-Clipperton zone, because the vessel needs to follow the harvesting crawler on the seabed to cover a large area to gather manganese nodules to achieve commercial production targets. The Nautilus Minerals VTS design for the Solwara 1 project is also a free-hanging riser carrying a pump that hovers over the seabed to transfer crushed massive sulphide ores. In both the above cases, a flexible hose jumper arranged in an expandable shape is used to link the seabed crawler to the bottom of the free hanging riser string to allow flexibility in the crawler's movement. At UMC 2018 in Bergen, the authors presented a radical proposal that in the mining of seafloor massive sulphide deposits a free-standing VTS solution can have many advantages over the 'conventional' free-hanging configuration. This is mainly attributed to the fact that massive sulphide mining involves a significant amount of digging, sorting and crushing before the ores are transported to the surface. Hence the mining activities take place in a relatively confined area that can be reached by a stationary surface vessel and VTS over a long period of time. The free-standing VTS can be deployed and retrieved by a separate, dedicated installation spread, but designed to be relocated by the production vessel. The riser is anchored to the seabed and maintained in a free-standing configuration by a buoyancy tank located far enough below the sea level to avoid waves and high surface currents. A flexible hose jumper connects the top of the free-standing riser to the production vessel that will de-couple the latter's motions from the riser. This jumper offers an important safety feature that its top end can be disconnected during bad storm conditions thereby allowing the vessel to seek shelter until the weather improves. This paper follows up the 2018 presentation by providing further definitions of such a deep sea mining free-standing VTS to demonstrate its technical feasibility. Experience will be drawn from the authors' first hand design involvements in several major oil & gas projects where such free-standing risers have been deployed and are still in use in water depths up to 2,500m. Specific mining requirements and operating scenarios with the seabed crawler are addressed.

Model Test of Skip Lifting System for Deep-sea Mining

Jianyu Xiao, Ning Yang, Sup Hong, John Parianos (IDSSE, China)

Skip lifting is a new concept of mechanical lifting system for deep-sea mining. It is expected that the skip lifting is capital cost effective and energy efficient compared to hydraulic pump lifting system. Furthermore, the less by-products of seawater and sediment is very attractive in the aspect of environment. This paper presents fundamental results of scaled model test conducted for the purpose of technological feasibility study on skip-lifting system. Main measurement factors are system configuration, angular response and horizontal acceleration of buffer station. It will provide reference data for the pilot test and the commercial realization. The hydrodynamic resistance of skips obtained from single skip test can explore the main composition of water resistance.

A Review of the R&D on Riser System for the Manganese Nodules Exploitation

Marcio Yamamoto (National Maritime Research Institute, Japan)

Since the 1970s, several countries have been carried out the research and development of technologies for the exploration of the manganese nodules located in Clarion-Clipperton Zone. In parallel, the Petroleum Industry has also developed its own technology, which currently can produce hydrocarbon in a water depth deeper than 2000m and to drill an exploratory well in water depth over 3000m. In this article, we will present a review of the R&D of the riser system for the manganese nodules exploitation over the last 5 decades. However, the CCZ contract holders have been focused on the exploration and appraisal of the reserves during the last decade resulting in a hiatus of R&D for the exploitation. To fill a small part of this gap, we will present an initial numerical study of the riser system, which was calculated using the state-of-the-art tools and knowledge borrowed from the Petroleum Industry. We intend to simulate the dynamic response of a rigid pipe under different sea currents and waves. Then we discuss the viability of this concept of the riser system in terms of criteria widely used in the Petroleum Industry.

Environmentally Benign Nodule Extraction Method Using Autonomous Swarm Robotics

Benjamin Pietro Filardo (Pliant Energy Systems)

The presentation will detail an alternate nodule mining method that deploys swarms of autonomous robots to retrieve nodules. The robots make minimal contact with the sea floor while plucking individual nodules from the sediment. This method holds the promise of overcoming the two greatest challenges to the establishment of a robust nodule mining industry. The first challenge is public perception of environmental harm and resulting pressure on elected officials and policy makers. The second challenge is the combination of high technical risk plus high CAPEX required to initiate commercial operations. The currently predominant nodule mining approach utilizes a large crawler that lifts nodules and the top layer of sediment to create a slurry that is pumped through a riser to a surface ship. Tailings are returned to the ocean. Benthic organisms along the mining path are killed, sediment is compacted by the crawler's tracks and plumes are created by the crawler and by tailings return. Defense against criticisms of this method compares potential ecological damage with the greater ecological damage of land mining and points out that only a very small portion of the world's abyssal plains will be mined. While valid, this defense may not assuage the growing visceral popular opposition that is threatening to delay the onset of commercial mining. If/when commercial mining commences, popular opposition will pose an ever-present risk of shut down. Therefore, a nodule extraction method that minimizes or eliminates environmental damage is needed. The proposed alternative method may also reduce techno-economic risk. A commercial-scale crawler is a large and complex asset. Failure of a single sub-component, such as a bolt on a caterpillar track, may cause the entire operation to halt. Retrieval of the crawler for repairs is expensive and risky. With the swarm robotics method, individual robot failures will not significantly impact operations. Small-scale commercial mining can begin with a lower number of fixed-size robots and be scale-up by increasing the number of robots. The manufacture of a very large number of small robots allows for economies of scale through mass production. The currently predominant approach utilizes a pumped riser to deliver nodule slurry to a surface ship, another process that is vulnerable to a single point of failure halting operations. Therefore, the economic feasibility of using solid propellant lift bags to raise baskets of nodules to the surface must be investigated. Retrieval of the baskets at the surface may be achieved through autonomous surface vessels delivering baskets to mother ship(s). The slide presentation will include an overview of several emerging 21st century technologies that make this approach possible, and an overview of the different vehicle types required. There will be a brief explanation of why the unique robotic platform being developed by Pliant Energy Systems is well suited for one of the required vehicle types.

Processing of Mn nodules with a combined pyro-hydrometallurgical "zero-waste" approach

Thomas Kuhn (Federal Institute for Geosciences and Natural Resources, Germany)

BGR and their partners at the Universities of Aachen and Clausthal in Germany have developed a combined pyro-hydrometallurgical route for the processing of the Mn nodules. This approach ensures that the nodules will be used as a whole with almost zero waste production. In a first step the nodules will be dried and pre-reduced in a rotary kiln at about 800°C followed by their feeding into an electric arc furnace (EAF). Complete smelting of the nodules in the EAF is realized at about 1450°C with the addition of fluxing agents (mainly quartz and lime) and coal as reducing agent. At these temperatures the target metals cobalt, copper, nickel, and molybdenum will be reduced to their metallic state and concentrated in a metal melt at the bottom of the arc furnace. A part of iron will inevitably be enriched in the metal melt as well and has to be removed in a successive step. Manganese and all silicate phases remain in the molten slag. The liquid metal melt can be separated from the liquid slag because of its higher density and can, thus, be tapped from the bottom part of the EAF. The metal melt will be transferred into a top-blown rotary converter (TBRC) and oxygen is blown (from a top lance) into the melt to oxidize and remove most of the iron. Finally, the metal melt will be cooled down to form a metal alloy either as granulate (< 1 cm grain size) or it will be atomized to form a powder with less than 5 mm grain size (Sommerfeld et al., 2018). Mass balance calculations show that the final metal alloy makes up only about 4.5 mass-% of the charged manganese nodules which is a significant reduction of the mass flow for the following hydrometallurgical treatment. The latter is necessary to separate the metals from each other (which is not possible through pyrometallurgy) and produce marketable intermediate products such as copper-cathode as well as Ni and Co salts. A Mn-rich slag will be produced during the first melting step, i.e., during melting of the Mn nodules. With 49 wt.% MnO, this slag is similar to manganese-rich primary ores such as from the Comilog mine in Gabun. Thus, through further melting of this Mn-rich slag at about 1550°C and subsequently at 1650°C as well as with the addition of further fluxing agents it is possible to produce ferromanganese and silicomanganese, respectively. Both of which are products which can be sold to the steel industry. The remaining final slag is chemically and mineralogically stable and free of toxic substances in terms of its use under normal environmental conditions. Therefore, it could be used either as additive during cement production or as filling material for roads, buildings or landfill sealings. This approach was developed at extended lab scale (20 - 30 kg of nodules per experiment) and a demonstration project at pilot plant scale (100 - 300 kg per hour over 72 hours) is currently in progress.

Exploration Systems for Seafloor Massive Sulfides - A Conceptual Design

Steinar Ellefmo (Norwegian University of Science and Technology)

Seafloor massive sulfides (SMS) could potentially be mined for metals in the future. A prerequisite is that deposits are found, delineated and evaluated to determine its economic potential. Different acknowledged standards are used worldwide to ensure a transparent and comprehensible delivery of exploration results to the public. The purpose of exploration is to gather, manage and analyze sample material to obtain necessary data for an evaluation of the mineralization. The challenges to obtain sample material and the high costs associated to deep-sea SMS exploration have so far hindered a broad investigation of the numerous SMSs distributed globally on the ocean floor. Several remotely operated seafloor drill rigs and smaller drilling attached to work class ROVs have been developed for this. Despite the developments, representative samples from more than 50 meters below the seafloor at water depths down to thousands of meters remains an engineering challenge. The industry and the scientific community have experienced great complications while drilling regarding sample integrity. This decreases the confidence in the data and the obtained estimation results. The sampling challenges combined with high costs for drilling remain an overall limiting factor for SMS exploration and define a need for the development of technology that makes subsurface geological data from SMS more accessible. The use of reverse circulation, a stronger implementation of borehole logging tools that potentially enables an early detection of waste rock to terminate boreholes in time and thereby preventing excessive sampling of waste material, could reduce exploration costs significantly. In this work, a framework for the design of a conceptual SMS exploration system using a systematic approach to engineering design is developed. The goal is to reduce exploration costs while maintaining the required data quality that enables resource classification and associated reporting. Design theory for a conceptual design has been applied to propose a conceptual design. A stakeholder analysis has been performed to identify the requirements for the exploration system. Design goals and metrics for evaluation are developed and characterized. A solution neutral functional structure for an exploration system is developed. The functions are based on technical principles mapped and presented in design catalogues. Seven different systems are created from the principles mapped in the design catalogues. The designs are studied, presented and qualitatively evaluated with defined metrices. A conceptual design utilizing full hole percussive rotary drilling, reverse circulation sample recovery from a seafloor drill rig and seafloor-based sample analysis with borehole logging and side wall coring is proposed. The paper will present and discuss the methodology and the results.

A new approach to 3D SMS mineralization assessments

Fredrik Soreide (Norwegian University of Science and Technology)

In 2011 NTNU established a new research initiative to investigate the marine mining potential in the deep sea in Norway. Due to the high resource potential indicated by these studies, the Norwegian government included marine minerals in its mineral strategy for the first time in 2013 and issued draft legislation for the management of marine minerals within the Norwegian extended continental shelf in 2017. This legislation was announced on 22 March 2019 and came into effect on 1 July 2019. In May 2020 Norway initiated the opening process for mineral activities on the Norwegian continental shelf. The government decided to start an opening process for mineral activities and to increase funding for mapping of subsea minerals and knowledge building. The opening process includes areas between Jan Mayen and Svalbard. This area includes areas that are assumed to be prospective in terms of both SMS deposits and manganese crust. To reduce the uncertainty of the current estimates of the mineral resource potential along the extended Norwegian continental shelf, more exploration and sampling is needed. One of the most interesting remaining research and commercial question is how the mineralization varies at different depths. It is clearly necessary to establish the depth and the characteristics of the mineralization to work out the total amount of mineralized material in a mound. This has only been achieved a few times, at the TAG site in the Atlantic Ocean (part of the Ocean Drilling program) and Nautilus Minerals' Solwara project in Papua New Guinea. However, both were accomplished using very complex and expensive drilling programs. The Norwegian company RenOcean is currently developing an interesting new drilling uniUdrilling tool. Originally developed for fish farm and oil and gas applications, it can be used to drill a 64 mm drill sample up to 30 meters deep. The tool will measure both the exact depth of drilling and accurate positioning of the drill bit. By collecting and storing the drill cuttings at specific 3-meter intervals and possibly supplement the analysis and characterization of the cutting with down-the-hole sensors, a detailed geometric and qualitative characterization of the mound is possible. The whole drilling process can be accomplished in a matter of hours, while a complete characterization of the total amount of mineralized material in a mound can in theory be accomplished in only a few days. The tooling is installed on RenOcean's crawler machine, REN Spider 01. This is a tool carrier for various tooling, and its ability to maneuver in steep terrain makes it an interesting alternative for more detailed investigation of SMS mounds. REN Spider 01 can operate in up to 50% slopes, down to 4000m water depth and can be operated from vessels of opportunity. NTNU is therefore working with RenOcean to develop a case study, based on a known site. Loki's Castle is a field of five active hydrothermal vents in the mid-Atlantic Ocean, located at 73 degrees north on the Mid-Atlantic Ridge at a depth of 2,352 meters. The vents were discovered in 2008 and are the most northerly black smokers located to date. Initial results indicate that this site can be drilled using the REN Spider 01 as most of the slopes are below 50 degrees. This paper will present the proposed drilling program, suggesting that this can enable a much faster and more detailed 3D characterization of a SMS mound at relatively low cost. Having more precise knowledge of the total resource potential of a specific site will be an important next step for realizing marine mining as a new industry.

Mapping seafloor minerals with AUV

Arnt Helge Olsen (Kongsberg Maritime)

Kongsberg Maritime develop and manufacture AUV Autonomous underwater Vehicles but most important a wide range of sonar systems and integrate these as one system in the AUV. The Syntetic aperture sonar SAS is a unique system with very high resolution even to the outer edge of the swath. It is tightly coupled to the integrated navigation system of the AUV. The AUV is rated for 6000m of water depth and is equipped with other environmental sensors as well as laser and camera and sub bottom profiler. The paper shows how an AUV is capable of mapping and searching for minerals in very deep water with very high resolution and confidence. Examples from case studies using the AUV.

Real-Time Agile Volumetric Sonar Solution for Mapping, Identification, Monitoring and Mapping

Blake Holton (Coda Octopus Products Inc.)

The Echoscope4G is the world's highest resolution real-time 3D sonar. Built around unique patented technology, it generates a complete 3D model, composed of over 16,000 soundings, from each and every acoustic transmission. This 3D model is entirely refreshed up to 20 times per second with each new transmission. The Echoscope has been used extensively on deep sea mining operations to provide a comprehensive map of the Ecosystem to identify potential resources while also informing risk of extraction. The Echoscope then monitors the extraction process to minimize the ecosystem damage and finally re-map to validate clean execution and ecosystem recovery. With sounding densities far in excess of those generated by other sonars, and with the new increased 20Hz ping rate, the Echoscope4G presents unrivaled clarity of dynamic operations and moving objects in video-like data format in low-visibility water conditions. All the Echoscope4G range take advantage of patented statistical rendering techniques to further enhance the clarity of the image, presenting the user with an intuitive and easy-to-interpret image. When monitoring underwater activity, even when the target and the Echoscope are moving independently of each other, the 3D imagery remains clear and accurate, giving the viewer an instant three-dimensional understanding of the underwater environment. In mapping and inspection tasks, the ping geometry of the Echoscope4G will allow a target to be visualized many times in a single pass, allowing a target to be viewed from many different angles. This allows complex subsea structures to be mapped with fewer shadows and a level of confidence and detail far beyond anything that can be achieved using alternative methods. The new 5-D and 6-D Echoscope® PIPE sonars embed the Company's new innovative high-powered and extensible real-time processing engine. The current Echoscope® variants in the market can output up to 16,384 points per ping within the sonars field of view using a single set of processing parameters. In our new 5-D and 6-D sonars we can not only capture (for offline beamforming), and process the full backscatter (time series) data of up to 40 million points per ping, but make all of this data available in real-time for top-end visualization and processing. Supported by a range of advanced signal processing options, Echoscope® PIPE is revolutionary as it allows our customers to access the entirety of the available sonar data for multiple simultaneous outputs such as multiple 4D Images with different processing and/or the full backscatter (time series) output given much greater range and image fidelity – all from a single sensor in real-time. From complex live operations to autonomous vehicle data collection missions, this technology and capability presents a paradigm shift for marine and ocean monitoring and mapping. This ground-breaking technology's ability to process all of the acoustic 3D backscatter data (up to 40 million points) within the viewing volume is CODA's 5-D full-time series capability. Processing the complete backscatter volume now offers extended range, coverage and density of targets with the ability to detect multiple targets within a single beam footprint (in 4D) and provide critical amplitude data around targets and seabed such as layers or marine growth or sediment penetration. The Company's new 6-D system builds on the 5-D full-time series and allows parallel and sequenced real-time processing and visualizing of many 4D real-time images at the same time, using different processing

parameters. 4D images can be processed by varying settings including field of view, range windows, beam detection method and many acoustic and beamforming filter options. Significantly PIPE can provide these multiple 4D imaging outputs in parallel over the network allowing different users to subscribe to the different image outputs they require. As an example, a single Echoscope® 5-D or 6-D sensor can deployed on a Remotely Operated Vehicle (ROV) for ecosystem mapping for a mining operation and can deliver real time volumetric outputs simultaneously such as a near field high resolution range 4D image for building 3D models of the seabed, and a second 4D image set to far range with a narrower field of view for obstacle avoidance. Additionally, the system can capture the full 5-D Backscatter data for further offline processing in PIPE to identify potential resources. The ability to specify these multiple image requirements ahead of survey or inspection with the specific beamforming parameters and beam detection methods can mean that PIPE could make redundant a number of other sensors – reducing complexity, power consumption and weight and significantly cutting costs and increasing productivity. For deep sea mining operations, taking multiple sensors is challenging for weight and power consumption purposes. Echoscope PIPE can complete the end-to-end workflow process, all from a single sensor. First, the Echoscope is used to survey the ecosystem to identify potential resources and inform of any risks of extraction for the ecosystem. The Echoscope can then be used to monitor the extraction process in real-time to reduce the ecosystem damage. Finally, the Echoscope can provide a post-survey to validate clean execution of the operation with mitigated ecosystem damage.

Preliminary economic feasibility analysis of mound type methane hydrate mining

T. Yamazaki, N. Nakatani (Osaka Prefecture, Japan)

A mining system of mound type methane hydrate (MTMH) on seafloor is assumed in the study and the economic feasibility analysis of MTMH mining venture is examined. The mining system assumed is almost the same one for seafloor massive sulfides (SMS). Three special processes added in the mining system are an application of back-pressure during the MTMH ore lift through the riser, the gasification of MTMH ore, and the pressurization for pipeline transport. The other processes and sub-systems in the mining system are assumed the same as SMS. On the basis of the economic feasibility analysis of the SMS mining venture, the capital expenditure (CAPEX) and the operation expenditure (OPEX) of a MTMH mining venture are calculated and a fundamental economic analysis of the venture is conducted. The production rate of about 700,000 m^3/day in methane and the gas price of $11.5 MMBtu are assumed for the economic calculation. The result shows a negative feasibility, because the income from the gas sales is quite smaller than the one from the SMS metal sales. Two points are necessary to improve the economy. One is the gas price and the other one is the reduction of the CAPEX and the OPEX.

Polymetallic Nodule Mining: Plume reduction at the source

Laurens de Jonge (IHC Mining B.V.)

Given the importance of some of the metals in Polymetallic Nodules to transform into an electrified society, it is inevitable that there are many parties looking at the exploitation of Polymetallic Nodules from the oceans. However, exploitation will only be allowed if there is a balance of interests between the economic, social and environmental factors and if the impact on the environment is minimal using the best available technology. Sediment plumes are the main environmental concern for deep sea mining of Polymetallic Nodules. Extraction will always have a local impact in the mining area, while the plume can potentially impact a much larger area due to the travel of the plume on currents and through dispersion. This presentation discusses the historic approach and technological challenges and new opportunities that can be used to reduce the impact of plumes at the source, while maintaining other requirements like efficiency and production rate. Key challenges when reducing the impact of the plumes are: first of all limiting the sediment pickup, second limit the amount of fresh water to be used, third to separate the nodules and the sediments most efficient, fourth to reduce the initial energy in the sediment plume when leaving the exhaust of the vehicle. Opportunities are first of all an integrated approach: since all elements of the pickup-separate-transport-exhaust process have influence on each other, it is essential to design all elements in parallel. Second opportunity is to (re)use the existing higher density slurries to optimize the pickup process and increase the density of the plume leaving the exhaust, thus reducing the amount of fresh water and the energy in the plume. Flocculation can than help to reduce the number of fine particles in the water column.

Sediment discharges from mining vehicles, experiments to find the optimal release conditions

Rudy Helmons (Delft University of Technology, the Netherlands)

One of the main challenges for deep-sea mining is minimizing its environmental impact while maintaining a viable mining process. Technology development for sustainable, reliable and efficient mining of polymetallic nodules in the deep seas requires careful design, thorough understanding of the physical processes and integrated testing of all equipment and systems. As the collector collects nodules, it also collects sediments, which need to be separated and discharged at the seafloor, generating a sediment plume that can spread over a vast area. Nodule collector devices are primarily evaluated based on their nodule pickup efficiency and capacity. However, these are only parts of the collector's performance, the sediment release conditions should also be included. Optimization of the sediment discharge conditions is expected to significantly reduce the spreading of sediment. It is in the so-called near-field region (<few hundreds of meters) relative to the mining vehicle, where engineering solutions can influence the development and spreading of the sediment plume. All sediment deposition that can be achieved in the near-field region, will help to limit the area affected by the sediment plume. Within EIT Raw Materials' Blue Harvesting project, a new concept for a hydraulic collector will be designed and tested, both in the laboratory and in the field. The work presented in this paper focuses purely on the sediment release conditions. In last year's UMC, preliminary results on diffuser discharge tests in the TU Delft Dredging Laboratory have been presented. In these experiments, it was observed that the discharged sediment occurs in several physical regimes. Starting as a buoyant jet and plume, that impinges on the seabed due to its increased density relative to its environment. When the plume hits the seafloor, it moves along the seabed as a turbidity current. Besides the diffuser experiments, lock exchange experiments to study the development of low concentrated turbidity currents have been performed. Both sets of experiments are used as a starting point to develop fully integrated lab-scale sediment discharge experiments, in which (natural) flocculation of sediment will also be incorporated. Finally, a preview will be presented of our future work within PLUMEFLOC (minimized PLUME dispersion through natural FLOCculation). In this project, the flocculation potential of sediments based on shear and concentration will be determined. This will be of use for the scaled laboratory near field plume dispersion experiments with various flocculation agents. Calibration and application of LISST in situ particle sizer and optical backscatter sensors to measure the particle size distribution in situ, will allow for in situ monitoring of flocculation in mining plumes.

Status of US DOE Project to Develop a Subsea Mining System that Mitigates the Environmental Impact of Sediment Plumes

Steven Rizea (Deep Reach Technology)

Environmental impact mitigation is one of the major challenges facing commercialization of deep-sea mining. To help address that challenge, Deep Reach Technology, Inc. ("DRT") was recently awarded a Small Business Innovation Research ("SBIR") Grant by the United States Department of Energy, Advanced Research Projects Agency- Energy ("ARPA-E") for the development of an "Improved Manganese Nodule Collector Design to Mitigate Sediment Plumes". ARPA-E is a United States government agency tasked with promoting and funding research and development of advanced energy technologies. The technology under development focuses on two areas: exclusion of sediment from the lift riser and coagulation of sediments. Excluding sediment from the lift riser is accomplished via careful design of the nodule slurry flow path downstream of the pickup heads and the injection of sediment-free water. The slurry flow path is designed to allow nodules reach a channel leading to the lift riser. In the process, the nodules are separated from the sediment water used by hydraulic suction heads to collect them from the seabed. The sediment-laden water is guided to a separate channel to be coagulated and deposited back on the seabed. Performance metrics include rejected sediment fraction, sediment-free water injection rate, and pressure drop. Coagulation processes the sediment-laden water excluded from the lift riser to increase the average effective particle size. The potential extent of a sediment plume is a strong function of effective particle size. Small particles settle slowly, travel far, and can result in a large plume. Large particles settle quickly, travel short distances, and result in a small plume. DRT's efforts include both design and physical testing of the coagulation system with sediments collected from potential deep-sea mine sites. Performance metrics include particle settling time and power consumption. DRT's presentation will review the core objectives of the study, give an overview of the results to date, and discuss means for industry partners to participate in the active project.

Deep-Sea Mining Sediment Plumes: Recent Progress and Next Steps

Thomas Peacock (MIT - Massachusetts Institute of Technology, USA)

Understanding the dynamics and scale of sediment plumes created by deep-sea mining underpins all capability to make reliable predictions of the extent to which the impact of mining activities will be felt beyond a direct mining site. The ENDLab at MIT continues to advance understanding of the nature of sediment plume discharges behind polymetallic nodule collector vehicles and associated potential midwater column discharges from a surface operation vessel. In this presentation, we will summarize advances in the state of knowledge over the past 12 months, including presenting new results from our supercomputer modeling research on three-dimensional gravity current dynamics behind a collector vehicle. We will also provide preliminary details on a new deep-sea sediment sensor that the ENDLab is developing in collaboration with Sequoia Instrumentation and Scripps Institution of Oceanography, which will have the capability to measure in-situ particle size distribution and sediment settling velocities in the abyssal ocean. This will be the first commercially available technology capable of making such key measurements for the deep-sea mining industry.

GSR Update: Technological Advances and Environmental Responsibility

Samantha Smith (GSR)

GSR's mission is to use best available techniques and the highest scientific standards to be a global leader in the responsible exploration and commercialisation of polymetallic nodules, contributing to the sustainable development of the planet.

The contract GSR has with the International Seabed Authority (or ISA) provides exclusive access to explore for minerals (contained in polymetallic nodules) in a part of the Clarion Clipperton Zone (CCZ), which is located between Hawaii and Mexico in the Pacific Ocean. There is much interest in the CCZ nodules because they contain more nickel, cobalt and manganese than the entire global terrestrial reserve base for those metals (Hein et al., 2012) and these are some of the key metals needed to decarbonize the global energy system. Continued population growth and urbanization is forecast to place further strain on the supply of these minerals

GSR is taking a step-by-step approach to project development. In 2017, GSR successfully trialed a tracked soil testing device (Patania I) to test and improve maneuverability and trafficability. GSR is now focused on delivering a successful deep-sea trial of its pre-protype nodule collector, Patania II, which is expected to take place in the CCZ during the first half of 2021. Earlier in 2020, GSR successfully completed two key assessments of Patania II. A state-of-the-art umbilical and winch combination was successfully evaluated mid-water in the Atlantic Ocean at a depth of 4500 m, the same depth at which Patania II will operate. In a separate validation check, conducted within Belgium's Exclusive Economic Zone, Patania II demonstrated its ability to drive and maneuver along the seabed. Subject to a successful deep-sea trial GSR will start to develop a prototype commercial-scale nodule collector (Patania III) which will have a riser to bring nodules from the seafloor to a surface vessel.

This step-by-step process allows GSR to learn and improve as the engineering program progresses, eventually leading to a final design. Environmental monitoring is an integral part of the program and the results of all trials will be incorporated into the Environmental Impact Statement for full-scale operations, which will be made public.

GSR is committed to full transparency in its approach to environmental management, partnering with the international scientific community to ensure decisions are based on the best science possible. For example, GSR is collaborating with the European research project "Mining Impact"[1]. Scientists from 28 European institutes will join with the German exploration contract holder, BGR[2], to provide independent monitoring of next year's trials to help understand the environmental effects of collecting mineral resources from the seafloor.

[1] Mining Impact is a project of the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPIO).
[2] Federal Institute for Geosciences and Natural resources

Cobalt, a Uniquely Deep-Ocean Critical Metal Resource

James R. Hein and Kira Mizell (USGS)

Cobalt is of crucial importance to current and evolving green technologies, especially energy-storage applications. The deep-ocean contains five types of metal-rich mineral deposits that are being explored for potential mining, two of which have high cobalt contents. These two deposit types are polymetallic nodules (also known as manganese nodules or ferromanganese nodules) and cobalt-rich crusts (also known as ferromanganese crusts or polymetallic crusts). Cobalt is a predominantly deep-ocean critical metal resource. The global deep-ocean cobalt resource is estimated to be ~910 million tons of cobalt, compared to 25 million tons of cobalt from terrestrial sources (USGS, 2020). Copper on the other hand is a predominantly terrestrial resource with ~5.6 billion tons of copper (USGS, 2020) versus deep-ocean crusts plus nodules of ~2.1 billion tons of copper. The crust/nodule tonnage ratio for cobalt is 2.52 and 0.06 for copper, based on a global estimate of 200 billion dry tons of nodules and 120 billion dry tons of crusts. The technology for mining cobalt-rich crusts is technically very difficult and has not yet been developed, whereas technology for mining nodules is in the prototype stage.

Polymetallic nodules form on the vast sediment-covered abyssal plains of the global ocean at water depths of 3,500 to 6,500 meters. They form by accretion of manganese and iron oxides around a nucleus. From a genetic standpoint, three types of nodules exist: (1) nodules that acquire most metals directly from ocean water; (2) nodules that acquire most metals from the pore-waters of sediment; and (3) nodules that acquire metals from both sources. The mean cobalt contents (grades) decrease from #1 above (mean ~3750 grams per ton (g/t), Cook Islands EEZ) to #3 above (mean ~2100 g/t, Clarion-Clipperton Zone (CCZ) NE Pacific and mean 1110 g/t for the Central Indian Ocean Basin), to #2 above (mean ~480 g/t, Peru Basin). For comparison, cobalt extracted as a byproduct of copper mining in west Africa has a grade of <1000 to 2000 g/t, similar grades to the deposits listed under type #3 above. Most polymetallic nodule fields occur in Areas Beyond National Judications (ABNJ) administered by the International Seabed Authority, the main exception being the Cook Islands EEZ. For the Cook Islands EEZ, a total weight of ~8.47 billion tons (dry) of nodules would yield ~35.3 million tons of cobalt. The total weight (dry) of nodules in the CCZ is ~21.1 billion tons, which would yield ~44 million tons of cobalt. For example, if 20% of that cobalt would be recoverable from various mine sites over the decades, that would equal 7.06 million tons of cobalt metal from the Cook Islands EEZ nodules and 8.8 million tons of cobalt from the CCZ nodules.

Cobalt-rich crusts form pavements or coat talus on nearly all rock surfaces in the deep ocean, from about 400 to 7000 meters water depths. They form by the accretion of colloids and precipitation of metals directly from ocean water. The mean cobalt contents vary regionally and the most prospective region is the Prime Crust Zone (PCZ), NW equatorial Pacific described by Hein et al. (2009). About half of the PCZ is in ABNJ and the other within EEZs of island nations. The mean cobalt content of the PCZ crusts is ~6660 g/t, whereas the mean for Indian Ocean crusts is about 3290 g/t and Atlantic crusts about 3600 g/t. For the PCZ, a total estimated tonnage of 7.53 billion dry tons of crust yields 50 million tons of cobalt. If 20% of that was recoverable, that would equal 10 million tons of cobalt. In summary, deep-ocean crusts and nodules offer an enormous potential resource for green-technology applications that will be required to move from a carbon-based to green-energy based future.

Resource considerations of phosphate-rich ferromanganese crust and phosphorite deposits from the summit of Rio Grande Rise

Mariana Benites, James Hein, Kira Mizell, Luigi Jovane (Universidade de São Paulo, Brasil)

Ferromanganese (Fe-Mn) crusts from the summit of the Rio Grande Rise (RGR) formed at shallow water depths (700-800 m) and have a distinct bulk chemical composition compared to typical Fe-Mn crusts from elsewhere in the global ocean due to the remarkable degrees of phosphatization. The crusts have the lowest Fe/Mn ratios (mean 0.56) and the highest P contents (mean 3.94 wt.%, maximum 7.67 wt.%) among crusts. The critical metals that are typically of greatest economic interest in Fe-Mn crusts (Co, Mn, Te, Mo, Bi, Pt, W, Zr, Nb, and Y) are lower in RGR summit Fe-Mn crusts compared to most crusts collected from the Pacific, Atlantic, and Indian oceans. On the other hand, RGR summit crusts are the most enriched in Ni (mean 0.55 wt.%, maximum 1.10 wt.%) and Li (mean 99 ppm, maximum 330 ppm) among other crusts analyzed; these high Ni and Li contents are typical critical metals of economic interest in CCZ and Peru Basin manganese nodules. Li is remarkably enriched in RGR crusts 36 times over crusts from the Prime Crust Zone in the Pacific Ocean and three times over other Atlantic Ocean crusts. Although the total rare earth elements plus Y (REY) concentrations are lower in crusts from RGR (mean 1319 ppm, maximum 3189 ppm) compared to crusts from elsewhere, the percentage of heavy rare earth elements plus Yttrium (%HREY) is the highest in RGR Fe-Mn crusts (32%, maximum 50%). The chemical composition of the younger, nonphosphatized crust layer considered alone is more similar to typical hydrogenetic Fe-Mn crusts studied from other locations. This underscores the fact that when not affected by phosphatization, the Fe-Mn crusts of RGR have among the highest concentrations of the critical elements Bi, Nb, Ni, Te, Rh, Ru, and Pt among crusts from other regions, however all crusts from the upper summit surface of RGR studied here are substantially phosphatized. Since phosphatization has been shown to be dependent on water depth, we suggest that crusts from water depths deeper than the summit (800 m) of RGR may be less affected by phosphatization and more interesting from a resource point of view for critical metals. Thus, further exploration is warranted to study Fe-Mn crusts from deeper water along RGR and on seamounts surrounding RGR. In general, the chemical composition of bulk RGR summit crusts was controlled by high biological productivity for most of the history of crust growth, and to the relatively shallow-water depths of the summit. The abundant nutrient-type elements that are rapidly remineralized were readily available for acquisition by the Fe-Mn crusts. In addition, the strong phosphatization that produced diagenetic carbonate fluorapatite (CFA) occurred under suboxic conditions due to an expanded oxygen minimum, which also had a major impact on RGR crust composition causing a diagenetic-like chemical signature (low Fe/Mn ratio, high Li and Ni contents). The phosphatization formed along the RGR summit also produced a phosphorite hardground substrate. The extraordinary amount of phosphorite and phosphatization indicates that RGR might be considered as a potential source of phosphorus, which is essential for agriculture industrial applications, as well as a rich source of fluorine. This type of plateau phosphorite deposits are being considered for mining on Chatham Rise offshore New Zealand and occurs in abundance offshore the southeast USA on Blake Plateau as well.

Deep Sea Mineral Resources on the Norwegian Continental Shelf

H. Brekke, J. Stenløkk, K. Solvi, A. Bjørnestad, S. Eriksen, N. R. Sandstå and P. Schiager

(Norwegian Petroleum Directorate)

In July 2019, the legislation for mineral activities on the Norwegian continental shelf entered into force. The Government is now moving towards initiating its impact assessment process in this regard. Part of the appropriate knowledge-base for this process will be the scientifically based information on the nature, distribution and volume of these resources. Much of the current database in that regard comes from the scientific research by academia, especially the long-term research program by the University of Bergen. In recent years, the database has been considerably expanded by the Government's dedicated seabed mineral exploration cruises carried out by the Norwegian Petroleum Directorate (NPD). The available data show that the continental shelf comprises possibly economic deposits of seabed massive sulphides (SMS) and Fe-Mn crusts, while Fe-Mn nodules are not recorded. The data also show that the Fe-Mn crusts have clear affinities with the crusts deposited in the Arctic Ocean and indicate that they may be organized into two groups of high and low contents of REE relative to other parts of the world oceans. As for the SMS deposits, the data indicate that they may be grouped into different types according to their mineral chemistry and their tectonic setting along the Mohns ridge, the spreading ridge of the area. There is a lack of data regarding the thickness (three-dimensional configuration) of both the SMS and crust deposits. This is an obstacle both to a better scientific understanding of the formation of the deposits, and to a well-founded estimation of the resources. To meet this problem, the NPD is considering methods for acquiring vertical information on the deposits (thickness), both drilling and acoustic methods. In its coming exploration cruises, the NPD plans to include testing of such methods.

Status of Exploration in the German License Area for Polymetallic Nodules

Annemiek Vink (BGR, Germany)

In June 2018, the German Federal Institute for Geosciences and Natural Resources (BGR) completed its ninth cruise to the German license area in the Pacific Nodule Belt. On the basis of previously available bathymetric and acoustic backscatter mapping, we explored the polymetallic nodule deposits and carried out environmental baseline analyses in three subareas with flat topography centered at 12° N/117°W. Based on data from 292 seafloor samples and using artificial neuronal networks and geostatistical methods, the total nodule mass of the eastern part of the license area was estimated to be 780 million metric tons (mt) wet weight. The three nodule fields that were explored in detail comprise a total area of 4200 km2 and contain 80 million mt of nodules. ADCP sensors moored for three consecutive years reveal bottom current velocities between 1 and 6 emfs (average: 3.5 cm/s) flowing predominantly in a south-easterly direction. Biodiversity studies in the German license area, that have been undertaken since 2010 using both morphological and molecular-genetic methods, show a high biodiversity but low density of individuals per species, and a tendency towards a wider distribution of larger species. Metallurgical experiments for nodule processing have allowed the development of a "zero-waste" method that was tested at lab-scale and is currently being expanded to pilot-plant scale.

The Hunt for Deep Sea Minerals - Identifying and Analyzing Formation Areas of Marine Minerals

Max Kaufmann (Camborne School of Mines, University of Exeter, UK)

The deep sea presents one of the more exciting and innovative mining prospects. The three main mineral deposits: Ferromanganese Crusts, Polymetallic Nodules, and Seafloor Massive Sulphides, contain a high proportion (approximately 5%) battery metals, which can help to lead the green revolution. This project utilized global datasets, such as bathymetry, in order to isolate the main formation conditions for each of these three deposit types. This was completed via the process of Mineral Potential Mapping, which overlaid highlighted variable ranges, collating these together. This identifies mainly the Pacific Ocean, between 0 to 30 N, as well as areas around Antarctica and New Zealand. The overlay process was repeated within smaller areas to select small scale final targets, between 3,000 and 75,000 km2 depending on deposit type. The highest value deposits were found to be West of Mexico for Ferromanganese Crusts, Eastern Pacific for Polymetallic Nodules, and, South of Hawaii and West of British Colombia (Canada) for Seafloor Massive Sulphides. 2D Block Modelling was completed, which allowed for average grades and tonnages to be calculated at differing cut off grades: no cut-off grade, an industry standard cut-off grade, and a median cutoff grade. Most of the Ferromanganese Crusts contained very low tonnage and grade, with the high value target containing 157.42 Mt at a cut off width of 74.51 mm, containing a predicted Cobalt grade of 0.73% and Nickel Grade of 1.47%. The high value target for Polymetallic Nodules contains 403.35 Mt at a median cut off abundance of 17.76 kg/m2, containing a predicted 3.37% of Nickel, 1.28 % of Cobalt and 3.99% of Lithium. Seafloor Massive Sulphides are found to be higher in grade than their terrestrial counterpart. Two high value targets were identified, with tonnages of 243.61 and 187.8 Mt at cut off grades 5.15 and 3.37 Copper %.

Traditional dimensions of seabed resource management in the Pacific

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(Université Catholique de Louvain, Belgium)

In most Pacific Islands, local communities have, since centuries, traditional, cultural, and spiritual attachments to the sea, in particular to species and specific marine areas, processes, habitats, islands and natural seabed formations. This great traditional knowledge, a diversity of customary marine management approaches and a unique integrated relationship between biodiversity, ecosystems and local communities help to ensure that benefits from management efforts would accrue to the local community, generally in a holistic, sustainable and equitable manner. The fusion between traditional knowledge, customary practices and western scientific knowledge in customary law has sometimes been challenging. However, it is presently acknowledged in legal systems of several Pacific countries and has been an incentive for setting up regional cooperation with different entities on resource, ecosystem, and area-based management.

In this article we present an analysis of the traditional dimensions of seabed resource management in the region coupled to a science-based overview of deep seabed and water column habitats in open seas and their vulnerability towards mining in integration with other activities and global change issues. We will then assess whether the current multilevel legal frameworks (at national, regional and national levels) attach sufficient importance to the traditional dimensions as well as the human and societal aspects of seabed resource management in the region. On basis of this analysis, we shall draw recommendations on basis of best practices in regulatory frameworks and on a new and forward-thinking paradigm that would integrate socio-ecological interconnectivity on the seabed and overlying waters.

Application of Artificial Intelligence technologies and workflows to support marine mineral resource estimation

Sean Aldrich, Shervin Azad (RSC Mining and Mineral Exploration & Goldspot Discoveries)

Mineral resource estimation for marine mineral deposits, in particular poly-metallic nodule deposits, presents a variety of challenges not as easily or cost-effectively overcome when compared to terrestrial projects. This is particularly relevant when a project is seeking to progress to higher resource confidence levels. To improve the classification of marine resources, and statistical confidence in marine resource models, new innovations to audit input data must be created. RSC and GoldSpot Discoveries Corp. have been exploring how this may be achieved, using Artificial Intelligence-enhanced image analysis of nodules both in-situ on the sea floor, and those recovered and brought to surface by sampling. The fit-for-purpose current model can geometrically measure individual nodules, assess size distribution, and count individual nodules using video or images captured at the seafloor or on surface. Improved data and metadata from sampled nodules will create more robust estimates of nodule content on the sea floor and will provide additional confidence as to the representativity of nodules both in-situ and collected, furthermore, data derived from image analysis of nodules on the seafloor provides additional samples and datapoints to the resource estimation. Through the use of GoldSpot's image analysis and machine learning techniques and workflows to provide additional supporting data, RSC is potentially able to provide additional confidence to the resource estimation resulting in an improved level of resource confidence. Keywords: resource estimation, image analysis, machine-learning, poly-metallic nodules Note: This paper is a collaboration between RSC and GoldSpot Discoveries Corp.

Blue Solutions for a Green Energy Future

Dr.-Ing. Sebastian Ernst Volkmann (Volkmann an Partners)

With his book "The Mineral Resources of the Sea", Geologist John Mero ignited the industrial race to the deep sea in the 1960s. Now, some 60 years later, deep-sea minerals could enter battery supply chains for the first time in less than a decade. The demand of cobalt and other metals needed to herald the era of green energy is forecasted to increase drastically. The metals will be largely sourced from natural ore deposits before a circular economy establishes. On the other side, there are growing voices calling for a moratorium due to concerns of potential damage to poorly understood ecosystems and adverse impacts. However, a moratorium could deprive industry and authorities of the opportunity to find solutions for blue mining, that, together with land-based mining and recycling, contributes to global sustainable development.

Although most of today's mining concepts are similar to those tested in the Pacific in the 1970s and 1980s, industry takes great efforts in lowering and controlling sediment plumes and processing-waste streams. For offshore systems, the innovation lies largely in the materials and components used to monitor, control and automate mining (support) operations. Digital services and high-tech sensors to collect "big data" will play a key role in ensuring efficient, but also environmentally responsible and safe operations, as they are revolutionizing mining and harvesting on land today. Blue solutions need to be invented, engineered and tested under reasonable conditions and timescales, involving considerable cost and efforts. A moratorium could prevent blue solutions from being mature when deep-sea minerals are needed.

Due to the predicted potential impacts and considerable area and resource requirements, commercial mining requires the control and regulation of human activities on the ocean surface and seabed as well in the affected water columns. Marine spatial planning and spatial mine planning solutions will be key to achieve sustainable development goals as well as operational, legal and environmental requirements yet to be defined. Moreover, there is an urge for an integrated ocean and seabed observation system as well as an effective Mining Code to manage human activities at different levels and scales. Instead of a moratorium, "deep-sea mining on probation" together with adaptive management, strict limitations and conditions could be the way forward to achieve blue mining and blue growth for a green energy future.

The UMC presentation outlines the challenges that industry, the scientific community and the authorities will have to face in the near future. The various stakeholders will be given insights into blue solutions that could be the key to blue mining and a green energy future.

Observations of Benthic Boundary Layer Processes for Marine Mineral Extraction

Mark E. Luther, Chris Martens (USF College of Marine Science, University of North Carolina, Chapel Hill, USA)

Observation and long-term monitoring of benthic boundary layer processes and transport rates, along with mitigating factors such as suspended sediment concentration, oxygen saturation state, microbial respiration and benthic coupling, are critical for understanding the potential impacts of seabed mineral extraction. Sensor technologies needed for such observations in an operational setting are currently limited by power source, calibration, bio-fouling and response time issues. We are developing new integrated multi-sensor, power, and communications systems to address these issues to provide autonomous operational capabilities for months to year-long in situ observations. Combined turbidity, chemical sensor and ADCP measurements will allow for quantitative assessment of boundary layer and water column transport processes controlling sediment plumes. Acquisition of such baseline ocean environmental information will better inform decision-making at locations where future ocean mineral extraction may occur. In collaboration with private sector partners Develogic GmbH and Franatech GmbH, we have developed a new mini-lander (ML) sensor system that can provide these measurements while deployed on the sea floor for extended periods. The ML sensor packages will combine turbidity sensors, dissolved oxygen (DO) optodes, and ADCPs to generate continuous suspended sediment, dissolved gas and current measurements on the seafloor for periods of months to a year. The ML system can include pH and CTD sensors plus a “pop-up” buoy with intake tubes to allow water sampling at multiple depths within 10m above the seafloor. The ML sensor package will utilize Mg-Seawater batteries (SeaMags) under development by our private sector partner, Develogic GmbH. Previous power sources utilized for multi-sensor benthic lander measurements have relied on specialized, expensive lithium battery packs that generally cannot support underwater time-series monitoring for periods longer than a month. The SeaMag battery system will provide over 50 watts continuously and is projected to support multiple sensor system measurements for periods of months to a year. Multiple SeaMag battery units can be placed in series to cover longer operating periods while avoiding safety issues associated with Li batteries or fuel cells. The ML measurements can provide continuous near real-time data telemetry via inductively coupled mooring wire and Iridium satellite communications using Develogic’s MI.Sat II buoy system (http://www.develogic.de/products/data-buoy-systems/misat-buoy-ii/). MLys operation in free vehicle mode allows for pre-planned data package transmission using an acoustic modem or release of disposable pop-up floats.

Ideas and suggestions for environmental baseline studies related to future mineral extraction on the Norwegian continental shelf

Jens Laugesen, Oyvind Fjukmoen, Randi Hagemann, Arne Myhrvold (DNV GL)

This presentation discusses ideas and suggestions for environmental baseline studies related to future mineral extraction on the Norwegian continental shelf (NCS). It also describes the state of the Norwegian legislation for mineral extraction on the shelf and what is known about the mineral deposits on the shelf. In Norway a new law on Mineral Activities on the Norwegian Continental Shelf, "The Seabed Minerals Act" entered into force in 2019. The law put the responsibility to carry out an "impact assessment for the opening of the area" on the Ministry of Petroleum and Energy. The impact assessment will assess potential impacts a possible opening might have on the environment as well as economic and social aspects of such activities. The law will be supplemented with a set of regulations, and that work has not yet started. For oil and gas activity on the NCS there is established a set of HSE regulations containing risk- and performance based requirements https://www.ptil.no/en/regulations/all-acts/). These regulations include requirements on environmental baseline studies both related to exploration in new and less surveyed areas, as well as prior to production development. The Norwegian Petroleum Directorate (NPD) has been assigned the task of mapping and proving deep sea mineral deposits by the Ministry of Petroleum and Energy. The resource estimate will serve as input to the opening process. An environmental baseline study should document the natural characteristics of the surrounding environment in the areas directly and indirectly affected by any planned underwater mining activity prior to the start of activities. ISA has established recommendations for environmental baseline studies for exploration, but so far not for exploitation where the draft regulations are in preparation. The recommendations and expectation for data gathering as part of exploration activities are quite extensive. For the NCS, it would be sensible to adapt the scope of the baseline study to the size and environmental sensitivity of the actual area. That would allow a more flexible system where for example a smaller and not very sensitive area could have a less comprehensive baseline study. We recommend that an assessment is carried out of what the relevant environmental factors are for seabed mining on the Norwegian Shelf and which of these factors are relevant for the baseline study at the actual site. This could be done by using the requirements for baseline surveys for the petroleum sector on the Norwegian shelf combined with relevant parts from ISAs recommendations.

Water-Column Physics, Seafloor Massive Sulphides, and Polymetallic Nodules

Rick Cole, Jon Wood (RDSEA International)

Authors, R. Cole (RDSEA) and J. Wood (Ocean Data Tech) have a combined experience of working in, and on, our worlds' oceans, of well over 70-years. Projects spanning U.S. Federal and State ocean sciences, academics, the oil and gas, and offshore energy sectors and now, the Deep-Sea Mining (DSM) realm, International and National Programs. Here; we discuss two areas of the DSM community: Seafloor Massive Sulphides (SMS) and Polymetallic Nodules (e.g. manganese nodules) and the monitoring of water-column physics and peripheral sampling of the projected mining regions as per the International Seabed Authority (ISA), Environmental Impact Assessment (EIA) protocol for the "Area" lease permitting process. The outcome and goals are to measure and understand the processes that govern the physics and water-quality of the area to be mined. Both shallow and deep-water system designs will be discussed covering full water-column applications.

Oceanographic moorings have been designed and deployed in the tropical Pacific Ocean to measure the physical properties and current flows in water depths of ~1000m, and exceeding 4500m. Acoustic Doppler current meters (ADCP), conductivity-temperature-depth (CTD), and turbidity sensors are deployed to collect high-resolution data in the deep benthic boundary layer and upper water-column at site locations. Downward-looking ADCPs are positioned 10-20m above the seabed, with upward-looking ADCPs in the same buoy, recording a near-continuous velocity profile 2m to 72m above the seabed. CTD sensors are attached to the acoustic releases and placed 3.5m above the seabed. The moorings are deployed for durations up to 2-years. Some data of previously collected currents and turbidity profiles will be discussed along with the variability between the bottom boundary and mid water-column layers of the deployment regions.

Ocean Minerals Program to Address the Critical Metals Supply Chain

Hans Smit (OML - Ocean Minerals LLC)

Ocean Minerals (OML) is a seabed minerals exploration and development company focused on sustainable and responsible commercial mineral supply chains for multiple critical metals required for 21st century high tech and green tech applications. We believe that for cobalt in particular the world will increasingly need to source these metals from the seabed, in order to address the projected global supply shortages. Cobalt's supply deficit becomes critical in the 2025-2026 timeframe, and is projected to widen from there, which means that seabed mining can play a pivotal role in providing responsibly developed projects in partnership with stakeholders to address these shortages. To that end, OML is advancing the development of our Cook Islands polymetallic nodule project (Co-Ni-Cu-Mn), as well as continuing to investigate the commercial viability of harvesting key rare earth elements (REEs) from the Cook Islands' deep seabed sediments.

In this paper, we will address our progress to date, and specifically the recent successful completion of our campaign to recover Cook Islands nodules and subsequent results of mineral process extraction testing. This is the first time, to our knowledge, the results of metallurgical testing of Cook Islands nodules has been reported. We delve into our future plans to achieve "first cobalt" by 2026, and in particular we discuss how, in addition to core project fundamentals (resource, mining system, processing and economics) our approach of an eco-system based environmental work program and hands-on community involvement may result in a commercially successful project with positive impacts for the Cook Islands local economy and population. Finally, we will present an integrated program plan, which we believe supports our story that sourcing cobalt and other metals from Cook Islands nodules can address the anticipated supply deficit in a significant and scalable manner.

Benthic foraminifera are useful indicators of ecological quality status for marine mining environmental impact assessment

Bryan O'Malley (USF College of Marine Science)

Deep-sea minerals are an important resource to the sustainability of a world with rapidly evolving technology and increasing demand for commercially important metals. To ensure the responsible and sustainable harvest of ferromanganese crusts, polymetallic nodules, and seafloor massive sulfides, benthic ecological quality status (EcoQS) should be determined prior to, during and following mining activity. It is important that environmental impact assessments and monitoring programs have a standardized component to allow for geospatial, temporal, and trophic comparison. The Ecological Quality Status, as implemented in the EU by the European Water Framework Directive, is a standardized metric for monitoring ecological health and developing reference conditions. One index used to define EcoQS is the AZTI Marine Biotic Index (AMBI), which pairs species abundance with environmental stressors to determine species specific sensitivities and tolerance. Benthic foraminifera (BF) are ideal bioindicators for ecological monitoring because of their high biodiversity, high preservation potential in the sediment, varying environmental sensitivities, and high abundance in all marine environments, which provides a reliable database for statistical analysis when restricted to small sample volumes conducive for a cost-efficient sampling program. To calculate the benthic foraminiferal AMBI (Foram-AMBI), species are assigned to one of five ecological groups ranging from sensitive (I) to first-order opportunists (V) based on their correlation to total organic matter and sediment grain size. The Foram-AMBI coefficient is calculated by the relative amount of each ecological group found at each site. The Foram-AMBI has been successfully implemented as a standardized EcoQS monitoring tool in the Mediterranean, the North Atlantic, and the Gulf of Mexico and can be adapted to areas of marine mineral exploration like the Clarion-Clipperton Zone. The Foram-AMBI is a proven, cost-effective monitoring tool that will aid provision of benthic environmental impact assessments in support of deep-sea mining efforts.

The Law of the Sea Amendment (BBNJ) and What this New Regulation Means to the Deep Seabed Mining Community

Paul Holthus (World Ocean Council)

The World Ocean Council (WOC) is working to provide consistent, comprehensive industry presence in inter-governmental negotiations affecting future of the Blue Economy, especially at the UN Law of the Sea, which is negotiating a new "Legally Binding Agreement" on Biodiversity in Areas Beyond National Jurisdiction (BBNJ). The BBNJ will strengthen regulation of activities and conservation of marine biological resources in the international ocean, i.e. surface waters, water column and seabed of "Areas Beyond National Jurisdiction" (ABNJ). The BBNJ "Package" covers: Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEAs); Area-Based Management Tools (ABMTs), including Marine Protected Areas (MPAs); Marine Genetic Resources (MGR) and Access and Benefit Sharing (ASBS); Capacity Building and Transfer of Technology. The BBNJ negotiations are planned to be competed in 2021 and will result in new, stricter requirements and controls by States over the activities conducted by companies under their control or jurisdiction and expanded or new national, regional and/or international authorities for BBNJ. The seabed mining industry is encouraged engage in the BBNJ process and the WOC can assist with this, as we have been doing with other sectors.

Prospectivity mapping of seabed minerals using satellite remote sensing data: the SAGRESsmart project

João Carvalho (ISQ, Portugal)

The global push for a low-carbon and greener economy together with the huge electric vehicle popularity rise is propelling the demand for base metals such as nickel, cobalt and copper. A recent assessment by The World Bank estimates that the production of minerals such as cobalt, lithium and graphite could increase by nearly 500% by 2050 to meet de growing demand for clean energy technologies. To meet this demand several private and government owned companies are proposing to explore for and mine mineral resources from the deep ocean seafloor to extract high concentrations and abundances of manganese, nickel, cobalt and rare earths. Currently, ISA has sign contracts for exploration of polymetallic nodules, polymetallic sulfides and cobalt-rich ferromanganese crusts with 30 contractors. However, a huge amount of seafloor is yet to be prospected and explored. Combined, the size of the granted exploration areas represents less than 10% of the overall area though as most favorable for the occurrence of the 3 types of mineral deposits above mentioned. This means that today's assessments on deep-sea mineral resources are only a rough approximation and optimum areas may yet to be found. SAGRESsmart project- Smart Support for Geological Prospection at Seabed based in Space Assets - aims is to develop and implement a web-based decision-support platform service to simplify and improve exploration for deep-sea mineral resources. As a purpose-built tool to increase knowledge, de-risk prospection and exploration activities and assess the potential for minerals, the proposed solution merges multi data sources (including satellite remote sensing) with machine learning to highlight and rank potential prospective targets. Having access to integrated information provided by a single, automated multi-criteria analysis solution can greatly speed up initial exploration and improve decision making and asset management.

An integrative metallogenetic study of seabed mineral deposits in the pan-European seas: GeoERA-MINDeSEA

Francisco Javier Gonzales (Geological Survey of Spain - IGME)

GeoERA-MINDeSEA project is an ERA-NET action, Horizon 2020, funding a transnational cooperative network of 12 Geological Surveys and Marine Institutes, at various points of common interest for investigation and exploration on seafloor mineral deposits in pan-European seas. MINDeSEA is producing cartography, datasets, genetic models and case studies for use by the European Commission, other stakeholders and society. The project is based on detailed studies and compiled data on geology, mineralogy, geochemistry, environmental and regulatory issues of hydrothermal mineralization, polymetallic nodules, ferromanganese crusts, phosphorites and marine placer deposits. Covering 15,000,000 km2, the panEuropean seas represent a promising new frontier for the exploration of mineral resources. More than 600 mineral occurrences and more than 1000 analyzed samples are reported in the MINDeSEA database, containing five main levels of information, with multiple attributes, for each occurrence: geographic, metallogenic, geochemical, economic, and environmental data. Cobalt, lithium, tellurium, nickel, rare earth elements, copper, and other strategic and critical metals are being investigated using cutting-edge technologies in several seabed mineral deposits under the jurisdiction of European coastal States, as alternative sources to land based mineral deposits. An enormous challenge in terms of research, technological innovation, environmental protection, spatial planning and social license is facing the European and international research and sustainable development plans. MINDeSEA will identify areas for sustainable resourcing and information to support decision-making on management and Marine Spatial Planning in pan-European seas as part of its core actions, besides stablishing strategic links with the EU EMODnet-Geology project. A first map of energy-critical elements, cobalt and lithium in ferromanganese deposits has been produced to support European climate actions and growth strategies.

Regional and fine-scale variability in chemical and mineralogical composition of the hydrogenetic ferromanganese crusts

A.Usui, H. Hino, M. Kurihara and H. Kobayashi (Kochi University)

The hydrogenetic ferromanganese crusts deposits in the Northwestern Pacific seamounts have been noted as most abundant and highest in cobalt and related metals, and therefore parts of the seamounts have been allocated to some international prospectors under the ISA. However, the regional to fine-scale mode of variation in abundance and grade and the controlling geological parameters are yet well understood. We attempted to characterize the patterns of variability in composition and abundance within the crust and among the seamounts, based on stratigraphy of drill cores of the ferromanganese crusts taken at around 4-5km intervals over the tops of seamounts and their geological correlations. The camera-monitored drill machine (BMS) was operated at rock outcrops of seabeds, after full coverage of multi-narrow beam topographic mapping over more than 6 seamounts in the area. We assume these hydrogenetic crusts have been formed since middle Miocene (around 15 million years ago) or earlier, with significant variation in metal flux (mass accumulation rate) or elements and minerals of various origins with time. On the other hand, the microstratigraphy is generally comparable and often correlated to each other, thus consequently showing similar bulk chemical composition among samples of the full growth lapse. Furthermore, the substrate geology and seamount evolution history may be related to the age and thus bulk composition of the ferromanganese oxide piles. In conclusion, the fine-scale geochemical and mineralogical description of full drill cores of the crusts is most important in characterizing their patterns of compositional variations within ores and in estimating potentiality of ferromanganese crusts deposits.

Geographic and Oceanographic factors that impact the composition of FeMn crusts

Kira Mizell (USGS)

Ferromanganese (FeMn) crusts have a high degree of compositional heterogeneity, with varying Fe, Mn, and other metal contents across spatial and temporal scales. Detailed research is still needed to address the geographic and oceanographic factors that control FeMn crust composition within continuous large regions. This research will lead to a shift from purely exploration-based recovery of FeMn crusts to more targeted expeditions that can precisely locate FeMn crusts with the characteristics (i.e. thickness, composition, substrate type) of interest. Geochemical analyses of recent FeMn crust growth from a continuous meridional transect of seamounts in the western equatorial Pacific shows that a variety of modern oceanographic and geographic parameters are well-recorded by FeMn crusts. Seawater oxygen concentration exhibits the greatest control over the concentrations of Mn and Mn-oxide associated elements like Co and Ni in FeMn crusts collected from a ~3000 km N-S transect, whereas water depth predominantly determined Fe contents. Silicon and Al showed meridional variations, and Fe, Ba, and Mg are enriched in FeMn crusts associated with high biological particle flux from the surface waters above. We also compared the composition of bulk crusts within the Tuvalu Exclusive Economic Zone as a subset of the larger sampled region, using the same oceanographic and geographic parameters. Mn, Co, and Ni in bulk FeMn crusts are also more enriched at shallower water depths and closer to oxygen minimum in the water column, even including phosphatized crusts. Fe in bulk FeMn crusts also tends to increase with depth as seen for the recent crust growth layers. The case study of FeMn crusts within the Tuvalu EEZ also illustrate how FeMn crusts collected from reconnaissance expeditions can determine the dominant controls on crusts in that region and help define permissive areas for more targeted future exploration.

Cobalt-rich Ferromanganese Crusts from the Canary Islands Seamounts: Mineralogy and Geochemistry

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Ferromanganese crusts from Canary Islands Seamount Province (CISP) have been thoroughly studied as part of a PhD project funded by GeoERA-MINDeSEA, EMODnet-Geology and Extension of the Continental Shelf of Spain projects. The work reports the first integrative study of 43 Fe-Mn crusts collected by dredge and ROV on eight seamounts (Tropic, The Paps, Echo, Bimbache, Drago, Gaire, Amuley and Las Hijas) on the west and southwest of the CISP in the northeastern Atlantic Ocean. Crusts pavements cover these seamounts whit thickness comprised between 2 mm up to 25 cm. Bulk studies show that main minerals are low crystalline vernadite (85-90%) and goethite (5-10%). Quartz and calcite can be recognized as minor amounts of detrital and authigenic minerals. Bulk geochemistry shows the highest contents for Fe (21 %) and Mn (15%) with less contents of the others major elements. For the trace elements the average contents of Co, Ni, Te and rare earth elements plus yttrium (REY) are as follows: 4200, 2000, 36, 2600 µg/g, respectively. High-resolution analysis of both mineralogical (micro XRD, Raman and FT-IR) and geochemical methods (microprobe and LA-ICP-MS) have been performed on selected crusts. These analyses confirm the prevalence of the hydrogenetic process forming vernadite with similar contents of Fe (21 %) and Mn (19%) and higher contents of Co (1%), Ni (0.3%), REY (0.4%) and Te (80 µg/g). Diagenetic laminae formed by todorokite and asbolane/buserite are of minor abundance and show high contents of Mn (40%), Ni (6%) and Cu (2%). Finally, hydrothermal minerals have been recognized with punctual Fe isotopic studies made with LA-ICP-MS. These minerals are usually enriched in Fe (50%) with low contents of all the trace elements. Fe-rich laminae in contact with substrate rock have positive 557Fe from +0.27 to +0.60%0 confirming their hydrothermal origin. On the other hand, hydrogenetic minerals show negative 557Fe ranging from -1.73%0 at the base of the crust to -0.57%0 at their top. All these studies confirm for CISP crusts a general hydrogenetic origin with slow growth rates ranging from 0.8 to 10 mm/Ma (cobalt-chronometer equation). Different environmental factors are proposed affecting crusts growth: the thickness of the oxygen minimum zone and the combination of several currents active in the study area; the presence and variable elemental inputs both from the Saharan dust and the volcanic-hydrothermal activity during crusts growth.

Reconstruction of hydrothermal ore-forming system evolution during 100 kyr based on massive sulfides

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The study of the age and evolution of oceanic hydrothermal systems was begun in the 80s of the last century based on the dating of massive sulfides (Lalou, Brichet, 1982). The same goal has been reached by study of the geochronology and geochemistry of bottom sediments in order to identify and to date core intervals corresponding to the peaks of hydrothermal activity and sulfide accumulation (Cherkashev, 1995). Both approaches have their advantages and disadvantages. The dating of sulfides is discrete in nature and makes it possible to determine only the specific time of the ore formation process within the hydrothermal field. An increase in the number of dating makes it possible to obtain a statistical series reflecting periods of hydrothermal activity. However, due to the random sampling of ore bodies, the obtained dating is still discrete and does not allow to characterize the duration/longevity of the hydrothermal activity stages. The second approach makes up this gap since it allows to reconstruct the hydrothermal input to the seabed/sediments in a continuous mode. Its disadvantage is the presence in the sediment core a cumulative effect from several closely spaced hydrothermal vents. In addition, ore material supplies to the bottom sediments both from the plume and from the weathering sulfide mounds, which complicates the reconstruction of the ore formation process. We made attempt to combine study of sulfides and sediments to better reconstruction of hydrothermal processes within Pobeda sulfide deposit. The Pobeda ore cluster, consisting of two ore fields, is located within oceanic core complex on the eastern slope of the MAR rift valley at 17,1 degrees N. 14 samples of sulfides and 3 cores of bottom sediments have been studied. Sulfide and sediment dating have been done using 230Th/U and paired 14C and 230Th methods respectively. The results of sulfide dating demonstrate that chronology of hydrothermal events within two hydrothermal fields is different. This may be due to both insufficient sampling of ore bodies and differences in the scenarios of hydrothermal systems development despite their close proximity (2.5 km). In the second case, the presence of two nearby heat sources (gabbro injections?) inside the ultramafic rocks of oceanic core complex should be assumed. The vertical distribution of iron in sedimentary cores indicates a continuous process of hydrothermal activity over the past 70 thousand years. The absence of pronounced anomalies in iron concentrations in the sediments does not promote to fix distinct stages of the hydrothermal activity. Nevertheless, the combination of data on sulfides and sediments allowed us to get better reconstruction of hydrothermal processes in this region of the MAR. Lalou C. and Brichet E. 1982. Ages and implications of East Pacific Rise sulphide deposits at 21 °N. Nature. 300. P. 169-171 Cherkashev G. 1995. Hydrothermal input into sediments of the Mid-Atlantic Ridge.

Ship Happens: Contingency Planning for Deep-Sea Mining in Light of Exxon Valdez

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Wind and solar power are among the many green technologies that countries are looking to in order to reduce their dependence on carbon-heavy fuels and cut greenhouse gas emissions. The ambitious Paris Agreement committed a majority of nations to prioritize efforts to combat climate change by implementing measures to keep global temperature rise below two degrees Celsius above pre-industrial levels. To meet their nationally determined contribution, each nation will need to reduce their dependence on fossil fuels and increase their use of efficient renewable technologies. The World Bank forecasts that "meeting the Paris climate target . . . will require a radical . . . restructuring of energy supply and transmission systems globally." Simultaneously, technology advances and smartphone use are on the rise globally. At the end of 2014, an estimated 1.64 billion people worldwide owned smartphones. With the growing demand for green technologies, renewable energy and smartphones, comes a growing demand for the minerals used to power them. The seabed provides a rich source for these necessary minerals. However, an increased demand for minerals brings an increased concern for the habitats and marine ecosystems of the seabed where mining for those minerals will take place. While moving from carbon-intensive energy sources is one way to meet climate change goals, "a green technology future is materially intensive and, if not properly managed, could bely the efforts and policies of supplying countries to meet their objectives of meeting climate" goals. Calls for tougher environmental regulations, or even a moratorium on deep sea mining, have resonated across the globe. Last year, for example, the President of Fiji pleaded, "I ask you all to… support a 10-year moratorium on seabed mining from 2020 to 2030 which would allow for a decade of proper scientific research of our economic zone and territorial waters." The International Seabed Authority (ISA), an intergovernmental body composed of representatives from each nation that has ratified UNCLOS, oversees the exploration and exploitation of minerals in the Area. UNCLOS prescribes environmental standards to be adopted by the ISA. Member nations, who control mining operations within their territorial waters, are similarly held to such standards. However, it is still unclear how strictly the requirements will be enforced or maintained. The oil industry has the potential to serve as a learning tool for the deep-sea mining industry. Looking at the regulation failures that led to one of the most severe marine pollution incidents in United States history, the Exxon Valdez oil spill, one can see that even the best-laid plans can fail. Government and public policy experts agree that the extent of the damage could have been minimized if national, state and industry policies were enforced. Adverse effects from mining activities are inevitable. No plan can account for every possible contingency that is guaranteed to occur during large-scale, experimental projects such as deep-sea mining. This Comment argues that as deep-sea mining ventures are undertaken in the coming years, the ISA, sponsoring nations, and private industries should not forget the lessons learned from the Exxon Valdez oil spill. Accidents will happen, and the mining industry must be prepared with quick and effective response plans and the equipment and financing to carry it out. This will involve coordination between international and state regulations with private mining companies' internal policies and strict oversight by the ISA.

IP Licensing for Deep Seabed Mining (DSM): Leave the Regulatory Gap or Fill it?

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In last year's presentation at UMC the author came to the conclusion that the "Common Heritage" principle governing the Area would not extend to intellectual property ("IP") such as e.g. patents. Neither the current draft rules of ISA on the exploitation of deepsea mineral resources ("Draft Rules") nor the UNCLOS provisions contain any obligation on holders of patents to allow their use where needed for the extraction of minerals for the benefit of another company, let alone mankind. A rare example of a corresponding rule in a neighboring field, i.e. draft Art. 12 of the BBNJ convention on biodiversity beyond national jurisdiction, is meanwhile under attack from important stakeholders in the UN negotiation process. The author had nevertheless proposed a "minimal approach": The present Draft Rules should be supplemented with an obligation on a holder of "Essential IP" (i.e. IP necessarily to be used in deepsea mining) to license them to others, on fair and reasonable (FRAND) terms, for any volumes or markets of protected products or processes he himself cannot reasonably cover commercially. The actual presentation shall explore this concept further: Even if the Draft Rules will remain silent on IP licensing (apart perhaps from current draft Reg. 89 No. 6 stating that IP rights shall not be affected), the matter is likely to be brought up in contracts once there is more than one technology sensible party in an exploitation consortium. Hence the paper undertakes to address the following questions: What would likely happen in praxis if neither the Draft Rules nor a consortium contract would regulate the matter? Would a limited license under DSM Essential IP as proposed by the author make political and economic sense in principle? If so, should it be only for the benefit of the consortium partners or also for third parties, e.g. in LDCs? What should be the scope: production only, or also sales, of products made or processed by using the patented technology? As to territorial scope: Should the license be worldwide or geographically limited? And as to conditions: should the market govern, or would there be place for a regime like "FRAND"? Relying again on examples and concepts from other areas of commercial activity, the paper will arrive at a set of model provisions which may either still find its way, in whatever form, into the ISA Draft Rules, or may be offered to future contractors for use in their consortium agreements if the need arises.