ISA draft regulations for exploitation

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On 13 July 2000, the ISA adopted the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area. The first contracts for such exploration were issued by the ISA the same year. The duration of exploration contracts is 15 years, after which the contractors are expected to go into exploitation. In 2013, ISA with the LTC initiated the process for developing the regulations for exploitation, and are currently working on the first draft to put forward for the Council. In the meantime, the first seven exploration contracts have expired, and been given five years extensions in order for the contractors to get ready to apply for exploitation contracts. According to the current draft of the exploitation regulations, an application for an exploitation contract shall be accompanied by all data acquired during the exploration phase, a mining plan, a financing plan, and a set of environmental plans (i.e. an environmental impact statement, an emergency response and contingency plan, environmental management and monitoring plan, and a closure plan). All of these plans have to be based on substantial scientific and technical data and information. The mining plan requires geoscientific data regarding the mineralogy and grade of the nodules, and the physiography of the mining site as a basis for the consideration of critical aspects, *inter alia* for making reliable resource estimations, design the mining operations, and forecast revenues. The environmental plans require the input of a substantial set of bioscientific data and information on the exploitation technology in order to establish base-lines, and monitor and evaluate the effects of the mining operations. Under the exploration contracts, such scientific data have been acquired and reported on an annual basis to the ISA. Some testing of mining equipment and experiments on the extraction of metals have also been performed by some contractors. These scientific and technical data from the exploration phase will be the

basis for the for the preparation of the studies, plans and documents required for the applications for exploitation. No time frame is specified for the preparations of an application but it must be assumed to take place before the expiration of the exploration contract.

The draft exploitation regulations also require that after having been granted an exploitation contract, but prior to the commencement of production, the contractor must submit a feasibility study, including a revised mining and financial plan, and a revised environmental management and monitoring plan and closure plan, for approval. The feasibility study and the revised plans may require further scientific and technical data and information. The time needed for carrying out extra data acquisition, the feasibility study and the prescribed revisions is not stipulated, but by inference is to be part of the exploitation term.

In addition to the above requirements and procedures related to the application for and granting of an exploitation contract, the draft regulations include sections on the rights and obligations of contractors; the protection and preservation of the marine environment; the financial terms of a contract; data management; inspections, compliance and enforcement; and the settlement of disputes. The draft regulations provide for a royalty to be paid by the contractors. A proposal for how this royalty is to be calculated is outlined in an appendix. However, it is indicative and presented for discussion only. A set of fees, guarantees and funds are also provided for, including an environmental performance guarantee, and the establishment of an environmental liability trust fund.

Keywords: International Seabed Authority (ISA), deep sea minerals, deep sea mining, exploitation regulations

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Deep Seabed Mining in National Jurisdiction: Key Challenges

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DEEP SEABED MINING IN NATIONAL JURISDICTION: KEY CHALLENGES

The talk focuses on the key challenges that arise from deep-seabed mineral exploration and development within areas of national jurisdiction, including legal and institutional challenge and options to address these challenges.

Keywords: Deep-Seabed Mining, National Jurisdiction, Exclusive Economic Zone, Continental Shelf, Marine Environment.

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Joshua Brien has acted for a range of Governments throughout the world, including small-island States and the developing world. This has included engagement in matters before the International Court of Justice, the Tribunal for the Law of the Sea in contentious and advisory proceedings, including provisional measures applications and prompt release cases.

He has extensive experience advising on law of the sea, with particular expertise concerning maritime boundary delimitation, the management of offshore resources, the preparation and defence of continental shelf submissions to the United Nations Commission on the Limits of the Continental Shelf ('CLCS') made under UNCLOS, and the legal aspects of the pioneer activity of deep-seabed mining both in the Area managed by the International Seabed Authority and within areas of national jurisdiction, including areas of extended continental shelf.

Joshua has been directly engaged in the successful conclusion of over 15 maritime boundary delimitation agreements in the Caribbean, African and Asia-Pacific regions over the past decade and has prepared over 19 Submissions to the CLCS. He continues to advise a range of States on the preparation of new submissions and in respect of the examination of existing Submissions. He has also advised a range of States on the development of national policies and laws concerning the regulation of deep-seabed mineral exploration and development.

He also provides advice to States and other clients on the policy and legal aspects of the development of the blue economy and the integrated management of ocean space. This includes advice concerning the reform and development of national laws and policies and management of marine resources including international fisheries and the development of new and innovative ocean-based industries in support of sustainable development.

Hydrothermal activity, sea level and glaciation: evidence of correlation from the Atlantic SMS

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INTRODUCTION

Based on geochronological data it was confirmed that hydrothermal discharge has an episodic character: active and inactive periods of the seafloor massive sulfides (SMS) formation alternate (Cherkashov et al., 2017). There is an assumption of correlation of the periods of magmatic and hydrothermal activity with the stages of glaciation (Lund et al., 2016). During the cold periods, the level of the ocean was reduced from 70 to 150 m depending on the glaciation scale (Spratt, Lisiecki, 2016). As a result, the hydrospheric pressure on the upper mantle decreased and could provide increased magmatic and hydrothermal activity (Lund, Asimow, 2011). This assumption is confirmed by the correlation of warming and cooling stages with increasing of hydrothermal input to the bottom sediment near hydrothermal fields. According to data (Lund et al., 2014, 2016; Middleton et al., 2015) the peaks of hydrothermal activity, expressed in the layers of metalliferous sediments at the East Pacific Rise and the Mid-Atlantic Ridge, roughly correspond to the last two periods of cooling (20 and 60 ka).

To test this hypothesis, we tried to compare the sequence of warm and cold periods in the Pleistocene with the dating of SMS reflecting the periods of hydrothermal activity.

Results

SMS samples were obtained from 12 sites within the Russian Exploration Area at the MAR segment 12-20°N. The results of dating 198 samples by the ^{230}Th/U method demonstrated the absence of correlation between hydrothermal activity periods in different hydrothermal fields (Cherkashov et al., 2017). It was proposed that each field has its own evolutions scenario. Considering this point, only the oldest SMS dating for each field which fixed the beginning of hydrothermal activity was selected for comparison with the cold/warming periods.

Figure 1 shows the periods of marine isotope stages reflected in the standard SPECMAP scale (Kazmin, Volkov, 2009) and data on the oldest $^{230}Th/U$ dating of SMS deposit from the 12 hydrothermal fields. The isotopic composition of oxygen in sea water ($\delta^{18}O$) is controlled by the amount of open ice on the planet and thus it is associated with global periods of warming and cooling. The periods of global glaciation and warming are characterized by high and low content of δO^{18} respectively (Imbrie et al, 1984).

Age dating is divided into two groups of SMS deposits - associated with basalts (circles) and gabbro-peridotites (stars). It follows from the figure that age of SMS associated with basalts coincides with the glacial maxima while the age of the SMS associated with ultramafic rocks do not show any temporary connection with glaciations in the Pleistocene.

The explanation of this observation could be the following: "basalt" fields have magmatic control and direct connection with magma chambers, while "ultramafic" fields activation is determining mainly by tectonic factor and are not associated with periods of magmatic activity. Taking account this consideration the correlation between magmatic/hydrothermal activity reflected in the events of basalt hosted SMS formation and global paleoclimate cold periods could be indicated. We realize that statistics of SMS datings is rather low and are planning to increase geochronological data base.

Conclusions

Thus, it can be concluded that additional arguments have been received in favor of the assumption of a connection between the periods of glaciation, magmatic and hydrothermal activity. Further research which will include data for metalliferous sediments as well as modelling of magmatic processes will help to obtain more data to elucidate the validity of this hypothesis.

References

Cherkashov G., Kuznetsov V., Kuksa K., Tabuns E, Maksimov F., Beltenev V. // Sulfide geochronology along the Northern Equatorial Mid-Atlantic Ridge. Ore Geology Reviews 87. 2017. P. 147–154.

Imbrie, J. , Hays, J. D. , Martinson, D. G. , McIntyre, A. , Mix, A. C. , Morley, J. J. , Pisias, N.G., Prell W.L. and Shackleton N.J. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record // Milankovitch and Climate: Understanding the Response to Astronomical Forcing. Dordrecht: D. Reidel Publishing. 1984. P. 269-305.

Kazmin S.P., Volkov I.A., Continental implications as global climate events of the quarter // Bulletin of commission for study of the quaternary. Western Siberia Quaternary Problems. 2009. № 69. P. 85–93.

Lund D.C., Asimow P.D. Does sea level influence mid-ocean ridge magmatism on Milankovitch timescales? // Geochemistry, Geophysics, Geosystems. 2011. Vol. 12. № 12. P. 1–26.

Lund D.C., Asimow P.D., Farley K.A., Rooney T.O., Seeley E., Jackson E. W., Durham Z.M. Enhanced hydrothermal activity along the East Pacific Rise during the last two glacial terminations // Science. 2016. Vol. 351. Is. 6272. P.478-482.

Middleton J.L., Mukhopadhyay S., Mcmanus J.F., Langamur C.H. Last glacial maximum and hydrothermal sediment fluxes on the mid-Atlantic ridge // Goldschmidt, 2015. Abstracts 2123.

Spratt R.M., Lisiecki L. E. A Late Pleistocene sea level stack // Climate of the Past. 2016. Vol. 12. P. 1079–1092.

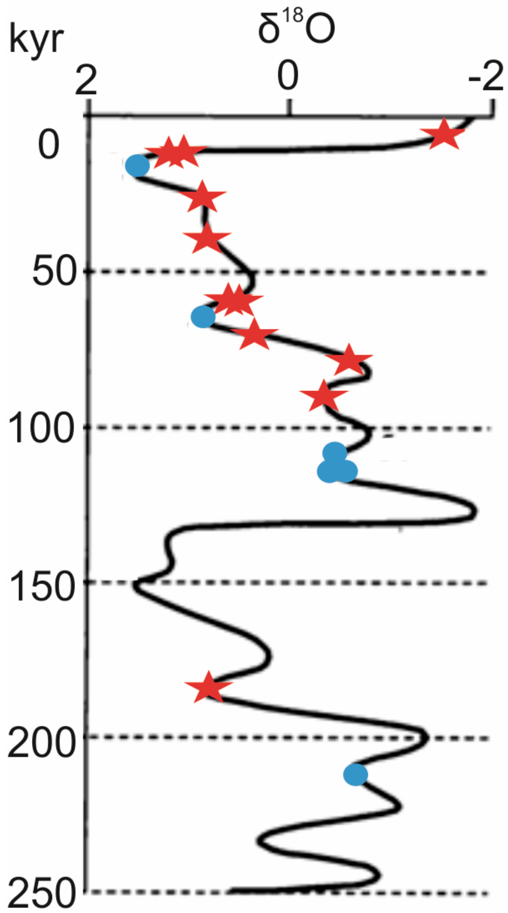

Figure 1. Changes of $\delta^{18}O$ in the seawater reflected cold and warm periods during 250 ky and the age of seafloor massive sulfides related to basalts (circles) and ultramafic rocks (stars).

Keywords: Hydrothermal activity, seafloor massive sulfides, oceanic magmatism, glaciation periods, sea level changes.

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Deep-Sea Mining: Intersections with Other Activities

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ABSTRACT

The ocean is increasingly seen as the answer for a myriad of challenges facing humankind. In effect, in addition to being vital for transportation and communication, the oceans contain living and non-living resources that are essential to meet the demand for food, and to the development of pharmaceutical products, energy resources, and high-technology products. This entails that the oceans are under pressure by different activities: navigation, fishing, oil and gas exploration and production, renewable energy development, laying of cables and pipelines, marine scientific research, bioprospecting, and deep-sea mining for minerals and metals.

The growing demand for essential minerals and metals such as cobalt, nickel, zinc, copper, and manganese, seen in tandem with technological advances in deep-sea mining, makes the latter an increasingly attractive activity, both in areas within and beyond national jurisdiction. At the same time, the further development of deep-sea mining adds to the problem of the competing uses of maritime space and accentuates the need to balance and articulate the interests of the different users of the seas (States, sponsored deep-sea mining investors, oil and gas investors, fishermen, shippers, etc.). Furthermore, as deep-sea mining activities increase and move on to an exploitation phase so does the possibility of new disputes (for instance during deep-sea mining exploitation a communication's cable is severed, a vessel conducting deep-sea bottom fisheries damages deep-sea mining equipment, etc.).

The Law of the Sea Convention (LOSC), which establishes a legal order for the seas and oceans articulating the freedoms, rights and obligations of the States, takes into account the interaction between the different sectoral uses of the seas. However, whilst the LOSC offers some guidance in how to approach the competing uses of the seas, it uses balancing terms such as 'due regard', 'reasonable regard', 'unjustifiable interference', and 'reasonable measures' which are open-textured. Consequently, these terms offer limited guidance in balancing the different interests. Moreover, it is difficult to see whether there is/should be a hierarchy of the different interests, and how to prioritize interests when different users of the sea cannot carry out their activities simultaneously.

In addition, this topic also highlights the need for conflict avoidance and cooperation between deep-sea mining and other activities, and elicits the question of the role of integrated ocean and coastal management plans, and of area-based management tools, in articulating the different activities and interests, both in areas within and beyond national jurisdiction. It also raises the issue of institutional cooperation between the International Seabed Authority, Regional Fisheries Organizations, the International Maritime Organization, etc..

In view of the foregoing, this contribution aims to: *i)* provide an overview of the different intersections between deep-sea mining and other activities; *ii)* inform of the relevant provisions of the LOSC containing guidance on how to balance the different activities and interests and relating both to areas within and beyond national jurisdiction; *iii)* discuss options for collaboration and management across deep-sea mining and the other activities; and *iv)* discuss what happens is a dispute does arise between deep-sea mining and another activity (from the perspective of contractors and States).

The range of topics and depth of this contribution may be adjusted taking into consideration the time allotted by the organization for the presentation.

Keywords: Law of the Sea; deep sea mining; other activities; legitimate interests; due regard; interference; disputes; integrated ocean management; area-based management tools.

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Upscaling towards Deep-Sea Mining by Vertical Transport Experiments over 130 meter.

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1. Introduction

Technology development for sustainable, safe, reliable and efficient mining of polymetallic nodules in the deep seas requires careful design, thorough understanding and integrated testing of all equipment, physical processes and (sub) systems involved (Dasselaar et al [1]). Proceeding from Vertical Transport System (VTS) experiments at IHC laboratory scale by Van Wijk [2], with typical system dimensions of several meters, to prototype or pilot scale testing with typical dimensions of several kilometers, is a giant leap. Naturally, intermediate steps are required in order to mitigate the possible risks in the full-scale system's (physical) processes.

Within the EU program Blue Mining (2014-2018), possibilities emerged for performing experiments at intermediate scale: the so-called medium-scale vertical slurry experiments. Near Freiberg, Germany, the village Halsbrücke possesses a 140 meter deep empty vertical mine shaft, perfectly suited for housing the test setup. For this purpose, a 318 meter long 145 mm pipeline circuit was constructed, including both a 130 meter high vertical riser and fall pipe section. A purpose-built sediment injection and separation system was deployed, including a 55 kW centrifugal pump. The riser section has been equipped with sensors capturing pressure, temperature, flow velocity, volumetric concentration and flow visualization.

The planning, modification and construction of the test facility site itself is described by Müller et al [3]. The present paper describes the objectives, experimental program, equipment, and the preliminary results. Publications on in-depth results are foreseen in the (near) future.

2. Objectives

The following main objectives, as basis for the experiments, were identified:

1. Obtain insight in the vertical hydraulic transport process of sand, gravel and polymetallic nodule slurries;
2. Investigate the occurrence and behavior of instabilities or density waves in the riser;
3. Investigate the use of pressure sensors to determine the slurry density inside the riser;
4. Obtain an unique data set for validation of the existing physical flow modeling (e.g. the 1DVHT model by Van Wijk [2]), and support the development and improvement of mathematical flow models on friction losses and transport velocities; and
5. Reduce the gap between small-scale experiments and full-scale experiments, by increasing the Technology Readiness Level (TRL) and gain experience in deploying and controlling a scaled VTS.

3. Experimental Program

The experimental program is designed to gather data that can be used to complete all objectives that have been set. Objectives 1-4 are completed by gathering and analyzing data from the experimental setup. In order to get a consistent dataset, a test matrix is created, in which the influence of a single parameter can be measured per experiment. Objective 5 is a tangible objective, and is considered to be complete when the system is successfully tested, the experience gained is reported and when all lessons learned are logged.

The test setup is designed and built as a closed loop circuit, see Figure 1 and Figure 2. The circuit inner diameter is D_{in} = 145 mm, total length L = 318 m, with 255 m vertical pipeline and 63 m horizontal pipeline.

Figure 1 Top-view of above-ground construction. Riser and fall pipe are located just below roof hole, see next figure. Source: Lutz Weidler

Figure 2 Overview of full test setup. Source: Sven de Jong.

The closed loop nature is different from full-scale, where riser and fall pipe are decoupled. Initial tests showed that the system started to show instable behavior in concentration. This is caused by the closed loop nature of the test setup. The instability in the system called for an update of the preliminary test matrix. In the final test matrix, lower sediment concentrations are used compared to the initial program, which lowers peak density concentrations to acceptable levels. The test matrix used during the experiments is shown in Table 1. This matrix contains experiments with a slurry of sand, gravel and nodules, in different ratios.

Next, the test sequence is described briefly. Before each slurry experiment (2 – 7) mentioned in Table 1, experiments 0 and 1 are conducted. These experiments are performed water-only to ensure that system base parameters can be compared for each run. When a slurry experiment is conducted, a fixed amount of solids is inserted in the loop while running at high flow rate, resulting in a constant average solids concentration. For example, in Figure 6 the insertion of the material is seen in the first 700 seconds of the test. After all sediment is inserted, the slurry velocity is lowered in predetermined steps – for fixed time intervals whilst capturing a data point – until the lowest acceptable mixture velocity is reached. After this, the experiment is stopped and the sediments are separated from the system whilst replaced by clean water.

Table 1: Test matrix. CFP = centrifugal pump control.

Exp. #	**v_m [m/s]**	**c_v [-] average**	**Material**	**Main purpose of experiment**
0*	0	0	Water only	Hydrostatic test for pressure sensor check.
1*	1- $v_{m,max}$	0	Water only	Experiment to check system hydraulic resistance
2	1- $v_{m,max}$	0.05, 0.1, 0.15	Sand d_{50} 1 mm	Validation of friction models. CFP control.
3	1- $v_{m,max}$	0.05, 0.1, 0.15	Gravel d 8-16 mm	Validation of friction models. Observation of density waves. CFP control.
4	1- $v_{m,max}$	0.05, 0.1	Sand and gravel 1:1	Validation of friction models. CFP control.
5	1- $v_{m,max}$	0.05, 0.1	Sand and gravel 1:2	Validation of friction models. CFP control.
6	1- $v_{m,max}$	0.05, 0.1	Sand and gravel 2:1	Validation of friction models. CFP control.
7	1- $v_{m,max}$	0.05	Manganese Nodules	Show we can do it. Validation of friction models. Observation of density waves.

4. Equipment

In this paragraph an overview of the equipment as used in Halsbrücke is given, followed by an overview of the sensors used to perform the measurements. Figure 3 contains an overview of the components used in the setup that were above-ground. Marked number 4 is the container in which the pump is located. The pump inlet pipe comes from the 20ft container, the outlet pipe goes to the mineshaft where slurry enters the fall pipe. Inside the 20ft container, sediment is inserted by opening gate valves of the 1 m^3 hoppers that contain a measured amount of sediment. These hoppers are marked number 3. After an experiment is finished successfully, the slurry is separated by rerouting the slurry flow into the tank number 2. In this tank there are three big bags of 2 m^3 each, hung off in custom build frames. By emptying this tank, the water drains from the big bags leaving them filled with the used sediment. Marked number 1 are the sedimentation tanks, which contain up to 7.5 m^3 of water each. The sedimentation tanks are used to fill the system with clean water at the start of a test and to let sediment fines settle after a test is finished.

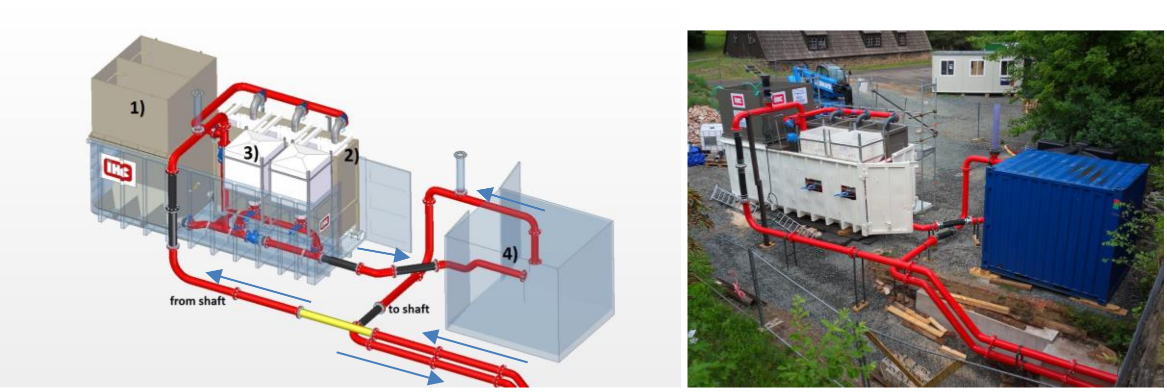
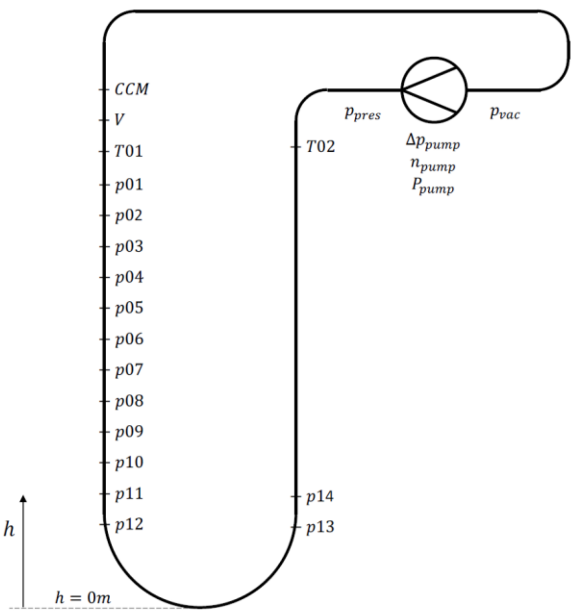


Figure 3: Overview of above-ground system components (left) and as-built situation (right). Source: Siemen Dasselaar.

In order to obtain all required data several types of sensors are used. For monitoring and control of a full-size VTS, mainly pressure sensors around the booster stations and flow measurements at the top are a viable option (Blanken et al [4]). The test setup's riser is fitted with twelve pressure sensors, spaced roughly eleven meters apart, an electromagnetic flowmeter and a Conductivity Concentration Meter (CCM). Both the riser and fall pipe contain a temperature sensor. An overview of all sensors is shown in Table 2. The locations of the sensors in riser, fall pipe and centrifugal pump container are shown in Figure 4.

Table 2: Sensor overview

Symbol	Parameter	Sensor Name	Sensor Type
$\boldsymbol{V}\ [\boldsymbol{m/s}]$	Mixture velocity	V	Krohne Optiflux 2300
$\boldsymbol{T}[°\boldsymbol{C}]$	Mixture temperature	$T01, T02$	Krohne Optitemp PT-100 -50…300 degC
$\boldsymbol{p}\ [\boldsymbol{kPa}]$	Riser pressure	$p01 \dots p14$	Krohne Optibar P2010c absolute 16 bar, 25 bar
$\boldsymbol{p}\ [\boldsymbol{kPa}]$	Pump pressure	p_{pers}	0…10 bar absolute UNIX 5000 series
$\boldsymbol{p}\ [\boldsymbol{kPa}]$	Pump vacuum	p_{vac}	-1…2 bar absolute UNIX 5000 series
$\boldsymbol{\Delta p}\ [\boldsymbol{kPa}]$	Pump differential pressure	Δp_{pump}	0…10 bar differential UNIX 5000 series
$\boldsymbol{n}\ [\boldsymbol{rpm}]$	Pump revolutions	n_{pump}	Optical counter, Banner QS18VP6LPQ8
$\boldsymbol{P}\ [\boldsymbol{kW}]$	Pump electrical power	P_{pump}	From frequency drive



All sensor data is recorded and shown in a control cabin, located on site. This way each experiment is monitored in real-time, which creates the possibility to quickly intervene during unexpected situations. The control screen, shown on the right in Figure 5, displays from top to bottom; the flow velocity, CCM measurements, temperature measurements and pressure sensor data.

Figure 4 Schematic overview of the flow loop with positions of the sensors. Source: [1]

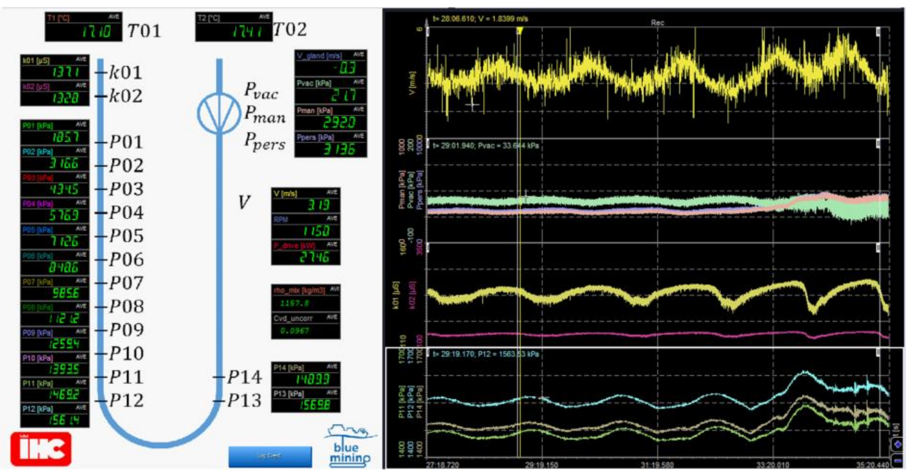


Figure 5 Left: live readings of sensor values. Right: sensor read screen in time. Source: Edwin de Hoog.

5. Preliminary Results

This paragraph describes the preliminary results of the medium-scale slurry experiments. First, typical results and trends of the experiments are presented. Second, trends in nodule degradation are described.

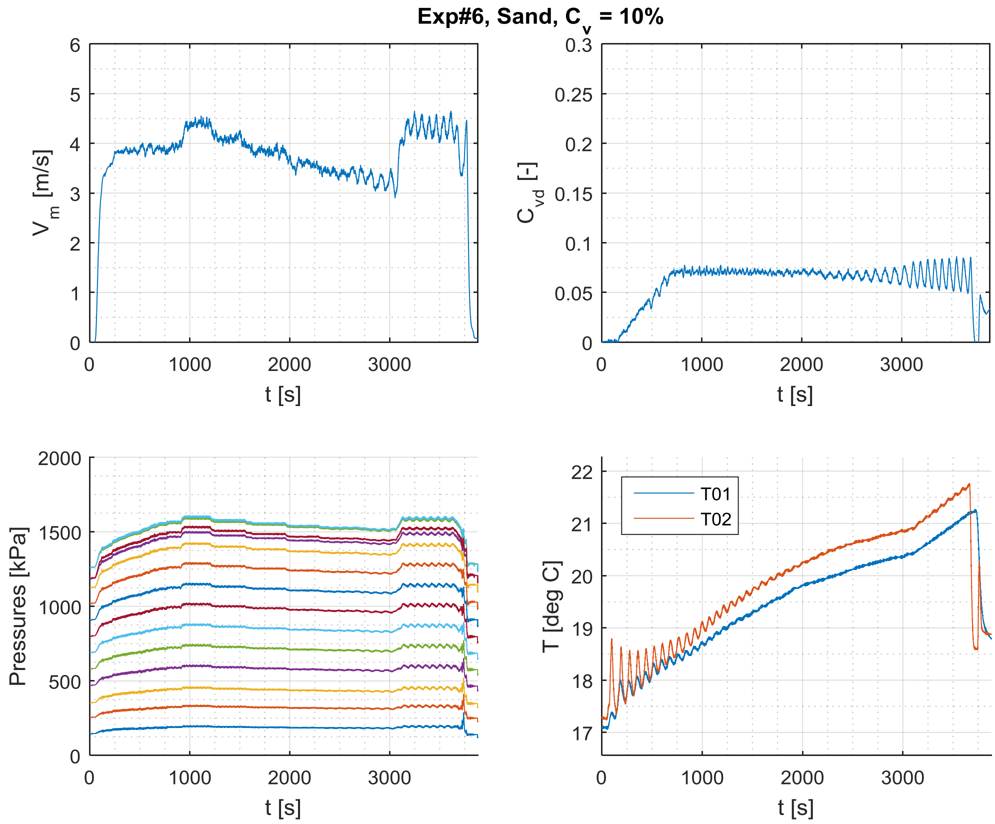


Figure 6 Typical results of a sand-water experiment in the medium-scale test setup. Top-left shows the mixture velocity inside the circuit; top-right shows the delivered concentration; bottom-left shows the measured absolute pressure; bottom-right shows the temperature in riser and fall pipe at height of the concentration meter. Source: [1]

The typical results of a sand-water experiment are shown in Figure 6. Sediment injection takes place in the first 700 seconds. It can be seen from the delivered concentration graph that small instabilities start to form at t = 2200 s. They accumulate over time till t = 3700 s. The formation of instabilities is considered an artefact of the test setup; see paragraph 3. These instabilities are not expected to be present in a full-scale VTS system, because then the riser and fall pipe are decoupled and do not form a closed loop.

The pressure sensors give a clear and constant value over time. Furthermore, they record the instabilities, and can clearly be used for determining the mixture density between two pressure sensors, by determining the pressure difference divided by gravity and height. The temperature sensors show that the mixture temperature increases during the experiment; mainly due to wall friction, pump heat generation and ambient conditions.

Degradation of (prior crushed) nodules was observed during the final experiments. The degradation of nodules is ascribed to solid-wall interaction (abrasion), particle-particle interaction (attrition) and pump passage (impact). Nodule samples were collected after 6, 12, and 36 pump passages, respectively, to investigate the degradation of the nodules (see Figure 7 top). The degradation trend line is shown in Figure 7 (bottom). It can be seen that, for this experiment, the degradation versus pump passages starts linear, but evolves to asymptotic. The data gives an estimate of the development of typical sizes, but it does not allow for detailed analysis of the influence of individual processes. Current research focusses on the individual processes by conducting dedicated abrasion, attrition and impact experiments (Van Wijk [5]).

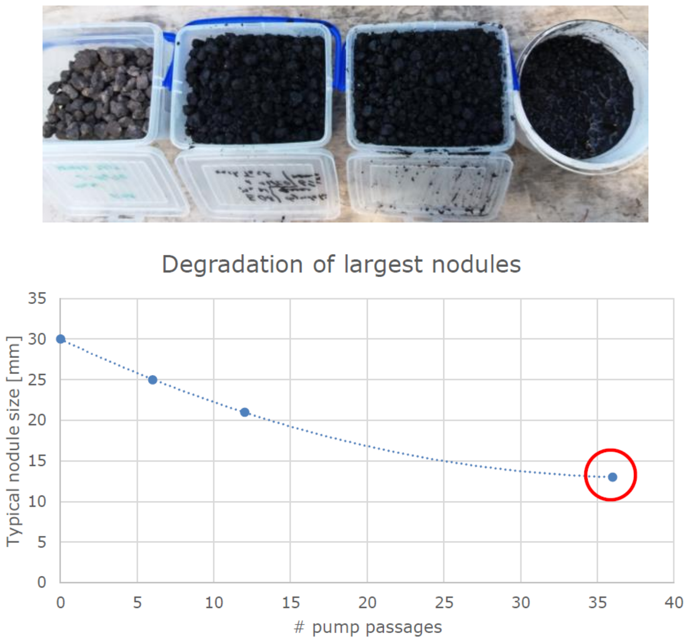


Figure 7 Top: Visualization of nodule degradation as function of pump passages: 0, 6, 12, 36 (from left to right). Bottom: degradation of largest nodules as function of number of pump passages. Source: Siemen Dasselaar.

6. Conclusions and Recommendations

This paragraph briefly describes the main conclusions from the medium-scale vertical coarse slurry experiments as well as recommendations for a full-scale VTS system design.

Conclusions:

- A medium-scale test setup was successfully deployed for vertical transport experiments of coarse slurries, enabling thorough investigation of the (sub) system processes and answering the objectives set in paragraph 2;
- A unique data set was generated for coarse slurries, including polymetallic nodules, in vertical hydraulic transport;
- The behavior of polymetallic nodules inside a riser is in a way comparable to that of gravel;
- Usage of pressure sensors as means of concentration measurement is proven; and
- The closed loop setup resulted in growing accumulation of material. These are considered an artefact of the closed loop circuit and they are different in nature from density waves. This type of accumulation is not expected in the full-scale VTS.

Recommendations:

- Selection of equipment that is fully watertight, resistant for conditions like salt water, low temperature and ambient pressure, is key for the durability and performance of a full-scale VTS system; and
- In transportation of polymetallic nodule slurries, the use of a Conductivity Concentration Meter (CCM) is discommended due to conductivity of the metallic particles. Instead, concentration can be derived by means of pressure sensors.

Keywords: deep-sea mining, polymetallic nodules, vertical hydraulic slurry transport.

References

[1] S. Dasselaar, E. De Hoog, S. De Jong, T. Mueller, R. Rotteveel, J. Van Stappen and J. Van Wijk, "Development and demonstration of a test setup for large scale slurry transport tests - Blue Mining D5.52," Blue Mining FP7, December 2017.

[2] J. Van Wijk, Vertical Hydraulic Transport for deep sea mining - a study into flow assurance, Delft, 2016.

[3] T. Muller, H. Mischo and J. Van Wijk, "Planning and construction of a large scale test facility for flow analysis of vertical transport of water and coarse material as part of the European research project Blue Mining," Freiberg, 2017.

[4] A. Blanken, S. Dasselaar, R. Harrison, M. Karch, J. Lorscheidt, J. Luo, K. McConnell, A. Rotteveel, P. Vercruijsse, J. v. ‘. Westende and J. v. Wijk, "System for condition monitoring and control of the VTS.," Blue Mining Deliverable 4.52, 2016.

[5] J. Van Wijk, "The influence of nodule degradation on the vertical hydraulic transport of manganese nodules," in *18th international conference on the transport and sedimentation of solid particles*, Prague, Czech Republic, September 2017.

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GSR's PROCAT-Project: Technical de-risking of deep sea mining equipment – A step-by-step approach towards future exploitation

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ABSTRACT

Since 2013, GSR has undertaken 4 exploration campaigns, which focused on environmental baseline monitoring (marine biology), resource definition and technological change.

The seabed nodule collection vehicle has a significant influence on the achievable production rate and is for that reason thought to be a serious risk in developing an economical viable mining operation. GSR is currently working on a pre-prototype of a seabed nodule collection vehicle. The program, called ProCat, started in 2015 and will take up to end of 2019. ProCat can be split up in 2 phases:

- ProCat#1 [2015 – Q2 2017]: separate parallel testing of the nodule collection- and driving mechanism (Tracked Soil Testing Device Patania I – TSTD Patania I). The trafficability was tested in-situ; the collection mechanism was tested in a laboratory. Phase 1 has been completed successfully in September 2017.
- ProCat#2 [Q3 2017 – end of 2019]: the knowledge acquired during the first phase was used in this 2nd phase. Both collection mechanism and driving mechanism were integrated into the design of a pre-prototype seabed nodule collection vehicle (Pre-Prototype Vehicle Patania II – PPV Patania II). This pre-prototype vehicle will be used for a simulated mining test in Q2 of 2019 in the GSR- and BGR license area.

The main objective of the ProCat research program, and especially the 2nd phase, is to integrate the nodule collector on the tracked chassis and develop an operating vehicle causing minimal environmental impact hereby validating the requirements for a full scale polymetallic nodule collection vehicle in the actual operational environment of the CCFZ. Following the ProCat project, GSR is working towards a system-integrated mining test once exploitation regulations have been agreed by the ISA and its member States.

Microtexture mineral analyses – a preparatory stage in SMS mineral processing

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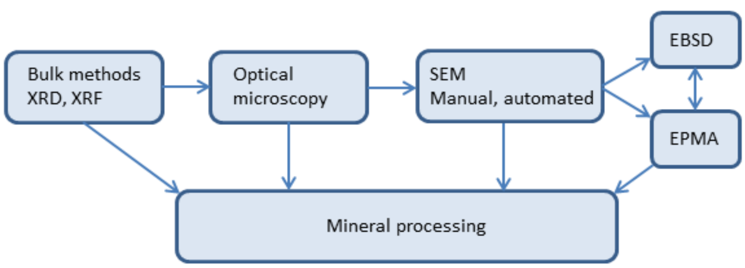
ABSTRACT

Efficient and successful mineral processing is dependent on detailed knowledge of the materials and minerals that are to be separated and concentrated. Common bulk methodologies such as XRD and XRF are fast and easy, and can provide an overview of the mineralogy and bulk chemistry of the material. However, they will not provide any textural information. Knowledge of the often intricate interaction between minerals in seafloor massive sulfide deposits is crucial in plant design for mineral processing. Samples from the Loki's Castle hydrothermal vent have been characterized by X-ray diffraction (XRD), X-ray fluorescence (XRF), optical microscopy, Scanning Electron Microscopy (SEM), QEMSCAN, Electron probe microanalyzer (EPMA), and Electron Backscatter Diffraction (EBSD). Processing experiments used froth flotation and leaching techniques. The typical line of operation in ore characterization is shown in Figure 1. Mineral processing may be commenced after any stage of ore characterization. However, it is ideal to have completed as many steps in the ore characterization as possible in order to have the most information of the initial feed material.



The main economic minerals in the samples are isocubanite ($CuFe_2S_3$), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS), with minor galena (PbS) and trace amounts of Au and Ag. The minerals show complex intergrowth textures down to the nanometer scale. These samples exemplify the need for advanced microtextural analyses to adequately characterize ore material prior to processing. The complex textures hamper the use of flotation as an efficient technique, due to the inability to sufficiently liberate the different minerals and problems with selectively floating isocubanite. Thus, leaching was the preferred method for extracting metals.

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Keywords: Microanalysis, SMS, mineral processing, ore mineralogy

An oral presentation is preferred, but the presentation is equally suitable for a poster.

The abstract may be archived.

Kristian Drivenes

The presenting author is currently a postdoc at NTNU. My research interests revolve around magmatic-hydrothermal processes and related ore formation, particularly what information the mineral chemistry and textures can provide of the crystallization processes and environment. Also, the continuously evolving area of microanalysis and new applications for existing methodology is a major field of interest. With an MSc in tungsten mineralizations, a PhD in granite petrogenesis, and a reputation for flashy guitar playing, I am sometimes called the master of heavy metal and doctor of rock.

Towards an improved nodule resource estimation and classification using hard and soft data

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ABSTRACT

The deep-sea ocean floor offers a great potential for mineral resources. The evaluation of these resources is both time consuming and costly and require as any resource evaluation data; geodata. The collection of hard data, physical samples, is of course preferred because the associated uncertainty is low. However, the collection of soft data or image derived data can offer a valuable supplement. In this paper image derived nodule uncertain abundance data from an area in the Pacific is utilized. Implementing these uncertain data improves the estimation when the quality of the estimation is measured using the classification indicators like the kriging standard deviation, the relative prediction error, the slope of regression and the weight of the mean. It is concluded that uncertain data is better than no data.

INTRODUCTION

The deep-sea offers vast mineral resources (Cathles (2011), Hannington et al. (2011), Hannington (2013), Singer (2014)).

A mineral resource can according to increasing geological confidence be classified as an inferred, an indicated or a measured resource. The classification is performed by a competent- or qualified person and is dependent on the amount, quality and characteristic of available geodata. The competent person must have at least five years of experience relevant to both the style of mineralisation, the type of deposit and the performed task. Typical examples of a "task" is for example resource estimation and classification or planning- and execution of exploration activities and presentations of the results. The competent person must also be a member or a fellow of a professional organisation and thereby be bound by reporting code (-s) that defines minimum standards, recommendations and guidelines for public reporting.

The deep ocean floor is vast and underexplored. Exploration and geodata collection is expensive and time demanding. Geodata utilisation and uncertainty quantification is therefore a key to prioritize exploration efforts and do resource estimations. This means exploiting all data for potential information. Geodata used in resource estimations can be either hard or soft.

Typical examples of hard data are drill cores, push cores or box cores. These are association to a low to non-existing uncertainty. Soft data are proxies and associated with a significant uncertainty.

This paper aims to investigate the potential to enhance the nodule resource estimation based on image data. Potentially, image data can be used along with expert knowledge to assess and define an interval within which the target variable will be and implementing this into the kriging with inequalities algorithm (Chiles and Delfiner 2012). Alternatively and as implemented in this paper, a correlation between image derived estimates and box core data can be established. The quality of the regression defines the uncertainty associated with the image based abundance estimate. This paper illustrates the methodology on a case from the Pacific where real image data has been artificially positioned into an area with box core data.

RESOURCE CLASSIFICATION INDICATORS

Classifying a resource rely heavily on the experience of the competent person performing the classification. Given a thorough understanding of the geological processes forming the deposit (-s) and the real geological continuities, possible parameters that can be used in resource classification are the slope of regression, weight of mean, average distance (compared to the deposit continuity defined by the variogram range), relative prediction error and kriging standard deviation (square root of the kriging variance). Rivoirard (1987) illustrates how the weight of the mean can be used as an indicator of how sparse the samples used in the estimation are. Armstrong (1998) gives examples illustrating how both kriging variance, the slope and the weight of mean can be used to indicate the quality of the estimator. The lower the kriging variance, the closer the slope is to 1 (one) and the lower the weight of the mean, the better. Knobloch et al. (2017) derive the relative prediction error (RPE) based on the kriging variance and use RPE and the average sampling distance to classify nodule resources in the Clarion-Clipperton Zone.

DATA

To illustrate the methodology, a box core dataset from the Pacific is used. Fig 1 illustrates the situation. Box core data is given by the widely spread crosses, whereas the image data have been collected along the linear features.

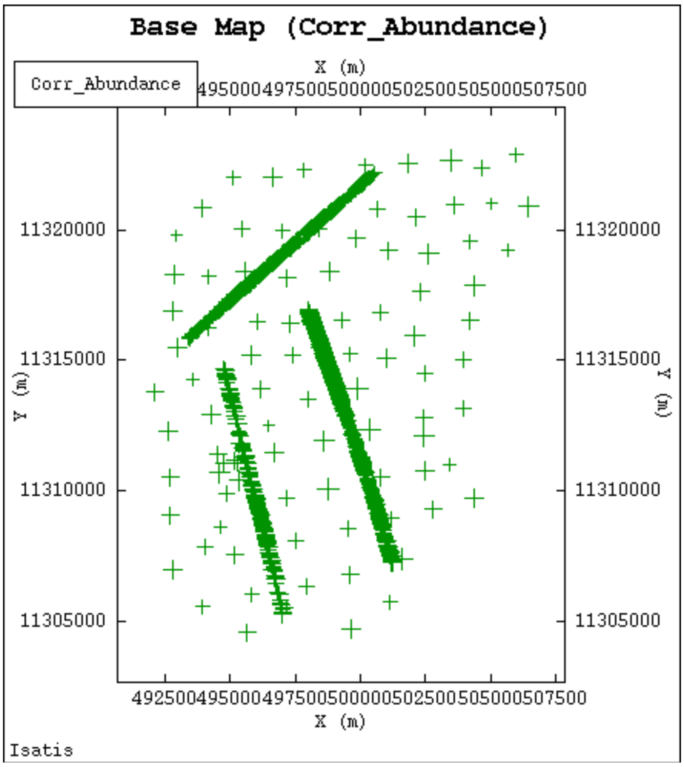

Figure 1 Figure shows the soft- and hard data locations.

Hard data (the box cores) comes without uncertainty. Their actual value is without interest in this study due to the focus on uncertainty and the effect of introducing uncertain data. The soft data (derived from the image data) collected along the linear features in Fig. 1 have an additional associated nugget effect defined by the correlation between image data and box cores given in Fig 2.

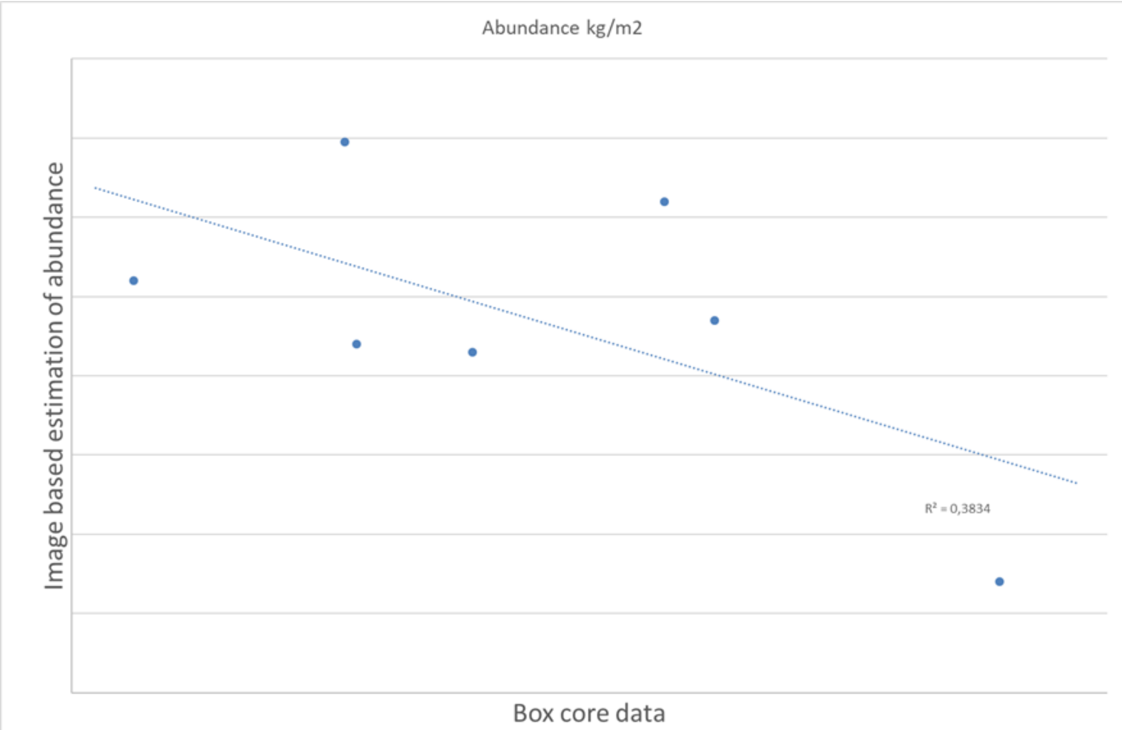

Figure 2 Correlation between box core data and image based estimations of abundance. This correlation is used to estimate image derived "box core" data and their associated uncertainty.

METHODOLOGY

Kriging is an unbiased linear estimator where the value at unsampled locations is estimated as a weighted average of a set of values measured at locations surrounding the unsampled location. The estimate is accompanied by the kriging standard deviation (kriging variance). Kriging is described in textbooks like Goovaerts (1997).

A standard deviation indicating the extra uncertainty associated to some of the data points can be used as a local nugget effect in the kriging algorithm. This uncertainty is added to the diagonal elements in the variance-covariance matrix used in the development of the kriging weights. In effect, the higher the uncertainty, the lower is the associated weight.

For this paper, the ordinary kriging (OK) algorithm has been used (see e.g. Goovaerts (1997)).

To estimate the extra uncertainty associated to abundance data derived from image data, the correlation between "box core" data estimate from the images and the real box core data presented in Fig. 2 is used. The associated uncertainty is defined as the root mean squared error (e.g. Witten et al. 2011):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)} \qquad \text{Eq. 1}$$

The variogram model is calculated based only on the hard data (in this case the box cores).

In accordance with Knobloch et al. (2017), a 2D block model with quadratic 1000 meter large blocks have been used. No attempts have been done to optimize the block sizes. The relative prediction error (RPE) from the same authors is defined as the kriging standard deviation relative to the predicted value. This RPE is also calculated and presented herein. A circular kriging neighborhood with a maximum distance of 3000 meter was used during the kriging step. A minimum of 3 samples inside the kriging neighborhood was required.

RESULTS

Given the correlation in Fig 2, the RMSE in Eq. 1 is calculated to 3.04. This extra uncertainty is linked to each of the image derived abundance data.

No anisotropies were detected so an omnidirectional variogram model was developed. The experimental variogram is given in Fig 3. To model the spatial variability of the nodule abundance a nugget of about 17% (1.5) was used together with a spherical variogram model characterized by a range of 1550 meter and a sill of 9. The nugget was included based on relevant deposit knowledge, experience from sampling in the area and the experimental variogram.

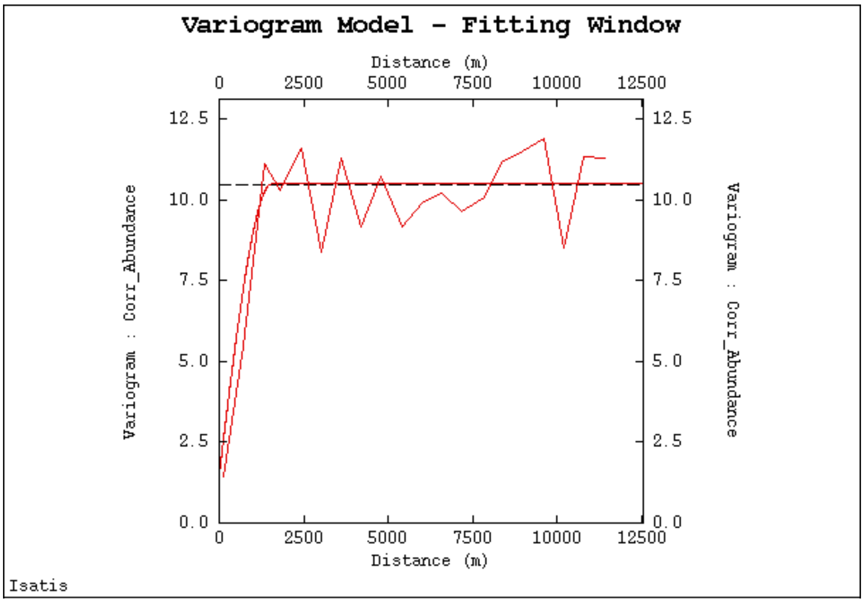

Figure 3 Variogram used in the calculation of the kriging standard deviation.

Fig 4 shows the RPE obtained through the application of the OK-algorithm in the area presented in Fig 1.

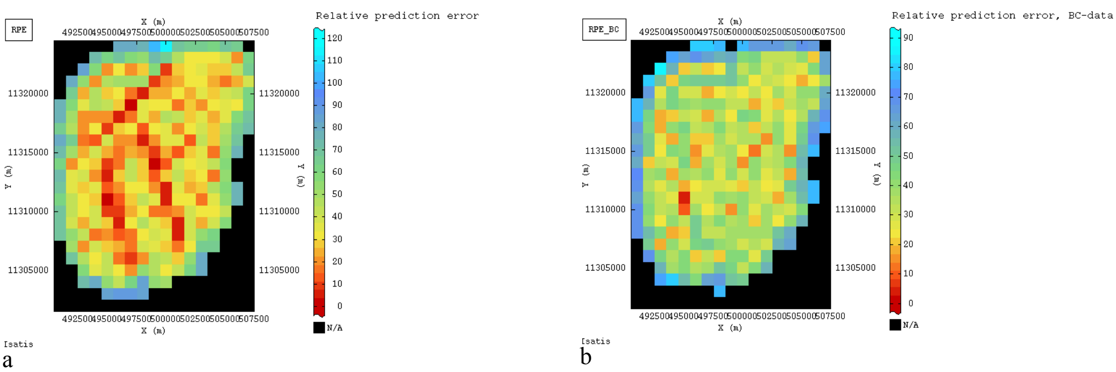

Figure 4 Estimates of the relative prediction error with (a) and without image data (b). A total of 309 blocks in a) and 303 in b) were assigned a value..

Despite the associated extra uncertainty attached to the image data, the differences between the RPE in Fig 4a and Fig 4b is clear. One clearly see the linear features with a low RPE stemming from the uncertain image data. Other classification indicators show the similar trends.

Table 1 shows the summary statistics of resource classification indicators for the kriged block model.

Table 1 Summary statistics of resource classification indicators for the kriged block model.

Indicator	# blocks	Minimum	Maximum	Mean	Variance
RPE	309	3,55	115,43	39,05	432,58
RPE only BC	303	3,96	86,10	40,49	267,12
Mean Distance	309	275,97	2744,95	1757,82	307868
Mean Distance only BC	303	1297,46	2722,24	1982,68	40719,39
Number of samples in the kriging neighborhood	309	3	221	25,46	986,88
Number of samples in the kriging neighborhood only BC	303	3	18	8,22	12,53
Slope	309	0	0,99	0,56	0,1
Slope only BC	303	0	0,99	0,53	0,09
Stdv	309	0,6	3,23	1,99	0,32
Stdv only BC	303	0,68	2,89	2,09	0,18
Weight of Mean	309	0,04	1	0,58	0,07
Weight of Mean only BC	303	0,06	1	0,64	0,04

Table 1 shows the improvement obtained when the image points are added. The average RPE, the mean distance to sample points, the kriging standard deviation and the weight of the mean is reduced. The number of samples in the kriging neighborhood and the slope increase. The variance for the case with the image data is consistently higher due to the slightly higher number of blocks.

DISCUSSION

The deep ocean floor contains vast amount of mineral resources. The minerals are at great depths and far from shore. Exploration campaigns are expensive and time consuming. Any piece of information must be exploited and used to the full. This paper presents a methodology and coins the idea of using image data to express a nodule abundance expectation and associate this expectation with an uncertainty quantified through the correlation between the image derived abundance estimations and box core results. An alternative approach would be to define the minimum and the maximum nodule abundance in the images. Through a simulation step these data could be replaced by a conditional expectation (conditioned on the data, the min and max value and on the spatial correlation quantified by the variogram calculated from the hard data (the box cores)) and a kriging standard deviation. This uncertainty indicator is implemented into the kriging equations and uncertain data is thereby taken into account and improve the estimate. The amount of improvement at a given point is dependent on data configuration; where box cores are taken and where the video transects are performed. The algorithm presented here opens up for a development of an exploration strategy that not only optimize the sampling locations, but also the location of the video transects.

Resource classification is a crucial step in resource development. The classification is a subjective endeavor relying on the experience and the competence of the competent person performing the evaluation. To make the subjectivity more objective, there are a number of resource classification indicators that can be used. Many of these indicators are prone to be misused. Such indicators should be combined with sectored neighborhoods and a requirement to the number of consecutive empty sectors to assure interpolation instead of extrapolation. In this paper, the effect uncertain data have on such indicators like the kriging standard deviation, the relative prediction error, the slope, the weight of the mean and the mean distance to sample points. All factors show improvement. What effect this will have on the resource classification is up to the competent person.

CONCLUSION

Uncertain data is better than no data; and they can and should be used in resource classification and -evaluation.

Keywords: Deep-sea mining, geostatistics, uncertainty.

REFERENCES

Armstrong, M. 1998. Basic Linear Geostatistics. Springer –Verlag Berlin. ISBN 3-540-61845-7.

Cathles. 2011. What processes at mid-ocean ridges tell us about volcanogenic massive sulfide deposits. Mineralium Deposita 46(5): 639-657. 2011a, Vol. 46, 5, pp. 639-657. doi:10.1007/s00126-010-0292-9

Chilès & Delfiner. 2012. Geostatistics: Modeling Spatial Uncertainty, 2nd Edition. ISBN: 978-0-470-18315-1 - 734 pages – April 2012

Goovaerts P. 1997. Geostatistics for natural resources evaluation. Oxford University Press, New York

Hannington, M, Jamieson, J, Monecke, T and Petersen, S., Beaulieu, S. 2011. The abundance of seafloor massive sulfide deposits. Geology. 2011, Vol. 39, 12, pp. 1155–1158.

Hannington, M D. 2013. The role of black smokers in the Cu mass balance of the oceanic crust. Earth and Planetary Science Letters. Volume 374, 15 July 2013, Pages 215–226. http://dx.doi.org/10.1016/j.epsl.2013.06.004

Knobloch A., Kuhn T., Rühlemann C., Hertwig T., Zeissler K-O. and Noack S. 2017. Predictive mapping of the nodule abundance and mineral resource estimation in the Clarion-Clipperton Zone using artificial neural networks and classical geostatistical methods. In Sharma R (ed). 2017. Deep-sea mining. Resource potential, technical and environmental considerations. Springer. DOI 10.1007/978-3-319-52557-0

Rivoirard J. 1987. Two key parameters when choosing the kriging neighborhood. Math Geol 19:851–856

Singer, D A. 2014. Base and precious metal resources in seafloor massive sulfide deposits. Ore Geology Reviews. 59, 2014, Vol. 59, pp. 66–72. http://dx.doi.org/10.1016/j.oregeorev.2013.11.008.

Witten, I. H., Frank, E. and Hall, M. A. 2011. Data Mining: Practical Machine Learning Tools and Techniques. Third ed. Elsevier.

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In 2006/2007, he was a Visiting Scholar at the W.H. Bryan Mining & Geology Research Centre (BRC) at the Sustainable Minerals Institute (SMI), Queensland, Australia. From 2007 to 2008, he was a Mine Geologist at North Cape Minerals AS, Norway. From 2009 to 2010, he was a Researcher with the Department of Geoscience and Petroleum, NTNU. Since 2010, he has been an Associate Professor at the Department of Geoscience and Petroleum, NTNU. Since 2013, he has been involved in the marine minerals initiative at NTNU within the strategic research area NTNU Oceans. In 2013/2014, he led the work that published the first estimate of the undiscovered mineral resource potential inside the Norwegian jurisdiction along the mid-Atlantic ridge. Since 2014, he has been the project manager of the interdisciplinary Deep-Sea Mining Pilot Project at NTNU. His research and teaching interests are within the broad field of mineral resource management and mining engineering, specifically geostatistics, 3D geometric ore body modelling, and mineral resource potential assessment.

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Plumes of deep-sea mining: what do we know?

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Active development of the exploration and further exploitation of deep-sea minerals requires special emphasis on the protection of the marine environment. The complexity of this subject lies in the fact that potential impact and effects of future mining activity are not completely known.

One of the main sources of potential impact near the seafloor, as it expected, would be a generation of sediment plumes, their dispersion and redeposition of sediment. Meanwhile, their dimensions, rates of dispersion and redeposition are a big issue.

Other plumes are expected in the surface layer as a result of discharges of processing waters and particles after sorting on board of mining vessel, and their features are also not clear.

At the same time, understanding of these aspects would be crucial for definition of environment impact area, delineation and designation of different types of protected areas (Areas of Particular Environmental Interest, Impact and Preservation Reference Zones) and future assessment of environmental impacts.

Attempts to address these issues demonstrated wide variations between the data of field experiments on the one hand and the results of analytical and numerical models on the other. According to *in situ* measurements, plumes were detected at a distance vary from one to less than 20 km [e.g., Burns et al., 1980; Sharma et al., 2001; Nautilus Minerals, 2008 etc.], whilst some models show results up to 100 km [Rolinski S. et al., 2001] and more. It seemed that results of in-situ experiments are preferable, but they were not many indeed. However, these data were used in different investigations rather widely, but their focus, as far as we know, was not on the matters related directly with plumes.

In our study, we tried to compile and analyze all available data of field experiments related specifically to plumes, their dimensions and spread and find some new outcomes as well. It could be useful for further understanding of potential impacts of future deep-sea mining activity and could provide a basis for comparison with results of new experiments, including test mining.

One of such expected experiments would be an initial equipment test planned by the Belgian company DEME in the Belgian and German manganese nodule license areas in April 2019.

Keywords: exploitation of deep-sea minerals, environmental impact assessment.

Reference:

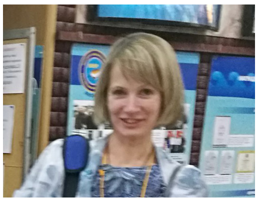
Burns R.E., Erickson B.H., Lavelle J.W., Ozturgut E. Observations and measurements during the monitoring of deep ocean manganese nodule mining tests in the North Pacific, March-May 1978. NOAA technical Memorandum ERL MESA-47. 1980.

Nautilus Minerals (2008). Environmental Impact Statement. Available online at: http://www.cares.nautilusminerals.com (Accessed August 9, 2016).

Sharma R., Nath B.N., Parthiban G., Jai Sankar S. Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining. Deep-Sea Research II, 48 (2001), pp. 3363-3380.

Rolinski S, Segschneider J, Sundermann J. 2001 Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. Deep-Sea Research II, 48 (2001), pp. 3469–3485.

Livia Ermakova



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Processes of metal sulfide oxidation at hydrothermal vents and in seafloor massive sulfides

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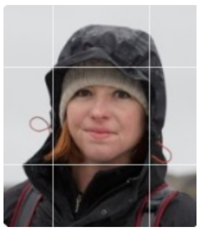
ABSTRACT

The interactions between hydrothermal fluids and seawater result in minerals that range in size from nano- to macro-scale and constrain mineral emplacement, whether in hydrothermal chimneys or metalliferous sediments. Although broad similarities exist, and sulfides are the most important component of seafloor massive sulfide deposits, the specific mineralogy, size and therefore reactivity of particles emitted varies between hydrothermal sites in the global ocean, and even at different sites within the same vent field.

The oxidation of sulfide minerals results in one of the major impacts of terrestrial mining of volcanogenic massive sulfides as it creates acid mine drainage. At marine hydrothermal vents, the chimneys themselves, as well as the 'black smoke' begin to oxidize as soon as they are in contact with ocean water; the breaking of sulfide minerals during marine mining will expose further surface area to seawater and oxidation. Although the cold temperatures and circum-neutral pH result in oxidation proceeding less rapidly than in many terrestrial systems, there is limited data on the kinetics of sulfide oxidation in seawater. Here, the oxidation of sulfide minerals in seawater and the implications for marine mining will be discussed, with an emphasis on nano-ZnS and sphalerite, including reaction kinetics, processes, and oxidation products.

Keywords: mineral formation; metal sulfides; sulfide oxidation

Amy Gartman



Amy is currently a Research Oceanographer at the USGS Pacific Coastal and Marine Science Center, where she began as a Mendenhall postdoctoral fellow in 2015. Prior to that she was a postdoctoral researcher at Harvard University's Department of Organismic and Evolutionary Biology, where she studied interactions between microorganisms and metal sulfides. She holds a B.S. in Chemistry from New York University and a PhD in Oceanography from the University of Delaware. Her current research focuses on the formation and dissolution of seafloor sulfides, emphasizing nano- scale processes. She has been a member of the U.S. DOS delegation to the ISA as a scientific advisor since 2016.

A System Approach to Survey, Exploration and Environmental Assessment

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INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are proven technologies used across market segments for survey, exploration and environmental monitoring tasks. When coupled with other autonomous platforms or sensor packages AUVs become part of an holistic system approach to exploration and environmental assessment and monitoring.

Recent developments have seen AUVs deployed remotely with instantaneous access to data via the cloud. Our goal is to deliver the capabilities of each of these elements and present a cohesive data set with automated processing tools over a cloud based interface.

Unmanned Technology

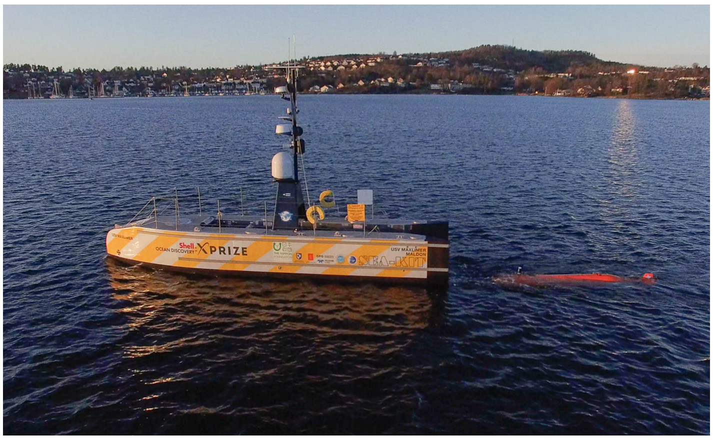
AUVs

The HUGIN AUV System is the most commercially successful AUV ever built. Operated as a single vehicle, or as part of a swarm, HUGIN's area coverage rate is unrivalled. Equipped with a comprehensive sensor package including Kongsberg's synthetic aperture sonar, it collects a data set. Some of these data are processed in-mission to enable operators to readily access it when the vehicle is recovered.

HUGIN is well suited to mining survey and exploration. Capable of reaching 6000 metre depths and conducting missions greater than 60 hours, HUGIN collects seabed sonar imagery, sub-bottom profiles, laser and camera images plus environmental data, with sensors running concurrently.

USV and AUV Systems

HUGIN has recently been combined with the SEA-KIT unmanned surface vehicle. This USV has been developed by SEA-KIT International Ltd in the UK, with funding from GEBCO and the Nippon Foundation. It is controlled by the Kongsberg Maritime K-MATE autonomy engine for USVs. K-MATE is the culmination of 25 years of development partnership between Kongsberg and FFI (the Norwegian Defence Research Establishment).



SEA-KIT can carry, launch and recover the HUGIN AUV making over the horizon autonomous operations a reality. It can also be supervised by radio or satellite. This enables the operator to remotely supervise both USV and AUV operations.

SEA-KIT is equipped with a HiPAP 502, and will have an EM304 multibeam echosounder installed in 2018. It is capable of trans-ocean ranges and conducting autonomous deep-water survey operations as well as AUV supervision.

Data and telemetry is sent from the AUV to the USV via the HiPAP link, and on to shore via satellite communications. Once the AUV is recovered onto SEA-KIT the data could also be transmitted to the cloud for processing on shore.

Gliders

Seagliders are a range of autonomous underwater vehicles (AUV) or underwater gliders developed for continuous, long term measurement of oceanographic parameters. Rather than an electrically driven propeller, these vehicles uses small changes in buoyancy and wings to achieve forward motion. The system's pitch and roll are controlled using adjustable ballast (the vehicle battery).

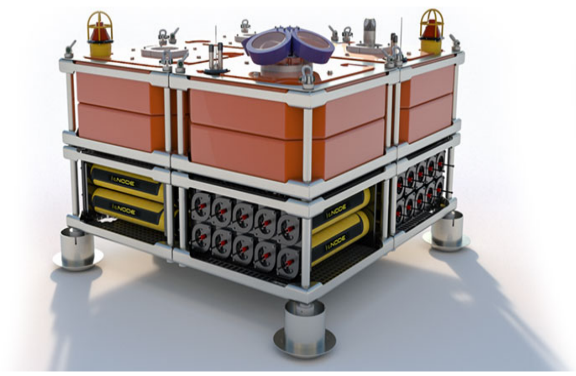
The Seaglider system is produced under license by Kongsberg Underwater Technology Inc. Development of the glider was started, and continues to this day at the University of Washington. The latest variant: the M6 is rated to 6000 metre depths and is designed for physical oceanography.

Low cost, easy to use with access via a web app makes Seaglider ideally suited to fleet operations. When running environmental assessment, prior to and during mining extraction operations, Seaglider is a simple way to generate a 3-dimensional reference dataset.

Landers

The K-Lander seabed observatory is the core of the KONGSBERG Modular Subsea Monitoring-Network (MSM). With a unique building block concept, the K-Lander mk2 can be customised for a variety of long-term deployments. The modular design, coupled with a self-floating buoyancy based recovery system, allows for easy integration and recovery of various sensors suited for diverse subsea monitoring applications.

The K-Lander system provides the opportunity to place a sensor package on the seafloor in a fixed location. Sensors typically include chemical sniffers, turbidity, passive acoustic monitoring equipment and more. There is an option for a Geodesy Module for seismic activity and tsunami warning.



The K-Lander can be equipped with long endurance batteries, data processing and storage capabilities. Data can be transmitted acoustically to passing AUVs or to the surface via a HiPAP link.

Data Handling and Access

Cloud-based Services

One of the most recent developments by Kongsberg Digital is KognifAI. This is an open architecture ecosystem of apps designed to make data access easier, faster and provide more options for processing and visualization. For mining applications, KognifAI can host data collected by AUVs, USV, Gliders, Landers and more. It can combine data into common projects and enable operators to access it globally at any time.

One of the benefits of KognifAI is the ability to scale processing power when required. Kongsberg and third party processing tools can be hosted in the cloud, with remote servers doing the heavy work for processing thereby reducing the need for local infrastructure.

Conclusion

Kongsberg Maritime designs, develops, manufactures and operates subsea equipment for a myriad of applications. It is this experience that enables us to combine sensors, vehicles and data into a cohesive system to add capability and value to subsea mining operations. From first exploration to post-exploitation assessment, our solutions can perform as a seem-less system, with data easily accessible almost as soon as it is collected.

Keywords: Autonomous Underwater Vehicles, AUV, Autonomous Marine Systems, AMS, Unmanned Surface Vehicles, USV, Glider, Seaglider, HUGIN, K-Lander, Environmental Assessment, Cloud-Based Data Services, KognifAI

This submission is for a 20 minute presentation accompanied by PowerPoint slides.

Richard Mills

Richard is the Director of Marine Robotics Sales with Kongsberg Maritime. He is responsible for the HUGIN, MUNIN and USV product lines. He leads a team of sales personnel based in Norway, the UK and USA covering commercial, defence, academic and governmental market segments.

Richard has a secondary role as Director of Solutions Sales for Kongsberg, making new business models and service offerings to the subsea market. This includes introducing new technologies and services to the market.

He has worked in the subsea industry for 10 years. Prior to joining Kongsberg in 2012, Richard worked for International Submarine Engineering Ltd. in British Columbia, Canada.

Richard is also on the board of directors for Eelume AS, a small Norwegian company developing articulated subsea robots designed to conduct inspection and intervention tasks in confined areas.

Autonomous robotic sea-floor infrastructure for bentho-pelagic monitoring (ARIM)

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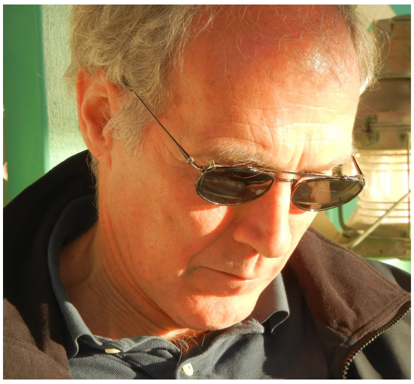
ABSTRACT

We present a science-based infrastructure for continuous online monitoring of the ocean interior including benthic, pelagic and the demersal habitats. It will reduce expensive ship based monitoring costs associated to offshore and coastal industries. We combine established Norwegian cabled observatory technology and German mobile seafloor robotic technology and thus supports the transition from local to spatial ecological monitoring. Both technologies are developed through science - industry partnerships. In Norway, the Institute of Marine Research has worked with Statoil ASA and Metas AS to install and operate the LoVe cabled observatory. The German technology is developed by iSeaMC and Kraken Robotik, two spinoff enterprises of the Helmholtz Alliance "ROBEX". GEOMAR has recently developed a lander-based deep-sea crawler that operates autonomously based on the original iSeaMC crawler system using the Kraken Autonomy. Combined with the Spanish image processing and modelling expertise in the SME Deusto Sistemas SA the consortium hosts the capacity to establishing a complete semi-autonomous real-time monitoring system. Merging of existing technologies into one operational autonomous product through the unique competence of partners' support international ambitions (e.g. Blue Growth, GES, Horizon 2020), and renew monitoring that assess impact of human use of the marine environment. The consortium has been invited to contribute to technology/science programs for the Yellow Sea and for European mining and offshore decommissioning industries, which demonstrates the leading role of our consortium. The project is funded through the EU Martera program and started in June this year.

Olav Rune Godø (PhD)



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Google Scholar Author profile

Dr. Olav Rune Godø graduated at the University of Bergen (UoB) in 1977 (Cand. real) and 1990 (Dr. Philos.). His scientific experience covers a range of fields; fish stock assessment, acoustic and fishing gear technologies, behavioural and evolutionary ecology. He has also worked on commercialisation and is cofounder of a technology company (www.mwtas .no). His more recent scientific focus has been towards improving marine ecosystem monitoring, where acoustics has had a prime role. Godø has served on and chaired several committees under the Norwegian Research Council. He has worked in several ICES committees, served on the scientific steering committee of Census of Marine Life as well as in a SCOR technology working group. He received in 1997a Rockefeller Foundation scholarship and has been invited speaker at a number of international conferences in biology and technology. He was Norwegian representative at the Scientific Committee of CCAMLR. He has worked for most of his career at Institute of Marine Research in Bergen but moved to Christian Mickelsen Research in January 2018.

Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials (MINDeSEA Project)

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ABSTRACT

The GeoERA Co-Fund action is a joint contribution of 48 national and regional Geological Survey Organisations from 33 European countries "Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe (GeoERA)". This is an ERA-NET action under Horizon 2020. The aim of GeoERA is to fund transnational projects contributing to the best use and management of the subsurface, addressing the following four themes: Geo Energy, Ground Water, Raw Materials and Information Platform.

The European Commission recognises the significance of raw materials through its Raw Materials Initiative (RMI), the European Innovation Platform on Raw Materials (EIP-RM) and Horizon 2020 funding, specifically through Societal Challenge 5 – Climate Action, Environment, Resource Efficiency and Raw Materials. The GeoERA Raw Materials Theme will contribute to research and innovative developments for minerals inventory, minerals yearbook, exploration, mapping, modelling, metallogeny and critical raw materials in the pan-European framework including the sea. A major element in Europe's long term economic strategy is to ensure security of supply for strategic and critical metals as part of the Blue Growth Strategy developing sectors that have a high potential for sustainable jobs and growth as seabed mining.

The project MINDeSEA results of the collaboration between eight GeoERA Partners and four Non-funded Organizations at various points of common interest for exploration and investigation on seafloor mineral deposits. The Geological Surveys of Spain, Germany, Greece, Ireland, Norway, Portugal, Sweden and Ukraine are organisations with responsibility for coastal, marine geological investigation and mineral resources studies and mapping in their respective countries. The Non-funded participants: the Instituto Português do Mar e da Atmosfera; the United States Geological Survey; the All-Russia Scientific Research Institute for Geology and Mineral Resources of the Ocean; and the Geosciences Institute, host important databases, they have an international reputation for excellence in both science and technology, and are internationally-known experts on seafloor mineralisation and hydrothermal systems.

This project addresses an integrative metallogenetic study of principal types of seabed mineral resources (hydrothermal sulfides, ferromanganese crusts, phosphorites, marine placers and polymetallic nodules) in the European Seas. The work program includes all the regional seas around Europe comprising the Atlantic Ocean, the Mediterranean Sea, the Baltic Sea and the Black Sea (Fig. 1). The MINDeSEA working group has both knowledge of and expertise in such types of mineralisation, providing exploration results, sample repositories and databases to produce innovative contributions. The importance of submarine mineralisation systems is related to the abundance and exploitation-potential of many strategic metals and Critical Raw Materials (CRM), necessary for the development of modern society.

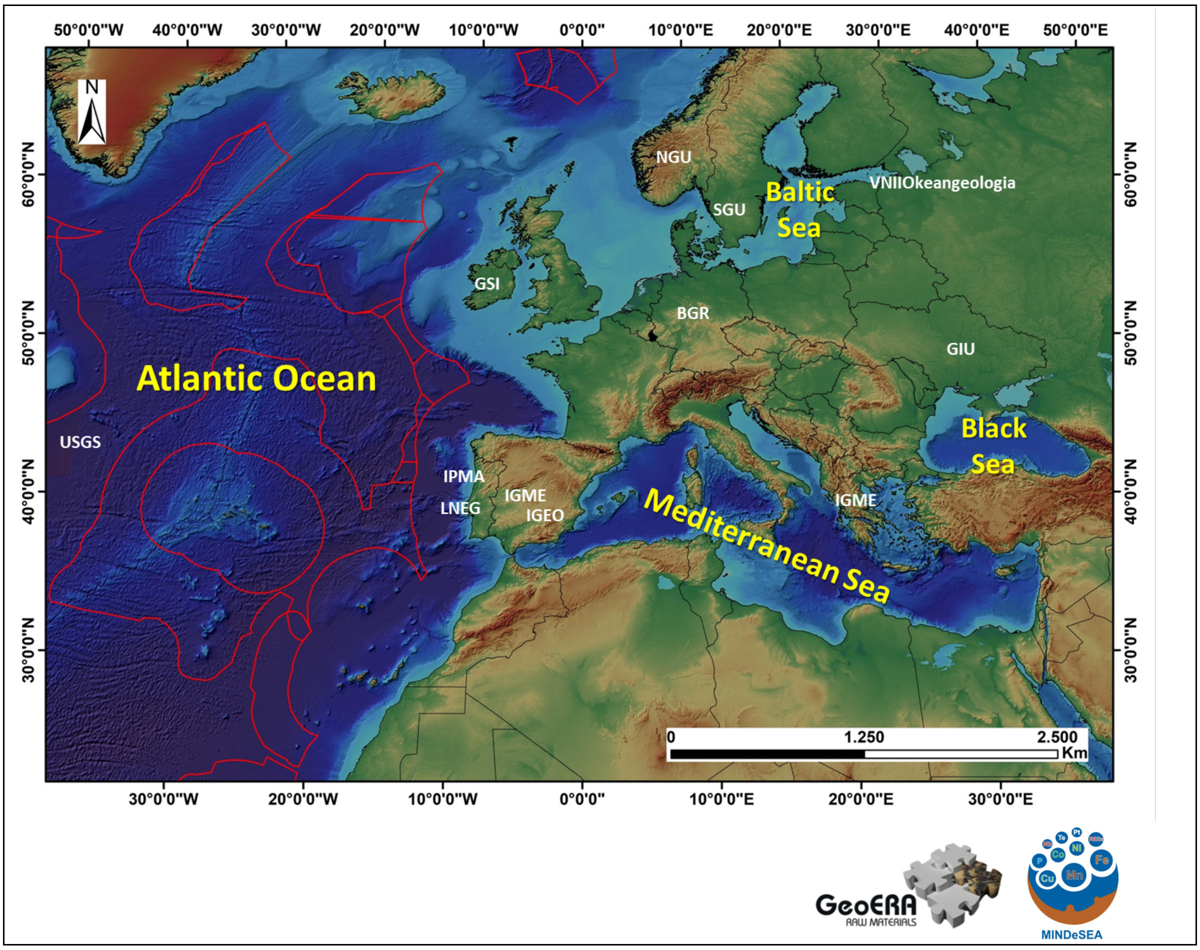


Figure 1: Pan-European Seas with delimitations of continental shelf and extended continental shelfs according to UNCLOS, and participant Organisations in the MINDeSEA project.

The objectives of this project are the following: 1) Characterise deposit types; 2) Characterise the trace element content of the deposit types including CRM; 3) Identify the principal metallogenic provinces; 4) Develop harmonised mineral maps and datasets of seabed deposits incorporating GSO datasets, along with mineral-potential and prospectivity maps; 5) Demonstrate how the case study results can be used in off-shore mineral exploration; 6) Analyse present-day exploration and exploitation status in terms of regulation, legislation, environmental impacts, exploitation and future directions. 7)

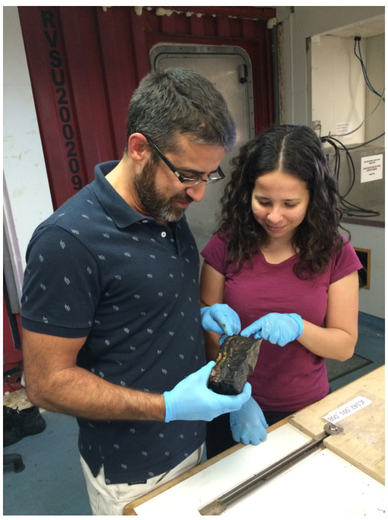
Demonstrate efficiency of a pan-European research approach to understanding seabed minerals and modes of exploration. The methodology will include: procedures for submarine minerals exploration; mineral evaluation and seafloor minerals mapping; a web service that will disseminate procedures, maps and information to the general public, downstream users and decision makers.

The Project webpage contain details for further information about the GeoERA Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe: http://geoera.eu/

Acknowledgments

This work has been supported by the European Union's Horizon 2020 research and innovation programme, GeoERA (Grant Agreement Nº 731166, project GeoE.171.001).

Key words: GeoERA, marine minerals, metallogeny, European Seas, deep-sea mining, critical raw materials



Javier González

Dr. Javier González is currently a member of the research staff in the Marine Geology Division at the Geological Survey of Spain (IGME), an autonomous institute attached to the Science Secretary. He is Collaborator at the Department of Crystallography and Mineralogy of the "Complutense University of Madrid" (UCM). His research activities are concerned with mineralogy, petrology, geochemistry and metallogenesis, especially on deep sea mineralization such as methane-derived carbonates, Fe-Mn nodules, Co-rich crusts and polymetallic sulphides related to cold seeps, seamounts and hydrothermal systems. He has mainly worked on the Iberian continental margins, Canary Islands, Scotia Sea (Antarctica) and the South China Sea, where he has been involved in several national and international oceanographic cruises and research projects related to marine mineral deposits since 2004. He is an expertise on ferromanganese deposits along the continental slope of the Gulf of Cadiz and the Canary Archipelago.

Development of exploration criteria for massive sulfides on slow-spreading ridges – lessons learned from the TAG hydrothermal field

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INTRODUCTION

Technological advances and the shift towards green energies in the last decades have led to a substantial increase in the demand for metal resources. With rising political tension, and quasi-monopolistic production of some key metals, a secured supply chain cannot be guaranteed [1]. Therefore, the focus of the international research community and mining companies has expanded to the seafloor, looking for additional resources. The seafloor may have the potential to contribute significantly to a secure metal supply in the future. However, we have only investigated a fraction of our oceans in sufficient detail to assess the global resource potential. A detailed exploration of the vast seafloor is currently economically not feasible, due to its extremely time-consuming and costly nature. Seafloor massive sulfides generally form along the active plate boundaries and at active volcanoes in arc settings. However, the resources are not evenly distributed on the seafloor. Large deposits tend to be more common along slow-spreading and ultra-slow-spreading ridges that make up the majority of the global mid-ocean ridge system [2]. Therefore, it is important to establish geological models and exploration criteria in order to narrow down the permissive areas, which are likely to accommodate economically interesting deposits. Based on a detailed study of the TAG hydrothermal field in the central Atlantic Ocean, hosting a large active mound as well as several inactive mounds, we develop exploration methods and criteria to define areas of potential massive sulfide occurrences along slow-spreading sections.

Geological Setting

The TAG hydrothermal field is located at 26°08'N, in the centre of a short (<40km) segment of the MAR. This segment shows a strong asymmetry, where the eastern flank, formed by a massif of three ridges, protrudes towards the west (Fig. 1). The western flank is characterised by axis-parallel ridges and faults, reflecting the common morphology of a magmatism-dominated MAR segment [3]. The hydrothermal field is situated at the shallowest part of the TAG segment, on the eastern half of the axial valley at the intersection of the eastern flank with the volcanic valley floor. While the segment is bound by two basins in the north and south, exceeding depths of 4,500m, the segment centre, in the vicinity of the hydrothermal field, rises to water depths of less than 3,600m. Previous studies have proposed that the TAG hydrothermal field is located on the hanging wall section of a large oceanic detachment system [4], where the permeability of the hanging wall is increased by intersecting faults and fissures [5].

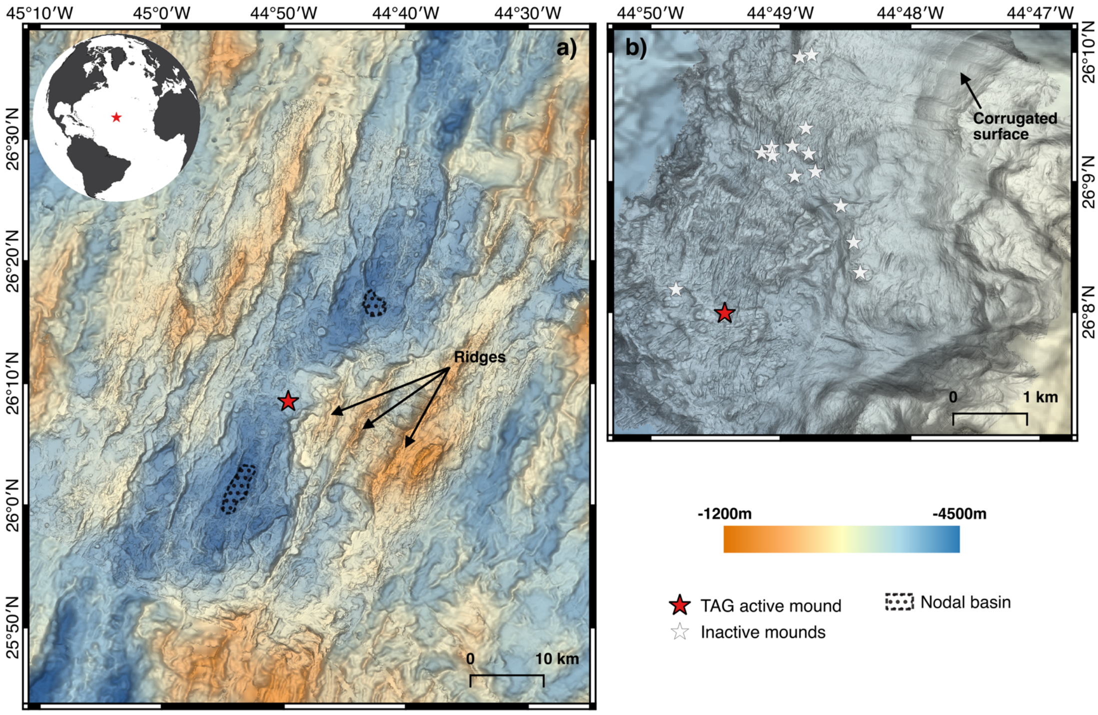

Figure 1: Bathymetric data collected during cruise M127 in the central Atlantic. a) Ship-based bathymetric map (30m resolution) of the TAG segment, which is dominated by the eastern massif formed by three ridges and limited by two nodal basins in the north and south. b) High-resolution AUV bathymetry (2m resolution) covering the hydrothermal field at the intersection of the volcanic valley floor and the eastern ridge flank.

Structural control of the TAG hydrothermal field

The regional setting is marked by the pronounced asymmetry between the western and the eastern ridge flanks. While most faults and ridges are parallel to the axis and dip inwards on the western ridge side, the eastern side shows a more complex pattern in detailed ship-based bathymetry (Fig. 2). Some of the major faults, bounding the three eastern ridges, are adjoined by multiple, smaller faults with varying dipping directions. Even though geophysical studies indicate the presence of an oceanic detachment system beneath the eastern ridge flank, no clear evidence such as corrugations or shallow dipping faults can be seen in the ship-based bathymetry. Some faults, to the north and the south of the hydrothermal field show an E-W trend, indicating an influence of the non-transform offsets that limit the TAG segment. While volcanoes are dispersed over the entire area, no continuous neovolcanic zone could be observed (Fig. 2). The location of most recent volcanism is marked by separated small neovolcanic ridges. Four of these ridges occur along the TAG segment.

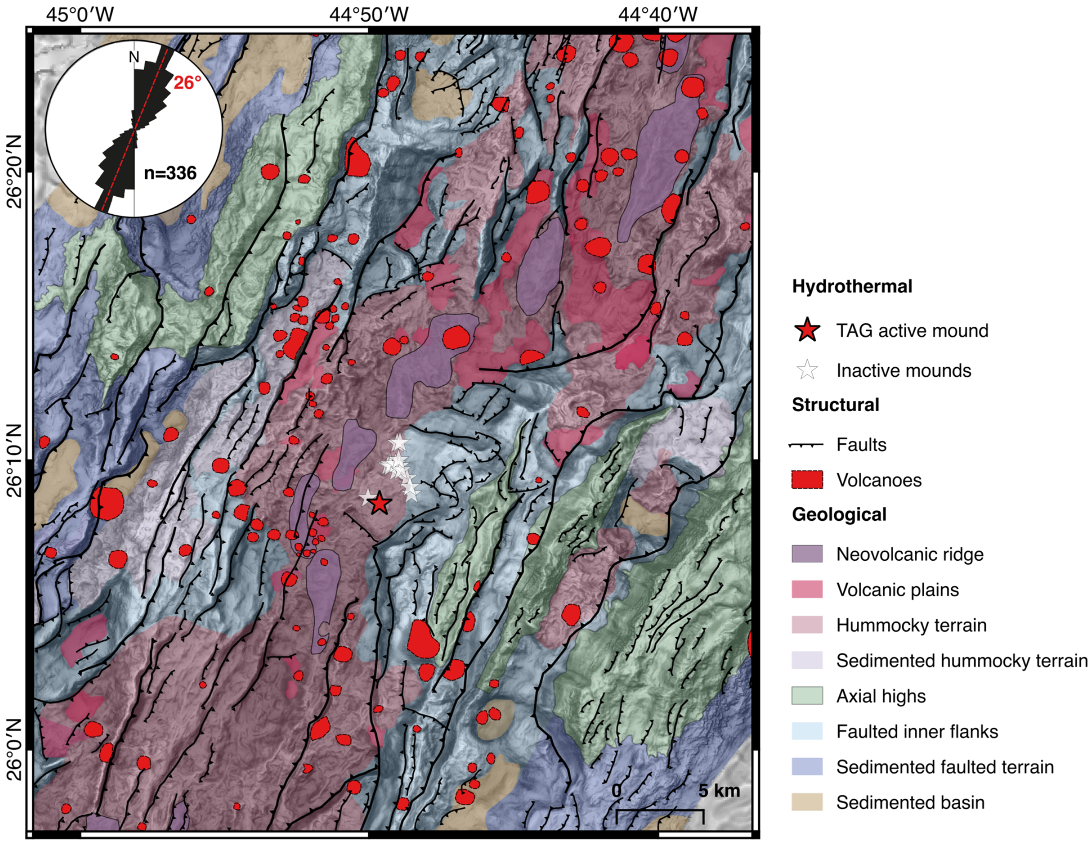

Figure 2: Geological interpretation of the TAG segment. The overall fault orientation (rose diagram upper left corner) correlates closely with the general trend of the spreading axis (indicated by the dashed red line). Larger fault systems seem to be controlled by the spreading motion of the plates. However, several faults deviate from main trend, striking up to 110° (ESE).

The eastern part of the median valley floor, hosting the massive sulfide mounds, was mapped by GEOMARs AUV Abyss in 2m resolution and shows morphologically distinct areas. The volcanic valley floor is dominated by hummocky volcanic mounds. However, they are highly dissected by extensional faults and fissures in areas with sulfide mounds while other areas remain intact. Axis-parallel faults are most prominent, but oblique faults and fissures are prominent around the active TAG mound. These lineaments (fissures or faults with undefined dip) occur in closely spaced corridors and well-defined areas. These corridors are likely caused by changes in the stress regime and may be enhanced by the propagation of shallow, lateral dikes, which induce further fissuring. This is supported by a smaller section of oblique fissuring in the north that lies in the extension of the neovolcanic ridge, located further to the west, and may be related to the propagation of a dike along a predefined weak zone.

The active TAG mound is located on the boundary of two structural units, close to the intersection of axis-parallel and perpendicular faults. The close proximity to intersecting fault systems results in an enhanced permeability of the upper crust and may provide the effective fluid pathways for hydrothermal circulation over prolonged periods of time. The inactive mounds show a similar setting. However, they are located at or close to the intersection of axis-parallel and axis sub-parallel to perpendicular fault scarps at the transition between the valley floor and the lower wall.

The presence of a 600m wide corrugated surface in the north (only visible in AUV-based bathymetry) increases the structural complexity of the hydrothermal field. However, we do not know the extent of this detachment at depth and its relation to the proposed larger detachment system.

Preliminary consideration for exploration criteria

The high-resolution data shows that the hydrothermal mounds are located within 200-400m of intersecting fissures or faults. Most of the larger faults can also be seen and traced in the ship-based bathymetry and are therefore a good indicator for long-lasting fluid pathways, a key precondition for the formation of large hydrothermal systems. Even though, there is no clear evidence for a major oceanic detachment system in the ship-based bathymetry, the presence of a young detachment fault and a corrugated surface in the high-resolution data shows, that the TAG segment is in a tectonic phase. This is also supported by the highly tectonized valley floor. Therefore, the existence of a detachment system, the presence of intersecting structural lineaments and a persistent tectonic episode of a ridge segment seems to be first order criteria for the presence of a large hydrothermal system in this area. Overall the presence of a short ridge segment, the asymmetry of spreading in the area, the proximity to non-transform offsets, and the complex nature of the ridge segment make the TAG area a prime target for exploration. This complexity may also explain why this segment is so endowed with massive sulfides when compared to many other mid-ocean ridge segments.

Exploration for seafloor massive sulfides has to be reliable and time-efficient. While our AUV survey resulted in high-resolution data, investigating an entire ridge segment or the 10,000km^2 of a single exploration license with only one AUV is not feasible. The deployment of an AUV swarm seems to be necessary. However, this approach is still in its infancy.

References

[1] Herrington, 2013. R. Road map to mineral supply. Nat. Geosci. 6, 892

[2] German, C.R., Petersen, S. & Hannington, M.D. 2016. Hydrothermal exploration of midocean ridges: Where might the largest sulfide deposits be forming? Chemical Geology 420, 114–126.

[3] Sempéré, J.-C., Lin, J., Brown, H., Schouten, H., Purdy, G.M., 1993. Segmentation and morphotectonic variations along a slow-spreading center: The Mid-Atlantic Ridge (24°00′ N– 30°40′ N). Mar. Geophys. Res. 15, 153–200

[4] Tivey, M. a., Schouten, H., Kleinrock, M.C., 2003. A near-bottom magnetic survey of the Mid-Atlantic Ridge axis at 26°N: Implications for the tectonic evolution of the TAG segment. J. Geophys. Res. Solid Earth 108

[5] Humphris, S.E., Kleinrock, M.C., 1996. Detailed morphology of the TAG Active Hydrothermal Mound: Insights into its formation and growth. Geophys. Res. Lett. 23, 3443–3446

Acknowledgements

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Keywords: seafloor resources, massive sulfides, TAG hydrothermal field, exploration criteria

Sebastian Graber

Sebastian Graber acquired a Master degree (MSc.) in Marine Geosciences at Kiel University, in cooperation with GEOMAR- Helmholtz Centre for Ocean Research Kiel, Germany. Since 2016 he is a PhD researcher at GEOMAR in the group for Marine Mineral Resources (MMR). His research focuses on hydrothermal systems in the central Atlantic Ocean, especially the TAG hydrothermal field, where he analyses the structural control of the active and inactive hydrothermal mounds. One main objective of his work is to develop geological criteria for the exploration for hydrothermal systems, based on multi-resolution bathymetric data, in order to establish a reliable resource assessment of the slow-spreading Mid-Atlantic Ridge. He has participated in international research cruises in the Atlantic, the Pacific and the Indian Ocean.

Eyes in the Deep – how autonomous underwater vehicles can support & enhance deep sea mining operations

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Introduction

Marine Autonomous Systems are making rapid progress from their early years as research tools for university departments & government institutes into having a growing number of real-world applications for industry, academia, statutory inspection, data acquisition and defence. Deep sea mining offers a distinct set of challenges that are very well suited to autonomous underwater vehicles (AUVs) and to a lesser extent for autonomous surface vehicles.

Deeper, smarter, more capable

Global demand for rare earth metals and high-grade ore will inevitably lead to exploitation of deep ocean resources as terrestrial reserves become depleted or remain unavailable for political or environmental reasons. Winning production licenses from the international seabed authority and especially gaining public trust to undertake deep sea mining activities and licenses will depend upon high quality pre-exploitation scientific surveys of the sea floor ecosystem, and subsequent monitoring of the impact of mining activity and remediation work. The actual area covered by the seabed mining operation may be quite small in terms of square kilometres, but still larger than can be patrolled by tethered 'eyeball' class Remote Operated Vehicles, so multi-spectral inspection, assessment and monitoring will be more effective when carried out by untethered AUVs. By using seabed recharging stations and data upload points the AUV can stay in situ in the deep ocean, rather than be repeatedly brought back to the surface.

The latest systems such as the BRIDGES ultra-deep glider are rated to 5000m depth, carry a comprehensive sensor suite and are capable of remaining on station for extended periods of time. Others such as the National Oceanography Centre's 'Autosub Long Range' offer even more capability and endurance, but at higher cost. AUVs can readily address the challenges of monitoring underwater noise, physical changes to the seabed environment, sediment fallout rates, direction of flow and near-real-time impact assessment and reporting. The presentation will mainly focus on the particular advances demonstrated by the BRIDGES glider (see http://www.bridges-h2020.eu/gliders-and-sea-explorer.php) which has a design and sensor suite optimised for use in support of potential deep sea mining operations, but will include references to other vehicles and the new generation of sensors such as eDNA that are soon to become available to industry, greatly enhancing the breadth and quality of data that can be acquired.

Having access to video, chemical, biological and acoustic data will build trust between licensing authorities and operators, help alleviate public concern about the actual impact of deep sea mining operations, and provide high quality datasets for long-term studies of the benefits and risks of deep sea mining. It can be envisaged that as the cost of autonomous systems falls, and capability/onboard intelligence increases, that these technologies may also be deployed by external agencies such as licensing authorities and environmental groups to monitor mining activities – it will not be possible for operations to take place without external actors having an awareness of what you are doing to the ocean floor and ecosystem.

The talk will highlight the rapid advances being made on AUV design and sensor payloads, and how the systems under development or already being manufactured for the hydrocarbons industry, defence and ocean monitoring roles can be readily adopted for use by the sea mining sector as a low-risk, high performance solution to the challenges of near-real-time surveillance of the impacts of mining in deep, pitch-dark waters far from the coastline – perhaps leading in time to the safe introduction of completely robotic mining systems, and/or semi-autonomous mining machines operated from the shore thousands of miles from the actual mining location.

Limitations of current marine policy and law for use of marine autonomous systems in areas beyond national jurisdiction will be briefly covered and suggestions for improvements made.

Keywords: Autonomy, AUV, ROV, mining, surveillance, ecosystems, assessment, robotics, eDNA, UNCLOS, ABNJ

Stephen Hall CMarSci FIMarEST

Stephen Hall is the Chief Executive of the Society for Underwater Technology, (SUT) established 1966 and headquartered in London. SUT is a Marine Science & Technology Learned Society serving the underwater technology sector and has around 2000 members and branches in Australia, Brazil, China, Malaysia, Norway, Singapore, UK, USA with new branches under development in Canada and Nigeria. Membership come from a wide range of underwater professionals including divers, archaeologists, oil & gas companies, equipment manufacturers, researchers, military users, renewable energy, aquaculture and education. SUT was an early supporter of the development of marine autonomous systems, publishing technical papers, operators guidance and peer-reviewed information for AUV operators as early as the late 1980s. SUT hosts the international Panel on Underwater Robotics and is an observer member of UNESCO’s Intergovernmental Oceanographic Commission.

Steve became SUT's CEO in April 2017 following 26 years with the UK's National Oceanography Centre and predecessor institutions working as a sea going oceanographer, AUV programme manager and later as a policy specialist, acting as the UK and Overseas Territories tsunami national point of contact and heading the UK's delegation to UNESCO's Intergovernmental Oceanographic Commission, where he was elected Vice Chair by Group 1 (USA, Canada & Western Europe) with a particular focus on marine autonomous systems, industry liaison and capacity building. He played a role in addressing ocean governance issues during the UN preparatory committee meetings on areas beyond national jurisdiction and is actively engaged in 'ocean literacy' activities with members of the international marine science education commi

Critical Elements in Hydrothermal Manganese Deposits from the Global Ocean

James R. Hein and Samantha Whisman

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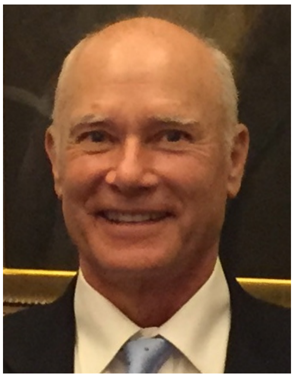
ABSTRACT

Hydrothermal marine manganese-oxide deposits (HMMD) are cemented and variously replaced volcaniclastic and biogenic sediments that were mineralized by distal, low-temperature, hydrothermal fluids. HMMD predominantly form below the seabed as sediment-hosted statabound deposits but can also form on the seabed. These deposits form at oceanic and back-arc basin spreading centers, volcanic arcs, and mid-place hotspot volcanoes. HMMD have traditionally not been considered to have an economic potential because they were considered to be devoid of economically valuable critical elements. This contrasts with their non-hydrothermal counterparts, ferromanganese crusts and nodules, which are enriched in many critical elements. However, manganese is now one of the critical metals and HMMD have the highest manganese contents (up to 55% Mn, so-called battery-grade Mn) of all the types of deep-ocean mineral deposits. There is a growing demand for this critical metal and an upward trend exists in the price of manganese on the global market. Also, other critical elements can occur in high concentrations in some HMMD and their economic potential has not been considered, especially for lithium (up to 0.17%) and molybdenum (up to 0.24%), but also vanadium (to 820 ppm), chromium (to 346 ppm), and nickel (to 0.45%), among others. Which of these critical elements are enriched and their concentrations depend on the types of rocks leached at depth by the hydrothermal fluids, the composition of hydrothermal minerals precipitated in the higher temperature parts of the circulation system, and the types of sediments mineralized by the manganese oxides. For example, mineralization of a carbonate sediment resulted in the highest lithium contents, whereas leaching of

ultramafic rocks at depth as a rule results in the highest chromium and nickel contents in the HMMD. These deposits are known to be widespread, especially in volcanic arcs, but their lateral and vertical extents and consequently size, tonnage, and grade have not been determined. Most samples of hydrothermal deposits have been collected by dredging and therefore the *in situ* relationships often are not known. One sample from the Mariana volcanic arc, west Pacific, was collected by ROV at 1274 m water depth from a layered outcrop 6.6 m thick that may be a sequence of pervasively mineralized volcaniclastic layers and offers the first clue as to the potential vertical extent that these deposits may attain. However, only the top ~0.4 m-thick layer was sampled, so it is not known whether the mineralization extents throughout the outcrop. Although large manganese deposits of various origins occur on the continents, they consist of manganese carbonates, silicates, or complex mixtures of manganese minerals. In contrast, marine hydrothermal HMMD exhibit relatively simple mineralogy that would make processing of this potential ore much simpler.

Keywords: Hydrothermal manganese, global ocean, critical metals

James R Hein



Jim Hein received a Ph.D. in Earth Sciences from the University of California at Santa Cruz in 1973 and has been a marine geologist with the USGS since 1974. He started working on marine mineral deposits two years later as a member of the DOMES team, a large interdisciplinary group studying Ni- and Cu-rich Fe-Mn nodules from the Clarion-Clipperton zone. In 1982, Hein became Project Chief of Co-Rich Fe-Mn Crust Program. That project produced cooperative funding agreements and cooperative research with a wide-range of collaborators globally. Those efforts evolved into studies of the full range of mineral deposit types that occur in modern ocean basins and comparisons with potential analogs in the geologic record. For example, Jim has been investigating hydrothermal deposits that occur at oceanic fracture zones, island arcs, and spreading centers. Those studies include rare-metal-rich sulfide, sulfate, and silica deposits and rifted continental-margin barites. Also, he is studying the oceanographic conditions conducive to formation of seamount and continental-margin phosphorite deposits. Hein has authored or co-authored over 550 papers and abstracts, including co-editing six books and three special issues of *Ore Geology Reviews* and *Economic Geology*. He is a Fellow of the Society of Economic Geologists and the Geological Society of America, Past President and currently on the Executive Board of the IMMS, scientific advisor to the DOS, and recipient of the prestigious Distinguished Service Award, the highest honor bestowed by the US DOI, and the Moore Award, the highest honor of the IMMS.

Deep-sea mining impacts above the surface:

Quantifying the fuel consumption and associated air pollution of a potential commercial deep-sea manganese nodule mining operation in the Clarion-Clipperton Zone

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ABSTRACT

(for an oral presentation)

Activities for preparing future deep-sea mining offer the unique opportunity to study environmental conditions and anticipate adverse environmental impacts prior to the commercialization of the activity. Until know, environmental research has first and foremost focused on understanding direct impacts occurring at the seafloor or in the water column such as the removal of substrate, the suspension of sediment or the creation of particle plumes. Impacts occurring above the sea surface have thus far rarely been considered.

The operation of deep-sea mining equipment, as well as of mining and transport vessels will be associated with a considerable energy demand. In the open ocean, this energy will be provided by heavy fuel oil (HFO), which is the cheapest and most common marine fuel. The combustion of HFO will be associated with the release of greenhouse gases and other pollutants. Deep-sea mining will thus directly add to already critical air pollution levels caused by international shipping.

To contribute to a holistic assessment of deep-sea mining impacts and to address the previously outlined knowledge gap, we present the methodology to quantify the fuel consumption and associated emissions of a potential typical commercial manganese nodule mining operation in the Clarion-Clipperton Zone (Fig.1). Using the mine set up and energy demand estimates from a study commissioned by the German Federal Ministry of Economic Affairs and Energy supplemented by

information from literature, we anticipate emissions of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (NO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter and non-methane volatile organic compounds.

The air pollution caused by deep-sea mining strongly depends on numerous factors including engine type, power rating, engine load factors, specific fuel oil consumptions (SFOC), travel speed and distance, production rates and technological choices. For our chosen study case, we calculate the annual fuel consumption to be between 33,040 and 36,332 t HFO, which causes a release of between 102,888 and 113,137 t CO_2 as a direct consequence of the combustion of HFO, or between 113,137 and 115,642 t CO2 when factoring in upstream emissions resulting from the production of HFO. The emissions of the remaining gases and pollutants are considerably lower. Examples include N_2O emissions between 5.3 and 5.8 t and CH_4 emissions between 1.98 and 2.18 t.

Complementing our analysis, we discuss policy-implications and raise questions regarding the allocation of emissions from deep-sea mining and the relevance of recent ISO pollution regulations.

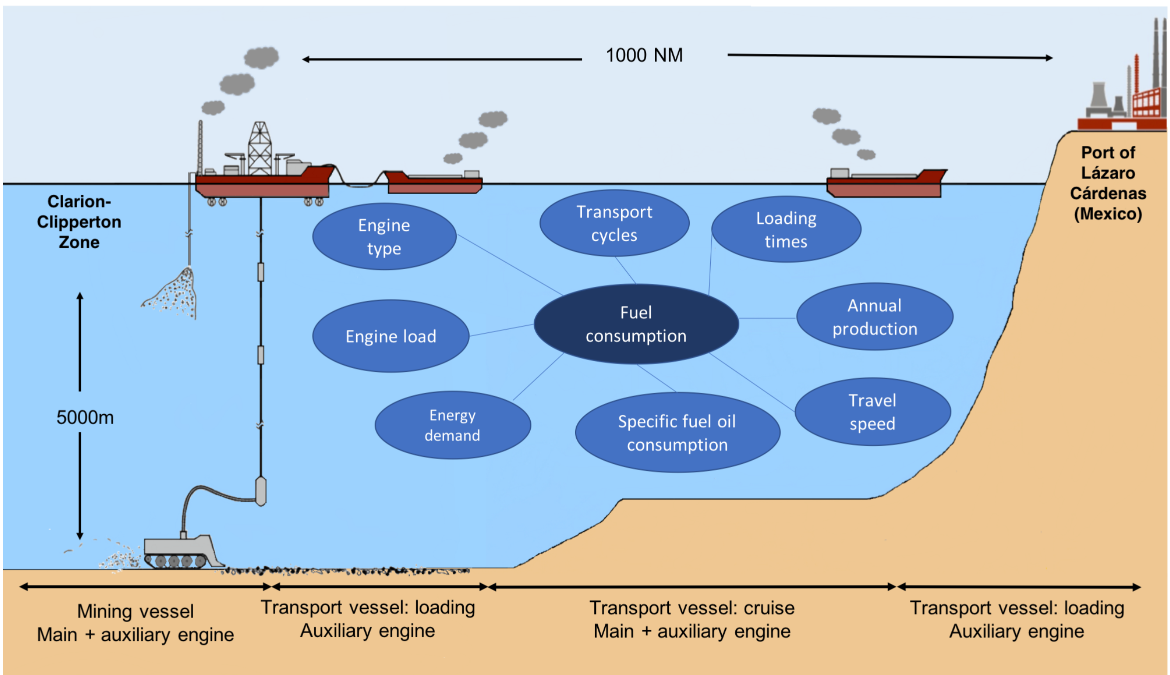

Figure 1: Overview of the mine scenario. Set values for the quantification of the fuel consumption are shown in black print, variables influencing the fuel consumption are shown in blue circles.

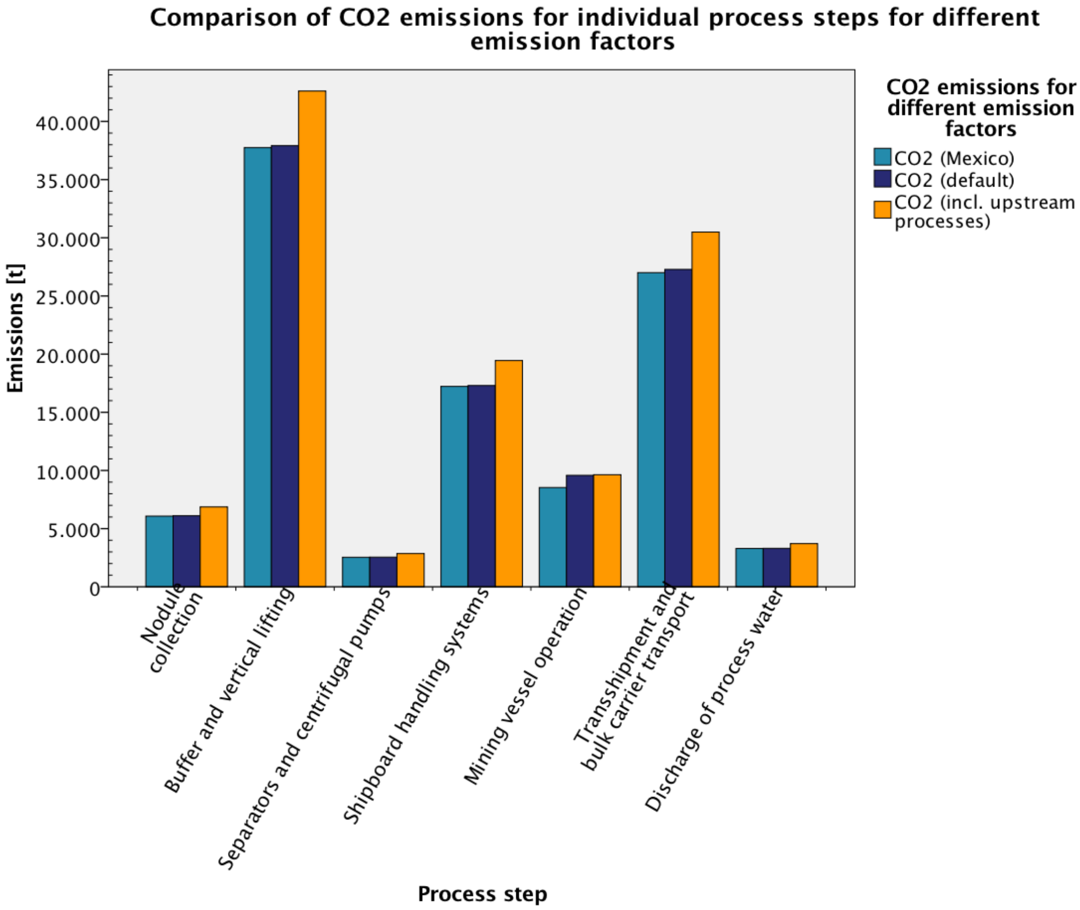

Figure 2: CO2 emissions for a mining scenario (SFOC ME: 170g/kWh; SFOC AE: 227 g/kWh; transport speed: 12 knots) based on different emission factors (Mexico, default and incl. upstream emissions from HFO production) (ME: main engine, AE: auxiliary engine)

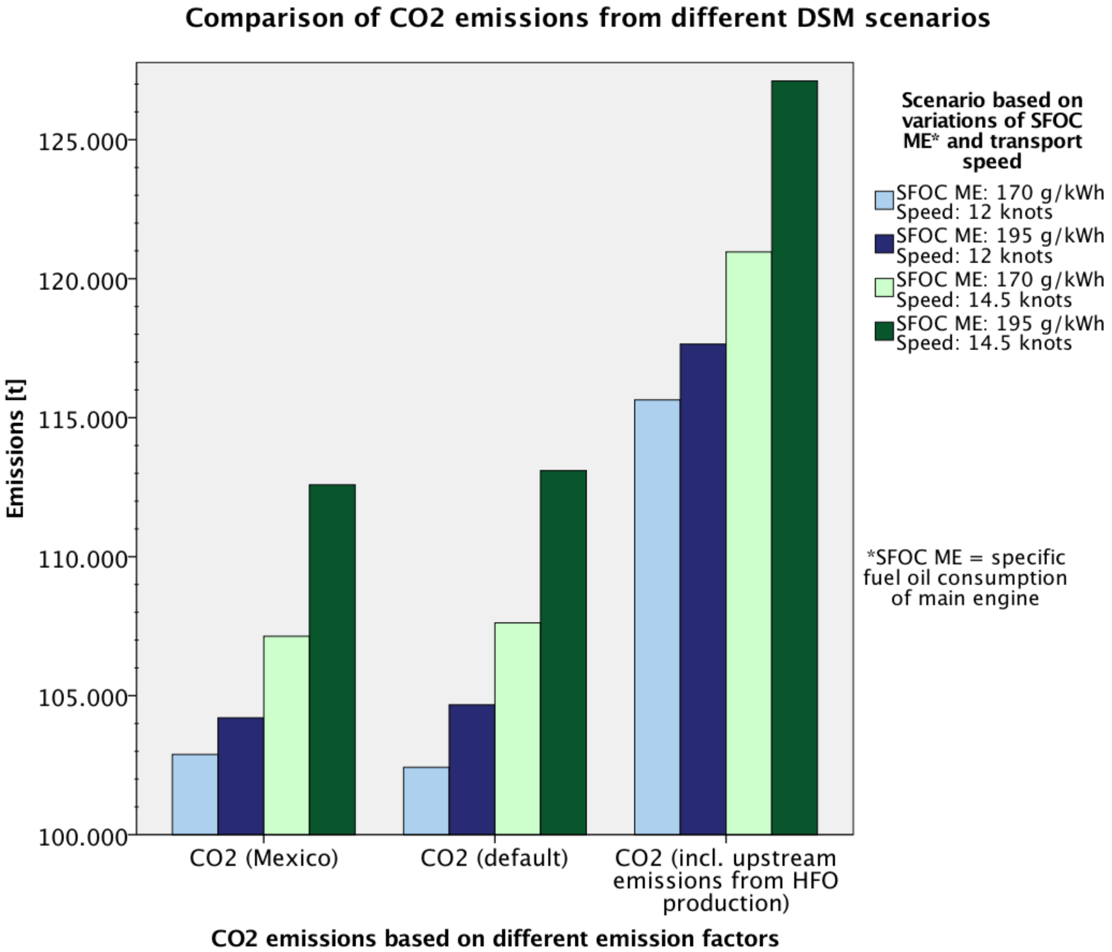

Figure 3: Comparison of cumulative CO2 emissions (mining vessel, equipment and transport vessels) for different mining scenarios (SFOC ME 170 and195 g/kWh, SFOC AE: 227 g/kWh; transport speed: 12 and 14.5 knots) considering different emission factors (Mexico, default values, default values incl. upstream emissions from HFO production) (ME: main engine, AE: auxiliary engine)

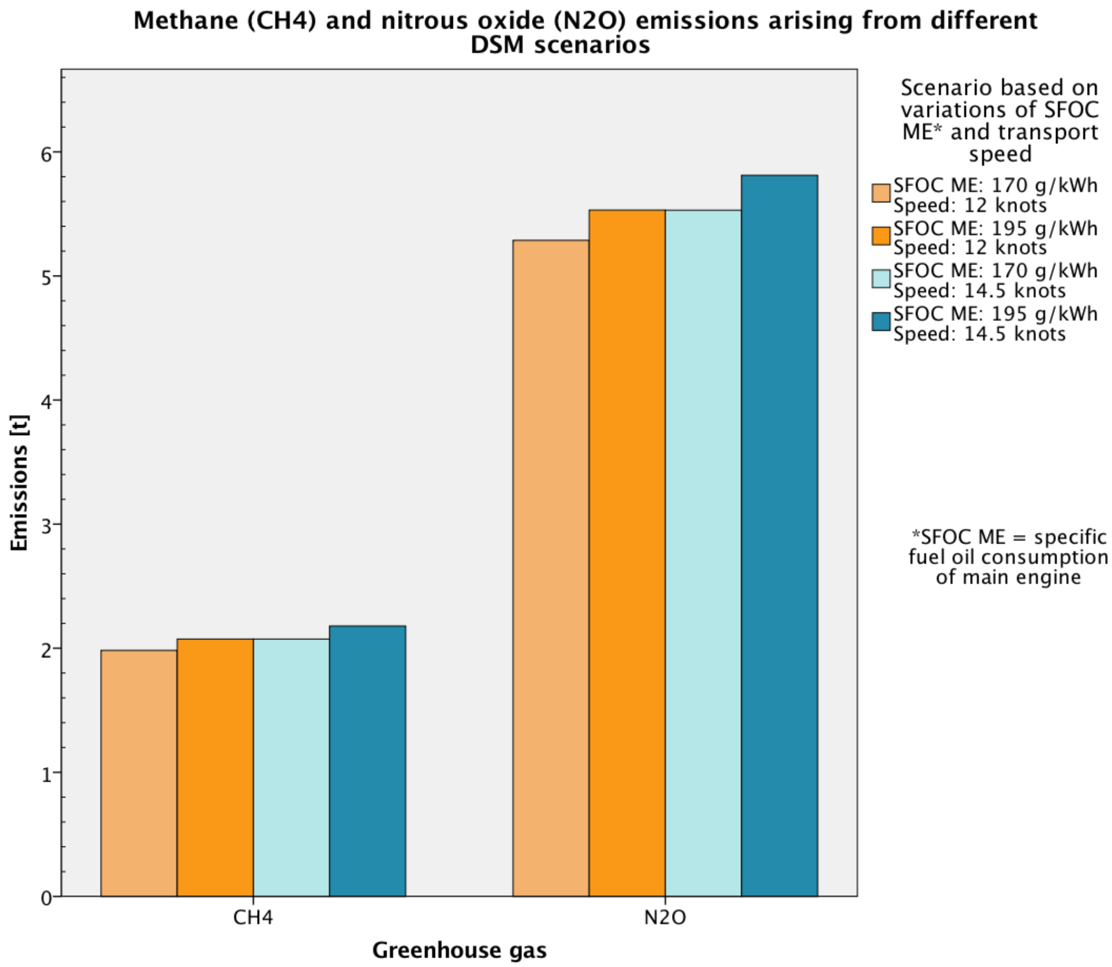

Figure 4: Comparison of cumulative CH4 and N2O emissions for different mining scenarios (SFOC ME 170-195 g/kWh, SFOC AE: 227 g/kWh; transport speed: 12-14.5 knots) (ME: main engine, AE: auxiliary engine)

Keywords: manganese nodules, heavy fuel oil, air pollution, energy demand, emissions

Luise Heinrich

Luise Heinrich is a PhD student in the work group of Prof. Andrea Koschinsky at Jacobs University Bremen since 2016. The main methodological focus of her work is the assessment of deep-sea mining impacts above the surface and the comparison to terrestrial mining. This includes the development of scenarios for commercial nodule mining process chains as well as the quantification of the fuel consumption and air pollution of a typical mining operation.

Before joining Prof. Koschinsky at Jacobs University, Luise Heinrich obtained a M.Sc. in "Environmental Studies and Sustainability Science" from Lund University in Sweden, where she studied the intersection of environment, economy and society. For her M.Sc. thesis, she conducted an integrated risk assessment assessing the vulnerability of the Norwegian coastal fisheries to the threat of ocean acidification. Prior to this, she graduated with a B.Sc. in "Integrated Environmental Studies" from Jacobs University Bremen.

In the past years, Luise Heinrich has worked in the Ocean Acidification International Coordination Center at the International Atomic Energy Agency in Monaco and for the German Marine Research Coordination, where she assisted in organizing a workshop on deep-sea mining at the European Parliament in Brussels.

Excavating the deep sea: modeling the pressure effect in rock cutting processes

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INTRODUCTION

Seafloor Massive Sulphides are typically found near the oceanic ridges at larger water depths (>1km). The physical properties of SMS, as shown in table 1, are comparable to the properties of weak rock. One of the technical challenges to enable extraction from these locations is the cutting or excavation process. Experiments have shown that the energy needed to excavate the material may increase with water depth (Alvarez Grima et al. 2015). Besides that, it is demonstrated that rock that fails brittle in atmospheric conditions can fail more or less in a plastic fashion when present in a high pressure environment, as would be the case at large water depths. The goal of this research is to identify the physics of the cutting process and to develop this into a model in which the effect of hydrostatic and pore pressures is included.

Table 1: Range of mechanical properties in SMS deposits (Yamazaki and Park, 2003)

Parameter	Min	Max
Wet bulk density [kg/m^3]	$2.4 \cdot 10^3$	$4.0 \cdot 10^3$
Solid bulk density [kg/m^3]	$3.6 \cdot 10^3$	$5.5 \cdot 10^3$
Porosity [-]	0.15	0.53
Unconfined compressive strength [MPa]	3.1	38
Tensile strength [MPa]	0.14	5.2

The cutting of rock is initiated by pressing a tool into the rock. As a result, at the tip of the tool a high compressive pressure occurs, which leads to the formation of a crushed zone. Depending on the shape of the tool and the cutting depth, shear failures might emanate from the crushed zone, which will eventually expand as tensile fractures that can reach to the free rock surface. Through this process intact rock will be disintegrated to a granular medium. For an overview of the process (figure 1). Additionally, the presence of water in the pores of and surrounding the rock influences the cutting process through drainage effects. The most relevant effects are weakening when compaction and strengthening when dilation occurs in shearing and tension. Deformation of the rock causes the pore volume to change, resulting in a under or over pressure. As a result, the pore fluid needs to flow. The magnitude of the potential under pressure is limited through cavitation of the pore fluid, limiting further reduction of the pore pressure (figure 2). The drainage effects cause the rock cutting process in a submerged environment to show a stronger dependency of both the hydrostatic pressure as well as the deformation rate (figure 3).

Figure 1: Phenomenological rock cutting model with corresponding failure envelope, after Van Kesteren 1995.

Figure 2: Schematic overview of dilation hardening, extension based on Brace and Martin 1968.

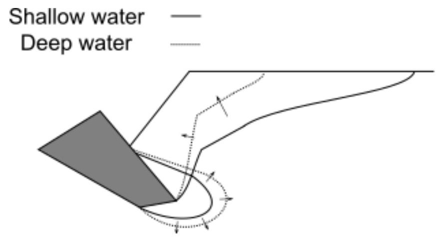

Figure 3: Effect of larger hydrostatic pressure (water depth) on the cutting process, after Alvarez Grima et al. 2015.

DISCRETE ELEMENT METHOD

In DEM, rock is represented as an assembly of rigid spherical (3D) or cylindrical (2D) discrete elements (particles) that have mutual interactions in normal and tangential directions. The translational and rotational motion of a particle is governed by Newtons second law. The equations of motion are integrated over time with an explicit multi-step scheme, i.e. the velocity Verlet scheme.

The interactions between neighboring particles can either be a collision or a bonded interaction. In both cases, the force at the contact is composed of normal and tangential components, with

$$F = F_n + F_s = nF_n + tF_s \qquad (1)$$

Where F is force vector, n is the unit vector normal to the particle surface at the point of the interaction, t is the tangential vector, and the subscripts n and s are respectively normal and shear. The interaction forces are modeled with a constitutive model. In this research, bonds are defined by a linear elastic perfect brittle model, see figure 4, meaning that a bond breaks immediately when either its tensile or shear strength is exceeded. The interaction between two particles is modeled as a collision when either their bond is broken or when never a bond has existed between these contacting particles. For collisions, a linear elastic model is used in both shear and normal direction. Coulomb friction is used to allow for sliding frictive behavior between particles. To ensure stability of the simulation, numerical damping is applied (Potyondy and Cundall 2004), which is described by

$$F_d = -\alpha_d \|\sum F\| sign(v) \qquad (2)$$

With damping coefficient α_d and velocity v.

Figure 4: Linear elastic perfect brittle bond model ,left normal interaction, middle shear interaction with contact after breakage and right shear interaction without contact after failure

FLUID MODELING

Because the bulk modulus of water is in the same order as the bulk modulus of the rock, water has to be considered as a compressible fluid. The low permeability of the rock and high hydrostatic pressure allows the pore fluid to be modeled as a pore pressure diffusion process, given by

$$\frac{Dp}{Dt} + M\nabla \cdot \left(\frac{\kappa}{\mu}\nabla p\right) = -\alpha M \frac{D\epsilon_V}{Dt} \qquad (3)$$

With pressure p, fluid bulk modulus M, intrinsic permeability κ, dynamics fluid viscosity μ, effective stress coefficient α and volumetric strain ϵ_V.

Since DEM is based on a discontinuum approach, it is not possible to directly solve the continuum equation (3) Through the use of a kernel interpolation function, like in the Smoothed Particle methods, the discontinuous data resulting from DEM simulations can be interpolated as a continuum field. In this modeling approach (referred to as DEM-SP), the interpolation points are collocated with the DEM particle centers, and move with them as well. Because the particle radii and masses are based on a random particle size distribution, these are randomly stacked together. Such an unstructured particle assembly can easily result in numerical instabilities and inaccuracies. To adjust for the random size and positioning of the particles, the Corrective Smoothed Particle Method (CSPM) is used (Chen et al. 1999), in combination with a Wendland C2 kernel (Wendland, 1995)

In CSPM, the kernel interpolation of a field quantity A and field gradient of quantity A is interpolated through respectively

$$A(u_i) = \frac{\sum_j A_j m_j W\left(u_i - u_j, h\right)}{\sum_j m_j W\left(u_i - u_j, h\right)} \tag{4}$$

With position vector u, the particle under consideration i, the neighboring particles j, particle mass m, smoothing length h and kernel function W

It is possible that due to deformations the fluid pressure drops below the vapor pressure during simulations. When this happens, the fluid will cavitate, resulting in a drop of several orders of magnitude of the fluid bulk modulus. In the simulations this is implemented in a fairly simple manner. When the locally the pore pressure drops below the minimum pressure, the pressure is fixed at the minimum pressure. From that point on it is only possible to increase the fluid pressure by having fluid flow towards the cavitated region, so

$$if p_i < p_{min} then p_i = \frac{p_{min} \wedge \partial p}{\partial t} = max\left(\frac{\partial p}{\partial t}, 0\right) \tag{7}$$

VALIDATION

The modeling approach is validated by comparing simulations with the results of several experiments from literature. DEM-SP is used to simulate a series of cutting experiments with varying cutting velocity and water depth. These results match both qualitatively and quantitatively. Additional validation cases, like tile cutting, tri-axial tests and drilling are presented in Helmons 2017. Additionally, both the experiments and simulations show the occurrence of a hyperbaric effect, as can be seen in figures 5 and 6.

Figure 7 shows a comparison of the simulated results with the data obtained from experiments and the fitted analytical model, both were presented in Alvarez Grima et al. 2016. Note that two regimes might be distinguished. Besides the brittle-ductile transition (as shown in figures 5 and 6) with respect to water depth, it is also noted in the simulations that the dominating bond failure mechanism changes from tensile failures to shear failures. This also corresponds with the phenomenological model, as shown in figure 3. Based on the data in the experiments and the simulations, it seems that the transition from a tensile failure dominated cutting process to a process that is dominated by shear failure occurs somewhere close to the 1-3 times the BTS value of the rock. This means that at a hydrostatic pressure which is significantly larger than the tensile strength of the rock the cutting process shear and cataclastic failure are more dominant, while at hydrostatic pressures significantly smaller than the tensile strength the cutting process is dominated by tensile failure and chipforming.

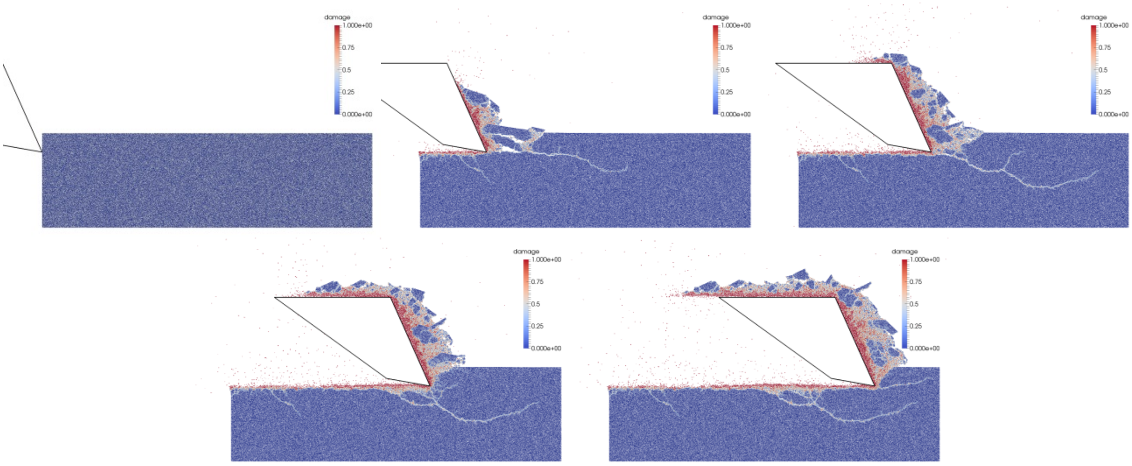

Figure 5: Cutting process for dredging at atmospheric conditions. For each image 0.07s have passed. Color depicts damage, blue perfect intact, red fully disintegrated, from Helmons et al. 2016.

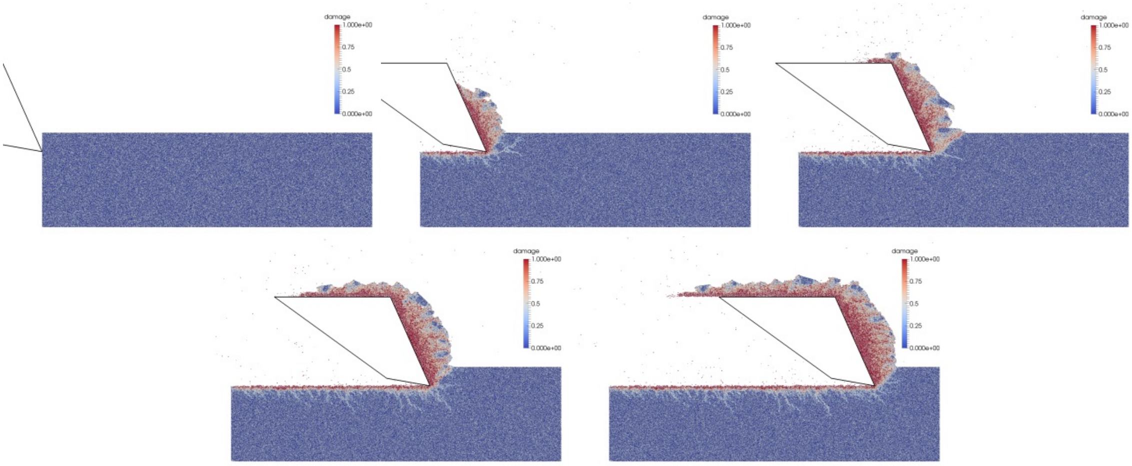

Figure 6: Cutting process for dredging at 1.8 km water depth. For each image 0.07s have passed. Color depicts damage, blue perfect intact, red fully disintegrated, from Helmons et al. 2016.

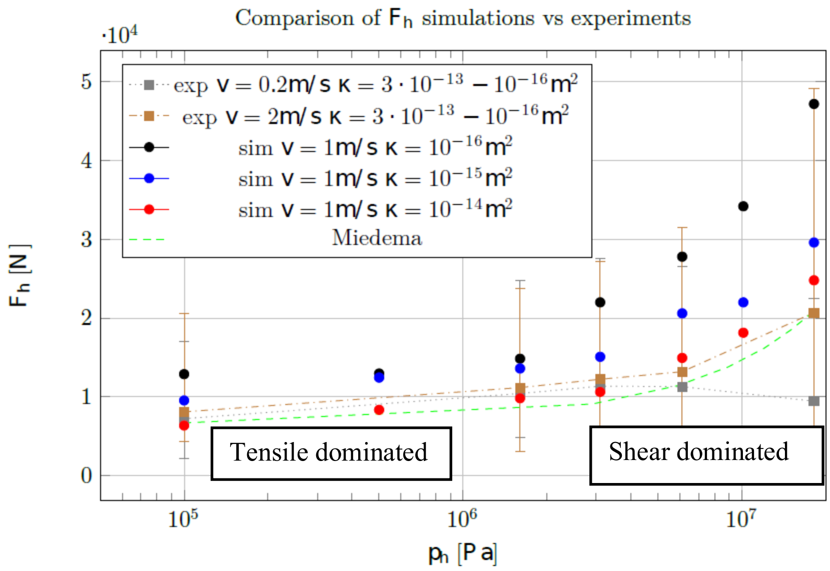

Figure 7: Time averaged cutting forces for DEM-SP compared with experiments and analytical model (Miedema), Helmons et al 2016.

CONCLUSIONS AND FUTURE WORK

It is proven that DEM-SP is capable of solving drainage related effects in deformation of saturated rock. A range of rock cutting experiments are simulated and the results match well both qualitatively and quantitatively with respect to cutting force and hydrostatic pressure. However, the plane strain assumption that is inherently in place in the 2D approach of DEM-SP make it that the methodology cannot sufficiently model the whole cutting process, especially for the normal force and the side forces (are not present at all in plane strain). Therefore the DEM-SP is being extended towards a full 3D model. As this extension to 3D is currently under development, preliminary results of the 3D approach will be presented at the conference.

ACKNOWLEDGEMENTS

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REFERENCES

Alvarez Grima M , Miedema S, van de Ketterij R, Yenigul N and van Rhee, C., "Effect of high hyperbaric pressure on rock cutting process", *Engineering Geology*, 196:24-36, 2015.

Brace W and Martin R, "A test of the law of effective stress for crystalline rocks of low porosity", *International Journal of Rock Mechanics and Mining Sciences,* 5:415-426, 1968

Chen J, Beraun J and Carney T, "A corrective smoothed particle method for boundary value problems in heat conduction", *International Journal for Numerical Methods in Engineering*, 252:231-252, 1999

Helmons R, Miedema S, Alvarez Grima M and van Rhee C, " Modeling fluid pressure effects in cutting of saturated rock", *Engineering Geology*, 211:50-60, 2016

Van Kesteren W , "Numerical simulations of crack bifurcation in the chip forming cutting process in rock", *Fracture of Brittle Disordered Materials: Concrete, Rock and Ceramics*, p505-524, 1995

Wendland H, "Piecewise polynomial positive definite and compactly supported radial functions of minimal degree", *Advances in Computational Mathematics,* 4:389-396, 1995

Yamazaki T and Park S, "Relationships between geotechnical engineering properties and assay of seafloor massive sulphides". In *13th International Offshore and Polar Engineering Conference*, volume 5, pages 310-316, Honolulu, Hawaii, USA

Keywords: Rock cutting, drainage, hydrostatic pressure, pore pressure, brittle-ductile, Discrete element

Rudy Helmons

In 2011, Rudy Helmons received his Master of Science in Mechanical Engineering from Eindhoven University of Technology in the Netherlands. His Master of Science thesis comprises the development of Computational Fluid Dynamics for vertical hydraulic transportation of solids, in collaboration with Royal IHC. After completing his masters degree, Rudy started his academic career at Delft University of Technology in the Netherlands, where he started his PhD research in the dredging engineering group. His research entails the cutting of rock for dredging, drilling and deep sea mining applications. In order to do this, he developed a numerical model that combines both rock mechanics and fluid mechanics in order to simulate the fracturing and damage of fluid saturated rock. In 2015, he got awarded with the IADC Young Author Award. Rudy defended his thesis in 2017 and obtained his PhD with Cum Laude. After his PhD he continued his research at Delft University.

Sustainability Aspects in Deep-Seabed Mining of Polymetallic Nodules

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INTRODUCTION

Metal components contained in deep-seabed mineral resources are being highlighted as "*energy metals*", which are widely utilized in the entire fields of energy: harvesting and generation, storage and transportation, and saving. Those are mostly trace and rare metals, and rare earth elements as well: manganese, nickel, cobalt, copper, molybdenum, tellurium, selenium, platinum, etc. Toward low carbon society, for global sustainability, the role of metals and minerals is growing up in industries of energy and transportation [1]. In this context, the production and supply of energy metals from deep seafloor have to be approached also based on sustainable development. In deep-seabed mining activity, the sustainability is focused on potential impacts on ecosystems in benthic area and water column. The environmental impacts in deep-seabed mining are caused basically by intervention in benthic zones and transportation of materials. Those are, in particular, removal of benthic habitats, generation and dispersion of sediment plumes, surface transportation of seawater and sediment, tailing from mining vessel, sound and light noises, and chemical leakage, etc. This paper is aiming at fundamental guidance towards sustainable mining of polymetallic nodules.

Benthic Interventions

The collecting process of polymetallic nodules from seafloor sediment layer requires a collecting machine crawling and dredging the nodules on seafloor. This process will cause inevitable impacts on benthic ecosystem. The upper layer of sediment areas, where collecting machine is operating, will be destroyed to a certain depth. Thus, the benthic impact is three dimensional in spatial sense. An *ideal* picking-up only nodules from sediments won't be feasible in aspect of commercial mining. Dredging operation will cause removal of sediment upper layers and benthic habitats together. So the size of mine site (A_s), calculated as area by Eq. (1), is to consider as volume in fact.

$$A_s = \frac{A_r \cdot D}{A_n \cdot E \cdot M} \qquad (1)$$

, where A_s is size of mine site (km^2), A_r is annual nodule production rate (dry tonnes/year), D is duration of mining operation (years), A_n is average nodule abundance in mineable area (kg/m^2), E is overall efficiency of collector (%), and M is mineable area (km^2) [2].

Sustainable mining requests a high level of collecting efficiency for the sake of reduction of benthic harms and achievement of annual production, simultaneously. The overall efficiency (E) of a collecting system is estimated as

$$E = e_d \times e_s \qquad (2)$$

, where e_d is nodule dredge efficiency and e_s is area sweep efficiency as following.

- Nodule Dredge Efficiency

The nodule dredge efficiency (e_d) is the ratio of minerals gathered by dredge head versus the minerals on the seafloor initially. There are various kinds of dredge head design showing e_d over 80%, however, those were tested mostly in laboratory conditions. The efficiency based on nodule recovery ratio is not enough for the sake of sustainability. An optimum operation condition is to find out in order to satisfy the required efficiency and minimizing the benthic damages, e.g. generation and dispersion of sediment plumes.

● Area Sweep Efficiency

The area sweep efficiency (e_s) is the area percentage of the seafloor swept by collecting machine with respect to the design area of mine site. The area sweep efficiency will be governed by mobility and controllability of collector vehicle. A high-precision seafloor navigation system is mandatory for the purpose of path tracking control of collector vehicle. A high mobility of collector vehicle, represented by *maximum speed*, *minimum turning radius*, *maximum upslope* and *relevant sediment penetration*, and a precise control algorithm will be the barometers on sustainable design of collector.

If e_s were around 60%, the overall efficiency (E) will be about 50%. On the other hand, in case of 80%, the E of collecting system will rise up to 64%. This makes a big difference in the aspect of sustainability: reduction of 25% in the size of mine site (A_s).

The major factors for enhancement of the overall efficiency (E) are as following [3]:

- Optimum design of collector machine/robot
- Control algorithm for path tracking based on high-precision seafloor navigation
- Optimum design of mining paths

Materials Transportation

Vertical Ore Lifting

Vertical lifting of nodules requires most energy in total mining operation. Hydraulic lifting, air-lifting and mechanical lifting have been studied by a large number of academicians, researchers and experts. In aspect of durability and reliability of lifting system, hydraulic lifting and air-lifting are standing in front line of candidates for commercial application. Hydraulic lifting has comparatively higher efficiency, but has disadvantages in durability and maintenance-and-repair of underwater pump stations. Air-lifting has advantages of maintenance-and-repair and relatively less water volume, but has disadvantages in efficiency and sound noise. Also, it is to foresee other problems in durability and safety due to drastic expansion of injected air bubbles and consequent impacts and collisions.

Efficiency of hydraulic lifting, represented by *volumetric concentration* of ores in lifting pipe, is raised by reductions of energy consumption and by-products (seawater and sediments) required for ore transportation. The main consequences of high efficiency are in aspects of profitability and sustainability as follows:

- Cost reduction (CAPEX, OPEX) for on-board treatment facilities and mining vessel
- Reductions of by-products and tailing

A buffer station between collecting system and lifting line plays an significant role in safety (flow assurance) and sustainability (sediments extraction) [4].

By-Products and Tailing

The inevitably accompanied by-products in nodule lifting are a great burden for sustainable mining. Fig. 1 shows schematic diagram of a suggested material flows in on-board treatment facilities. The treatment objects are nodules, seawater and sediments. Not to be flooded, the design of on-board treatment facilities of mining vessel should be based on relevant matching-up of types and capacities of sub-units in Fig. 1.

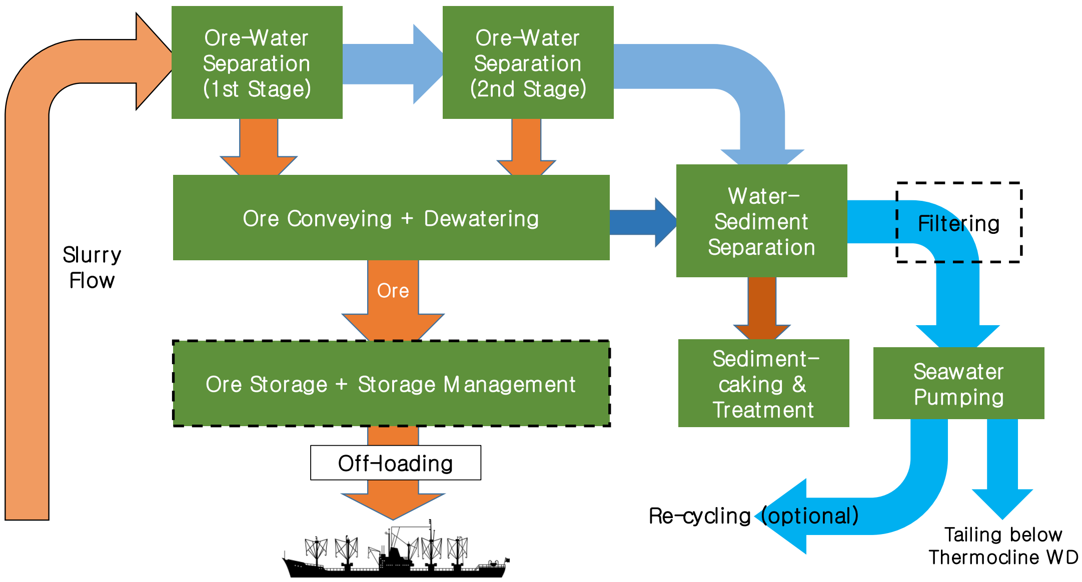

Fig. 1: A schematic diagram of on-board treatment processes

In aspect of sustainability, the design of deep-seabed mining system should not focus only on the achievement of annual nodule production, but also consider about the feasibility of by-products treatments. The on-board treatment processes (Fig. 1) have to be integrated in capacities to avoid any congestion and clogging and to secure smooth material flows.

Fig. 2 is representing the correlations between materials transportation and treatment. As of current approaches, the treatment of pumped seawater-sediment mixture will be a tough huddle for commercial mining. The criteria of seawater tailing (*to be defined*) will be another significant factor affecting cost and feasibility. A relevant recycling of treated seawater would be a solution for future of deep-sea mining.

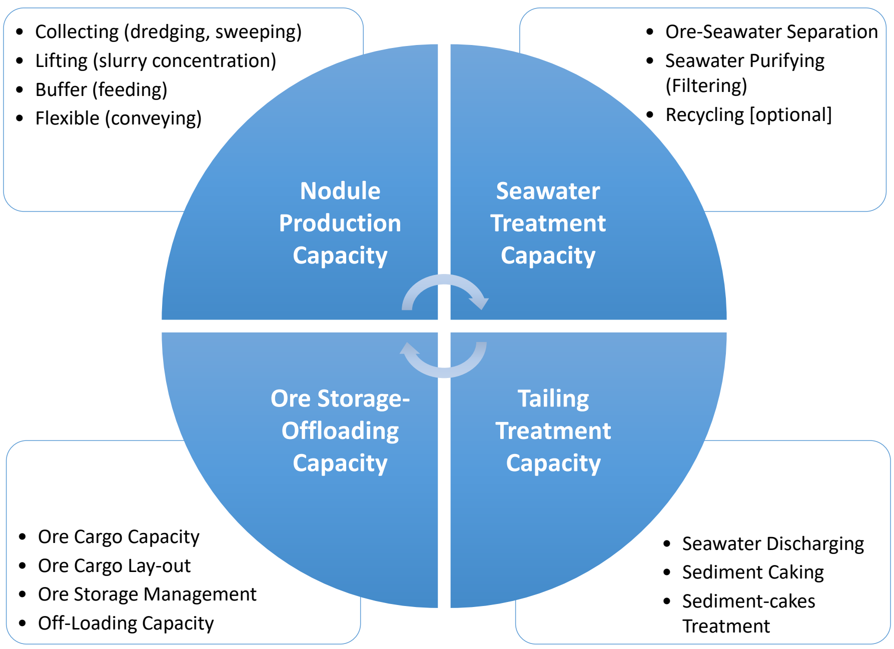

Fig. 2: Major aspects of materials flows in deep-seabed mining system

Keywords: polymetallic nodules, profitability, sustainability, materials transportation, materials treatment, tailing

References

[1] The World Bank Publication: *The Growing Role of Minerals and Metals for a Low Carbon Future*, International Bank for Reconstruction and Development, June 2017.

[2] UNOET (1987), Delineation of mine sites and potential in different sea areas. UN Ocean Economics and Technology Branch and Graham & Trotman Limited, London, 79pp.

[3] Sup Hong *et al.* (2013), Pilot Mining Robot for Polymetallic Nodules and Pre-Pilot Mining Tests. UMI-2013 Annual Conference, Rio de Janeiro, Brazil.

[4] Sup Hong *et al.* (2014), Development of Buffer Station for Safe and Eco-Friendly Mining of Deep-Seabed Mineral Resources. UMI-2014 Annual Conference, Lisbon, Portugal.

Dr. Sup Hong

He majored in Naval Architecture and Offshore Engineering at Seoul National University, Korea, and got academic degrees of Bsc (1983) and Msc (1985). He continued study on Offshore Engineering in Technical University of Aachen, Germany during 1985−1992. His doctoral dissertation (1992) was on "*nonlinear" analysis of flexible risers*. (It is why he loves so much *Antoni Gaudi*, one of the most beloved architects in the world, whose masterpieces are all full of beautiful "*curves"*.) Since 1993, he is working in the research field on development of deep-seabed minerals at *Korea Research Institute of Ships and Ocean Engineering* (KRISO). For the past over 20 years (1994−2016), he was in charge of the research and development of mining technology for deep-seabed polymetallic nodules. A series of Sea Tests of test collector (2009−2010), pilot mining robot "*MineRo*" (2012−2013) and pilot lifting system (2015) are invaluable assets in his expertise. *KISS*, *3M* and *CORE* (please, refer to his previous presentations at UMC) have been his fundamental principles in development works. He is convinced that being *Simple and Smart* would enhance *safety*, *reliability* and *eco-friendliness* in deep-seabed mining activities. He is now enjoying his deserved *Sabbatical Year* (from December 2017 to December 2018) in Sanya, Hainan, and pondering over *Sustainable Mining of Deep-sea Minerals*.

Towards a Formal Definition of Active and Inactive Seafloor Massive Sulfide Deposits

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INTRODUCTION

Hydrothermal vents that form seafloor massive sulfide (SMS) deposits represent unique biodiversity hotspots that host many species that are found only at these sites. The destruction of these habitats remains one of the greatest environmental risks associated with proposed mining of SMS deposits. For this reason, there is a growing movement to protect active vent sites from direct and indirect effects of seafloor mining (Van Dover et al., 2018). Mitigating the adverse effects of mining on these ecosystems may prove to be one of the greatest challenges facing the marine minerals industry.

At the same time, there is increasing evidence that inactive or extinct hydrothermal systems, which do not host the density or diversity of animals typical of active vents, may constitute a significant proportion of the SMS resource potential on the seafloor. Mining inactive SMS deposits may therefore present an extractive opportunity that does not necessitate the disturbance or destruction of active vent habitats. However, if mining of SMS deposits is to take place only at inactive vent sites in order to protect active vent ecosystems, a clear definition of what defines a site as active or inactive is necessary.

ACTIVE AND INACTIVE SEAFLOOR MASSIVE SULFIDE DEPOSITS

Our understanding of the number of inactive deposits, their size and grades, and how they are preserved on the seafloor remains limited, largely due to the challenges associated with finding these deposits. Over 90% of all hydrothermal vent fields discovered so far are hydrothermally-active. Almost all of these sites were discovered through the detection of chemical anomalies associated with active hydrothermal venting via water column surveys. Inactive sites have no associated hydrothermal plume, and thus the well-established plume survey exploration method is not effective. As a result, very few truly inactive sites inactive sites have been discovered. Alternative exploration methods, such as spontaneous potential (SP) surveys, magnetic surveys, and high-resolution mapping are required (Cherkashev et al., 2013; Jamieson et al., 2014; Tivey and Johnson, 2002). As methods for locating inactive deposits continue to develop, our understanding of the distribution and resource potential of these deposits will increase, and the focus of resource exploration will shift from active to inactive vent sites. However, for now, most exploration and deposit development activities remain focused on active vent fields.

CLASSIFICATION OF ACTIVE AND INACTIVE SEAFLOOR MASSIVE SULFIDE DEPOSITS

Two examples that illustrate the inconsistency with which the terms *active* and *inactive* are being used are the Krasnov and Solwara I vent fields. The Krasnov vent field, located at 16°N on the Mid-Atlantic Ridge, is classified in the InterRidge Vents Database (v. 3.4) as “inactive”. However, the Database also notes that the vent field was discovered by detection of a hydrothermal plume and that vent fauna were observed, including bacterial mats. Therefore, although this site may not currently host high temperature black smoker vents, it is clearly hydrothermally active to some extent. The Solwara I site, in the Manus Basin and within the territorial waters of Papua New Guinea, is also often described as inactive or waning (c.f. Peacock and Alford, 2018). However, Nautilus Minerals, which has been granted a license to mine this site, describes the vent field activity as “*variable*” in both space and time, and further states that Solwara I and neighboring South Su are “*a dynamic system and there is no durable differentiation of active and inactive areas*” (www.cares.nautilusminerals.com, 2018). Active vents with fluid exit temperatures of 302°C have been documented at this site for over a decade (Tivey et al., 2006; Yeats et al., 2014). These examples demonstrate the need for a clearly defined active versus inactive classification scheme.

DEFINITION OF ACTIVE AND INACTIVE SEAFLOOR MASSIVE SULFIDE DEPOSITS

Criteria to confirm whether a site is hydrothermally active include the presence of fluids discharging at elevated temperatures relative to local ambient seawater, and/or the presence of endemic vent fauna species. Determining whether a deposit is active or inactive with these criteria is relatively straightforward. However, the spatial scale at which these observations apply remains unclear. The recent pilot mining project by JAMSTEC, at an undisclosed location within Japan's exclusive economic zone, occurred at a site described as inactive, with the nearest active chimney "several hundred meters away" (Dr. Tatsuo Nozaki, 2017, www.cbc.ca). Therefore, although the specific extraction target was not venting at the time of the test mining project, it is situated within a hydrothermally-active area. The significance of this is twofold: 1) Nearby vent ecosystems may also be negatively affected by mining activities, especially by fall-out from particle plumes and release of toxic elements; and 2) Similar to volcanoes, hydrothermal vent sites that are not venting may not necessarily be extinct, but simply dormant (volcanoes are classified as dormant if they have not erupted in the past 10,000 years, otherwise they are classified as extinct). Radioisotope dating of the TAG hydrothermal field on the Mid-Atlantic Ridge indicates that the main mound has only be actively venting for between 5,000 and 10,000 years of its estimated 50,000 year history (Lalou et al., 1995). Time series observations at year to decade scales also point to systems that wax and wane, become inactive, and later resume venting. Therefore, any inactive vent site within a greater vent field that is hydrothermally active should be considered to have the potential to resume active venting, and only extinct SMS deposits should be considered for mining. But then what criteria should be used to differentiate truly extinct deposits or vent fields from inactive sites? If volcano activity classification is used as a guide, radioisotope dating to determine the age of most recent venting at a site could be a necessary step towards classifying a deposit as extinct.

It is clear that defining the criteria to classify a seafloor massive sulfide deposit as active or inactive is not a straightforward task, and will require significant consultation from all stakeholders. However, despite the difficulties, this will be an important step towards ensuring the protection of ecosystems hosted at active vents.

Keywords: Seafloor Massive Sulfides, Environmental Protection, Inactive Deposits

References:

Cherkashev, G.A., V. N. Ivanov, V. I. Bel'tenev, L. I. Lazareva, I. I. Rozhdestvenskaya, M. L. Samovarov, I. M. Poroshina, M. B. Sergeev, T. V. Stepanova, I. G. Dobretsova, and V. Yu. Kuznetsov, 2013, Massive Sulfide Ores of the Northern Equatorial Mid_Atlantic Ridge; *Oceanology*, v. 53, No. 5, pp. 607–619.

Jamieson, J.W., Clague, D.A., and Hannington, M.D., 2014, Hydrothermal sulfide accumulation along the Endeavour Segment, Juan de Fuca Ridge, *Earth and Planetary Science Letters*, v. 395, pp. 136-148.

Lalou, C., Reyss, J.L., Brichet, E., Rona, P.A., Thompson, G., 1995, Hydrothermal activity on a 10(5)-year scale at a slow-spreading ridge, TAG hydrothermal field, Mid-Atlantic Ridge 26-degrees-N; Journal of Geophysical Research, Solid Earth, v. 100, pp. 17855–17862.

Peacock, T., and Alford, M.H., 2018, Is Deep-Sea Mining Worth It?, *Scientific American*, pp. 72-77.

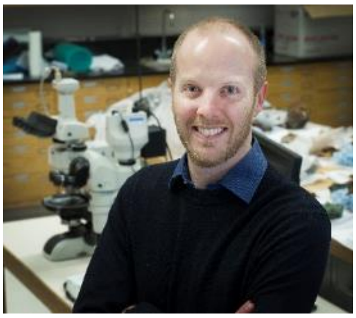
Thal J., Bach W., Tivey M., and Yoerger D.R., 2013, Volcanic and hydrothermal activity of the North Su volcano: New insights from repeated bathymetric surveys and ROV observations: *American Geophysical Union, Fall Meeting* , Abstract 1794263.

Tivey, M.A. and Johnson, H.P., 2002, Crustal magnetization reveals subsurface structure of Juan de Fuca Ridge hydrothermal vent fields; *Geology*, v. 30, pp. 979-982.

Van Dover, C.L., , S. Arnaud-Haond, M. Gianni, S. Helmreich, J.A. Huber, A.L. Jaeckel, Metaxas, A., L.H. Pendleton, S. Petersen, E. Ramirez-Llodra, P.E. Steinberg, V. Tunnicliffe, and H. Yamamoto, 2018, Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining; *Marine Policy* 90, pp. 20–28.

Yeats, C.J., Parr, J.M., Binns, R.A., Gemmell, J.B., and Scott, S.D., 2014, The SuSu Knolls Hydrothermal Field, Eastern Manus Basin, Papua New Guinea: An Active Submarine High-Sulfidation Copper-Gold System; *Economic Geology*, v. 109 (8), pp. 2207-2226.

John W. Jamieson



John Jamieson is a professor and the Canada Research Chair in Marine Geology at Memorial University Newfoundland. John received his Ph.D. in geology from the University of Ottawa in 2013 and was a research scientist in the Marine Mineral Resources research group at GEOMAR from 2013 to 2016, before moving to Memorial University. John's research focuses on the formation of seafloor massive sulfide deposits, with an emphasis on the fate of deposits once active venting has ceased. Radioisotope geochronology techniques are used to determine the age, growth, and oxidation rates of SMS deposits. Another research focus is the application of new AUV-based sensor technology for discovering and mapping active and extinct deposits, and predicting the locations of undiscovered deposits.

Deep Sea Miners' Obligations to Transfer Technology Under UNCLOS and ISA Rules

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INTRODUCTION

Due both to the political history of UNCLOS and the sensitivity of the ocean floor and environment to man made impacts, both the Convention (including also the 1994 Amendment) and subsequent codification (such as the ISA draft code on Exploitation of Mineral Resources in the Area) put a focus on information about, and conveyance of, technology employed by interested deepsea mining companies, to *inter alia* the Authority and developing countries. In contrast, companies usually are (or by their nature should be) interested in safeguarding their technology and business secrets in order to secure unique selling propositions in a competitive environment. On the background of the meanwhile maturing regulatory régimes on deep sea mining, the presentation will look into some of the key regulatory provisions mirroring these apparently antagonistic interests, how the players involved could deal with them, and how they might in some cases be reconciled.

Progress of Presentation

The presentation will start by briefly examining some classical methods of protection of technology, such as patents, copyrights, and (not the least) secrecy. It will be found that some of the statutory means of protection due to their territorial character may face problems in being implemented in areas outside national jurisdiction, such as the Area, but that, thinking globally, they nevertheless retain much of their value for the purpose of protection. Depending on available presentation time, a model case may be used to illustrate the above – and also some of the following – findings.

In a further chapter, the existing regulatory frameworks (such as UNCLOS) as well as the regulatory bodies under development (such as the ISA draft Code on Exploitation) will be scrutinized for rules imposing technology transfer– and technical co-operation obligations upon the companies interested in obtaining a deepsea mining license. The possible impact of such rules on the conduct of the respective companies will be highlighted; it will be shown that both the generality of some of the rules and the different compliance concepts involved (sometimes direct obligations of the contractor, sometimes obligations of the Flag/Sponsoring States to be handed down to the contractor) may at the same time pose an obstacle and an opportunity for the contractor involved.

A next section will briefly outline some of the instruments available to an interested company/contractor to absolve itself of the obligations found, such as the conclusion of license agreements or appropriate intellectual property provisions in development co-operation or joint venture contracts. Some caveats will be mentioned to be aware of in conjunction with the setting up of these contracts.

The presentation will conclude with an outlook on some actual developments suggesting interested companies to position themselves before too long regarding the handling of their technology in the deepsea mining context: Among these developments may be counted (1) the near future need for some holders of exploration licenses under ISA rules to commence exploitation (with the code for this activity still awaiting finalization); (2) the increasing awareness of the world community, in pursuance of the Sustainable Development Goals (SDG), and more particularly SDG14, of a need to reconcile deepsea mining régimes with the concerns about the superjacent watercolumn, the absence of a "common heritage" status of which may lead to increasing pressure on potential contractors to make mining technology transparent; and (3) the fact that ISA, intending to set up a mid term strategy for its further prioritization of actions (https://www.isa.org.jm/files/documents/EN/SPlan/SP-Presentation.pdf), has put the setting up of rules governing the technical assistance for developing countries on a list of nine of the most relevant midterm output goals of its work.

Keywords: Deepsea Mining, Technology Transfer, Intellectual Property, Licenses, UNCLOS, ISA draft Rules on Exploitation of Mineral Resources in the Area

Andreas Kaede

Andreas Kaede is a German lawyer (Rechtsanwalt), based in Gerlingen near Stuttgart, Germany. Born 1956, he studied law in Bonn and received his degrees in 1982 and 1985. After postgraduate assignments at the institutes of international law at the Bonn and Kiel universities (which latter first brought him in touch with the law of the sea) he started a career as corporate lawyer in a large Stuttgart based multinational company. For 27 years he worked predominantly in the field of intellectual property contract drafting, negotiation, and litigation, be it licensing, technical co-operation, or mergers and acquisitions. Since 2008, Andreas Kaede was head of the corporate licensing department of the company, managing and overseeing its IP contract practice on a world wide basis, yet always keeping an eye on UNCLOS and the régimes codified by it. Retiring from the industry function in 2015 he has established private practice in co-operation with the Stuttgart based law firm of Haver & Mailaender Partnerschaft mbB. His present main fields of activity include IP contracts and related strategic consulting, as well as the law of the sea, more specifically deepsea mining, where for the last three years he has been closely following the process toward regulation of the exploitation of minerals from the ocean floor. Moreover, he has given presentations in recent years on matters such as technology transfer in the deepsea mining context on several occasions such as the Deepsea Mining Summit and WOC Sustainable Ocean Summit conferences. Andreas Kaede is a member of the Stuttgart bar association, the Licensing Executives Society

(LES), the German-American Lawyers' Association (DAJV), and the World Ocean Council (WOC).

Towards operational environmental threshold levels for exploitation of mineral resources in the deep sea

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ABSTRACT

This paper discusses operational environmental threshold levels for exploitation of mineral resources in the deep sea. Such criteria are needed to be able to monitor and control deep sea mining with respect to the stringent environmental requirements that are needed. It is recommended to use existing environmental threshold levels for comparable underwater activities. Fields of application are mainly but not exclusively seabed mining operation activities under the governance of the International Seabed Authority (ISA).

The threshold levels and limits mentioned in this paper are proposed recommendations based on other activities than seabed mining but are a proven and accepted approach in other maritime industry activities. An example of such other activities with proven and accepted environmental threshold levels are Oil & Gas exploitation activities in the sea.

Background

The first exploitation of mineral resources in international waters is coming closer. Presently regulations for exploitation for mineral resources in the Area are being developed by the International Seabed Authority (ISA). The ISA regulations will contain the framework related to environmental monitoring of exploitation. However, the regulations will not contain operational environmental threshold levels for the Contractor.

Definitions related to environmental monitoring

Important definitions for the environmental monitoring are described in the (draft) regulations for exploitation for mineral resources in the Area (ISA, 2017a):

"Contract Area" means that part of the Area allocated to a Contractor and delineated in Schedule 1 to an exploitation contract.

"Environmental Effect(s)" means any consequences in the Marine Environment arising from the conduct of Exploitation Activities, being positive, negative, direct, indirect, temporary or permanent, or cumulative effect arising over time or in combination with other mining impacts.

"Environmental Impact Area" means that area of the Marine Environment where Environmental Effects (direct, indirect, or cumulative) are likely to occur as a result of Exploitation Activities, including the Mining Area, adjacent, surrounding and far-field areas as documented in the Environmental Impact Statement.

"Marine Environment" includes the physical, chemical, geological and biological and genetic components, conditions and factors which interact and determine the productivity, state, condition and quality and connectivity of the marine ecosystem(s), the waters of the seas and oceans and the airspace above those waters, as well as the seabed and ocean floor and subsoil thereof.

"Mining Area(s)" means that part or parts of the Contract Area allocated to a Contractor for Exploitation, defined by the coordinates contained in the exploitation contract.

"Mining Discharge" means the disposal, dumping as defined in Article 1 1(5), of the Convention, or release, disposal, spilling, leaking, pumping, emitting, or emptying of sediments, wastes and other effluents, including water evacuated from Minerals during shipboard processing, into the Marine Environment made as an integral part of, or as a direct result of activities in the Area or from shipboard processing immediately above a Contract Area.

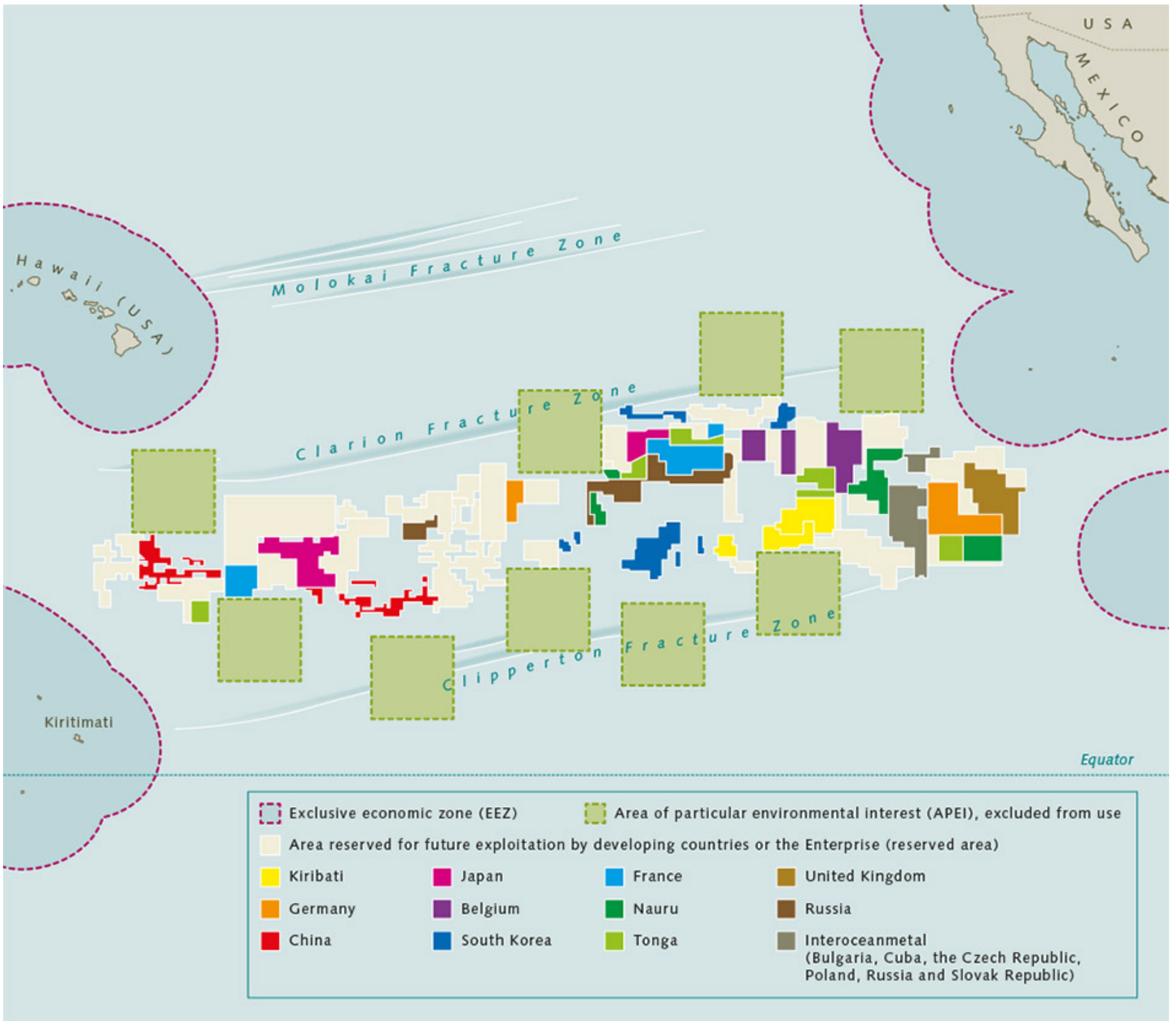

Figure 1. Picture showing the areas for the exploration licences that have been issued by the International Seabed Authority (ISA) in the Clarion-Clipperton Zone (CCZ) in the Pacific. Further the designation of the reserved areas and areas of environmental interest (APEIs) are shown. The CCZ covers an area approximately the size of Europe. https://worldoceanreview.co

"Monitor" or "Monitoring" means the systematic sampling and assessment of the Marine Environment in order to observe, study, detect or measure the Environmental Effects against, where practicable, quantitative and qualitative environmental targets.

"Serious Harm to the Marine Environment" means any Environmental Effect from activities in the Area on the living or non-living components of the Marine Environment and associated ecosystems beyond that which is negligible, or which has been assessed and judged to be acceptable by the Authority pursuant to these Regulations and the relevant rules and regulations adopted by the Authority.

These definitions are important because they delineate the areas of the exploitation project, i.e. the working areas for the contractor and the areas where environmental effects are likely to occur.

What shall be monitored?

Currently the seafloor with its benthic life where the seabed mining takes place and where the strongest environmental impact is expected, is under a special focus of all involved stakeholders in seabed mining. Therefore, the main target of this paper is to describe threshold levels of a possible sediment plume with the accompanying environmental impact around the activities at the seafloor. Also, other impacts like noise, temperature and light will be discussed.

Where should the environmental monitoring take place?

Based on a plume model prepared for the planned seabed mining activities considering the data collected by exploration and verified by testing, an assessment on the possible spreading of sediments shall be made. This outlook shall consider all possible variations that can occur during the exploitation activities (including seasonal variations).

As a minimum, environmental monitoring should include the Environmental Impact Area (the Mining Area, adjacent, surrounding and far-field areas). To avoid conflicts with the mining activities the fixed monitoring stations should be placed on the boundaries of the mining area. The monitoring locations should be based on anticipated current directions, obtained from measurements and plume modelling in the planning phase of the project considering all possible current variations e.g. depending on the season. If there is a prevailing current direction, this should be taken into consideration as well. The monitoring setup shall have the necessary flexibility to adjust for changes in current velocity and direction. Furthermore, the plume model should also be adjusted during the mining operations if any unexpected changes in water conditions would occur.

To have the best overview of the expected water conditions in the mining zone, current measurements as well as CTD (Conductivity, Temperature, Depth (pressure)) measurements should also be performed upstream the current.

If any endangered species have been registered during the preliminary investigations in the Environmental Impact Zone their location and protective measures have to be included in the monitoring program as well.

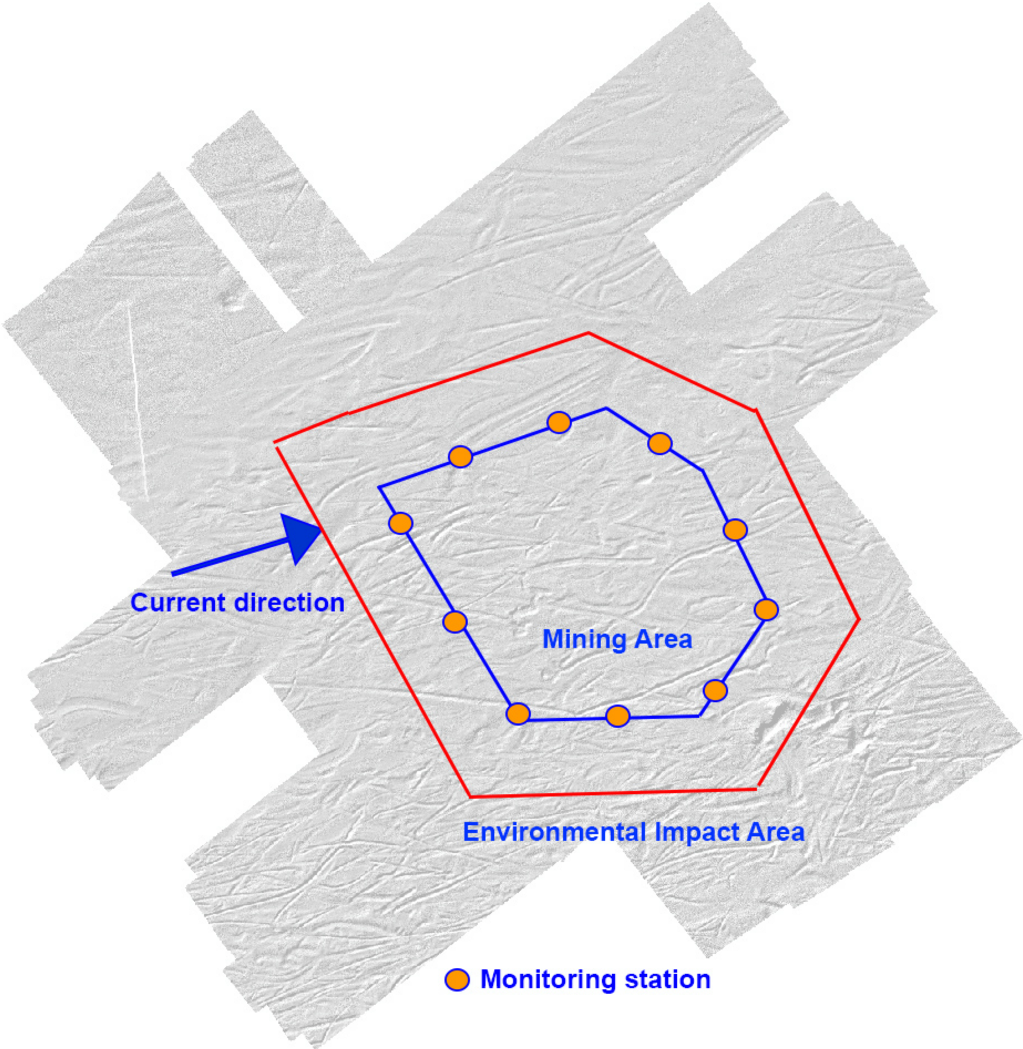

Figure 2. An example of a setup for sediment plume monitoring of a mining area, the blue line representing the boarder of the mining area, and the points representing the monitoring stations. The red line represents the boarder of the environmental impact area.

Which monitoring equipment and parameters should be included and how frequently should they be measured?

The most important monitoring is related to control the spreading of particles from the mining activities. Measurements to control spreading should be real-time to be able to implement mitigating measures immediately.

Turbidity meters (particles)

Online turbidity measurement is an indirect method to measure suspended solid particles by light emission and how the light is reflected. These measurements should be done continuously during the project.

Current meters

Online current meters will give regular measurements on current speed and direction in the water column (profiling meters) or at specific depth (point meters). The current data are used for anticipating spreading of particles and can be used for real-time modelling.

Contaminants

In addition to turbidity it is important to know if the particles are contaminated or not. This should be done regularly by carrying out water sampling and chemical analyses. The sampling should reflect the concentration in the sediment plume, the extent of the sediment plume should be determined by turbidity profiles (horizontal and vertical measurements). Parameters that should be analysed in the water should minimum be heavy metals and other possible contaminants generated by the mining activities.

CTD instrument

In addition to stationary real-time instruments, CTD (Conductivity, Temperature, Depth (pressure)) measurements should be performed. This data will give valuable additional information to interpret water samples and turbidity monitoring data. The CTD can be deployed on a carousel together with water samplers and other instruments such as turbidity meters.

Sediment traps

With sediment traps, long-term effects of spreading of sediments can be studied. Sediment traps collect settling particles. Traps can be placed to measure for shorter periods or the whole length of the mining activity. If the traps have been collecting sediments for the whole length of the mining activity they will indicate the total amount of sediments settled at the trap location. The sediments in the trap can also be chemically analysed to indicate if there has been spreading of contamination.

Noise

Noise may be harmful to aquatic organisms also in deep water. The monitoring can be performed continuously via hydrophones on the seabed.

Temperature

As deep sea organisms are expected to be vulnerable to temperature increase the possible sources of temperature effects (for example by the mining equipment and water discharge) have to be identified and assessed. If such effects are identified a temperature monitoring scheme should be implemented.

Light

Due to the darkness in the deep sea any light will influence the aquatic life. It is anticipated that strong light sources might harm the vision/sensory perception of the local fauna.

What should be the threshold levels?

Turbidity

The threshold levels for turbidity should be based on measured background levels. In other operations that can cause elevated turbidity such as for example dredging, the threshold level for stopping the operation is the background level plus an additional turbidity of for example 10 NTU. There is normally a time limit for the exceedance of the turbidity threshold, for example 30 minutes, to take into account that the amount of particles spread is the particle density (turbidity) multiplied with the time that the spreading takes place.

Naturally the turbidity and sediment load in the direct vicinity of an underwater mining activity is very high, whereas for defined distances a threshold level of < 10 mg/l could be set as it is used for shallow water sand mining (German Federal Agency for Nature Conservation, 2006).

Contaminants

For water the EU has through the EU Water Framework Directive described how to set "threshold values" for marine water quality. Such values have for example been set by the Norwegian Environment Agency.

Class	**I**	**II**	**III**	**IV**	**V**
	Background	**Good**	**Moderate**	**Bad**	**Very bad**
Metals					
Arsenic (µg As/L)	<2	2 – 4.8	4.8 – 8.5	8.5 - 85	>85
Lead (µg Pb/L)	<0.05	0.05 – 2.2	2.2 – 2.9	2.9 - 28	>28
Cadmium (µg Cd/L)	<0.03	0.03 – 0.24	0.24 – 1.5	1.5 - 15	>15
Copper (µg Cu/L)	<0.33	0.3 – 0.64	0.64 – 0.8	0.8 – 7.7	>7.7
Chromium (µg Cr/L)	<0.2	0.2 – 3.4	3.4 - 36	36 - 360	>360
Mercury (µg Hg/L)	<0.001	0.001 - 0.048	0.048 - 0.071	0.071 – 0.14	>0.14
Nickel (µg Ni/L)	<0.5	0.5 – 2.2	2.2 - 12	12 - 120	>120
Zinc (µg Zn/L)	<1.5	1.5 – 2.9	2.9 - 6	6 - 60	>60

Figure 3. Norwegian guidelines on classification of environmental water quality in fjords and coastal waters. Norwegian Environment Agency guideline 2229/2007.

Sediment traps

Sediment traps are useful to check the total amount of particles that are spread outside the mining area. This can be calculated as the total amount that is spread per day (in kg) multiplied with the total amount of mining days. The threshold level should be set at a level where no harm is done to the environment. E.g. for monitoring of drilling activities in areas with presence of cold water corals the sediment coverage is proposed to be below 10 mm in total to avoid considerable exposure (DNV, 2013).

Noise

Guidelines for offshore activities have suggested threshold levels for noise which can be adapted to deep sea activities. The threshold levels are mainly based on several studies about the different effects on larvae, fish and mammals which show that high noise levels can be stressful, harmful or even mortal. For ramming of piles into the seabed a noise level ≤ 150 dB(Mlf) at 100 m may be a starting point for seabed mining as well (Department of Planning, South Australia, 2012).

Temperature

To minimize adverse effects by temperature increase a temperature model for all underwater machinery and water discharges close to the seabed should be developed and assessed. If no other threshold levels are available, the temperature increase should not be more than 1 °C at the distance of 10 m from the temperature source.

Light

Excessive use of light in the deep sea should be avoided. For light no threshold levels are suggested, but in general the use of light should be kept to a minimum. Furthermore, it should be assessed if other solutions for navigation, orientation and operation control can be applied, like infrared, sonar etc.

Method for estimating the particle transport out of the mining area

For the calculation of spreading of contaminants from the mining area, the mining area is modelled as a polygon as shown in Figure 4 (defined by the blue line). On each of the line segments of the polygon there is one or several monitoring stations. The data collected from the monitoring station(s) on each segment represents the information on particle transport (flux) going out of that segment. By adding up the sediment transport out of each segment the total sediment transport out of the mining area can be calculated. To be able to do this also the height of the plume going out of each segment has to be known. This is done by measuring vertical turbidity profiles in each segment.

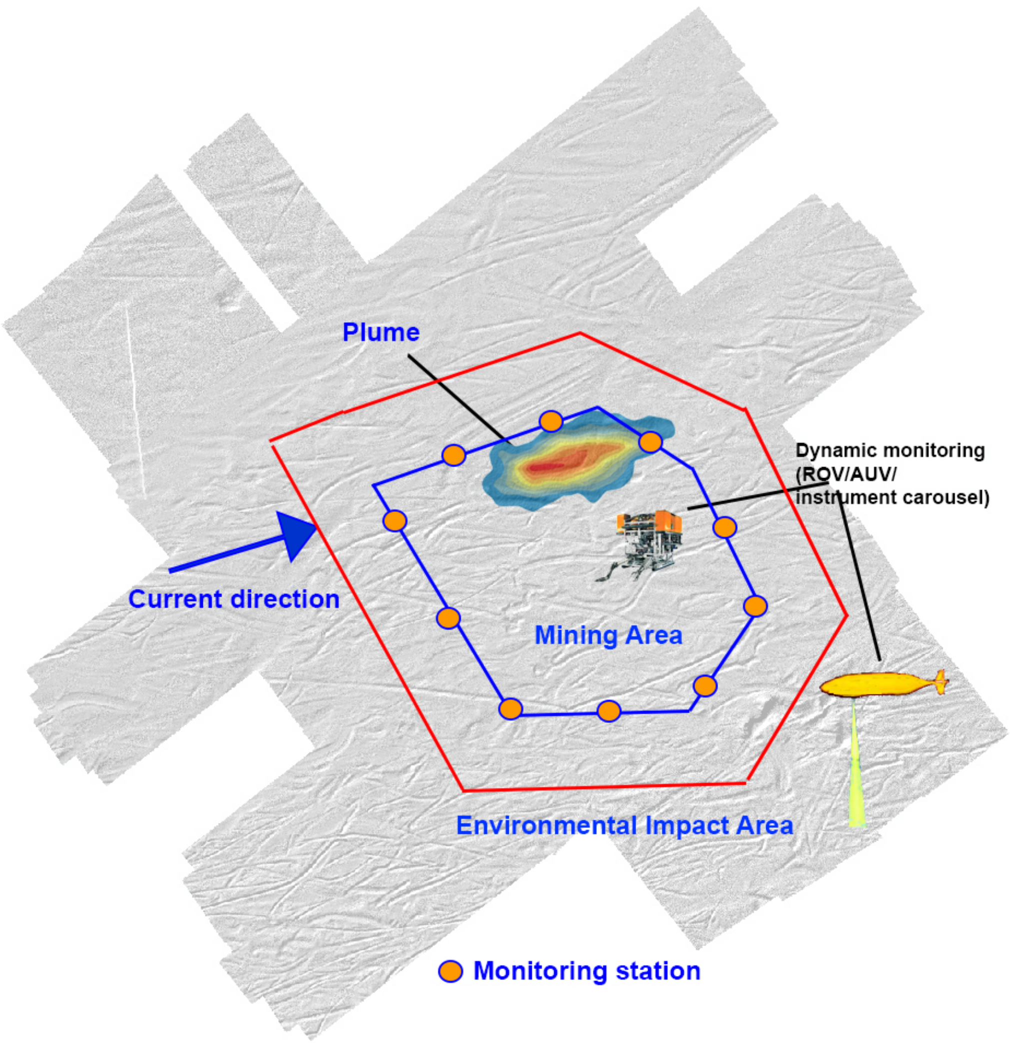

Figure 4. The polygon that encloses the mining area (blue line). Inside the polygon the turbidity plume from an ongoing activity on the seabed is visualized. The red line visualizes the environmental impact area.

Exceedance of threshold levels due to rapidly increasing current velocities

There will be a risk for periodic sudden changes in current velocities due to eddies, a natural phenomenon that is well known in the southern Pacific. Such eddies can reach to very large water depths and influence deep sea mining. In worst case such eddies can cause spreading of particles far beyond normal conditions on the seabed. This could also lead to exceedance of threshold levels for the actual mining site and cause stop in the activities.

Early warning mechanisms are important to avoid excessive spreading of particles during strong eddies. This means that not only current measurements are important but also models based on predictions from measured meteorological and hydrographical data.

Further information can be obtained by local current monitoring networks, for example by having current meters 1 km away from the mining area to give an early warning (about an hour before with typical current velocities).

Other environmental impacts

There are also other environmental impacts related to the operations of the surface vessel or the transport system, examples of such are:

- Release process water at the surface
- Release of transport water from deep sea (if a riser system with a fluidized transport is used)
- Return of mine tailings to the seabed (if separation of tailings takes place on the vessel)

All these planned impacts have to be monitored as well in a suitable way.

Conclusions

Operational environmental threshold levels for exploitation of mineral resources in the deep sea are needed. This is a first proposal trying to identify environmental threshold levels for seabed mining.

The threshold levels are based on experiences from other maritime industry activities than seabed mining where there are already existing and accepted threshold levels. There are still uncertainties how the deep sea environment will be affected by seabed mining. The proposed threshold levels have to be continuously updated according to new knowledge about the effects of seabed mining.

References

Department of Planning, Transport and Infrastructure, South Australia (2012). Underwater Piling Noise Guidelines.

DNV (2013). Monitoring of Drilling Activities in Areas With Presence of Cold Water Corals. Report for Norsk Olje og Gass. Report no: 2012-1691.

DNV GL (2016). Recommended Practice - Managing environmental aspects and impacts of seabed mining. DNV GL-RP-O601.

Federal Agency for Nature Conservation / Berlin University of Technology, Germany (2006). Ecological Research on Offshore Wind Farms: International Exchange of Experiences.

International Seabed Authority (2017a). Draft regulations for exploitation for mineral resources in the Area. ISBA/23/LTC/CRP.3*.
http://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/ISBA23-LTC-CRP3-Rev.pdf

International Seabed Authority (2017b). Developing a regulatory framework for mineral exploitation in the Area. A Discussion Paper on the development and drafting of

Regulations on Exploitation for Mineral Resources in the Area (Environmental Matters). https://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/DP-EnvRegsDraft25117.pdf

Norwegian Environment Agency (2007). Guidelines on classification of environmental quality in fjords and coastal waters – A revision of the classification of water and sediments with respect to metals and organic contaminants. Guideline 2229/2007 (in Norwegian).

Keywords: environmental threshold levels, environmental impact, exploitation, mineral resources, deep sea mining

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He is currently the leader of DNV GLs project group for Seabed Mining.

Towards operational environmental threshold levels for exploitation of mineral resources in the deep sea

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ABSTRACT

This paper describes operational environmental threshold levels for exploitation of mineral resources in the deep sea. Such criteria are needed to be able to monitor and control deep sea mining with respect to the stringent environmental requirements that are needed. It is recommended to use existing environmental threshold levels for comparable activities where such are existing. Fields of application are mainly but not exclusively seabed mining operation activities under the governance of the International Seabed Authority (ISA).

The threshold levels and limits mentioned in this paper are proposed recommendations based on other activities than seabed mining but are a proven and accepted approach in other maritime industry activities. An example of such other activities with proven and accepted environmental threshold levels are Oil & Gas exploitation activities in the sea.

Background

The first exploitation of mineral resources is coming closer. At the moment regulations for exploitation for mineral resources in the Area are being developed by the International Seabed Authority (ISA). The ISA regulations will contain the framework related to environmental monitoring of exploitation. However, the regulations will not contain operational environmental threshold levels for the Contractor.

Definitions related to environmental monitoring

Important definitions for the environmental monitoring are described in the (draft) regulations for exploitation for mineral resources in the Area (ISA, 2017a):

"Contract Area" means that part of the Area allocated to a Contractor and delineated in Schedule 1 to an exploitation contract.

"Environmental Effect(s)" means any consequences in the Marine Environment arising from the conduct of Exploitation Activities, being positive, negative, direct, indirect, temporary or permanent, or cumulative effect arising over time or in combination with other mining impacts.

"Environmental Impact Area" means that area of the Marine Environment where Environmental Effects (direct, indirect, or cumulative) are likely to occur as a result of Exploitation Activities, including the Mining Area, adjacent, surrounding and far-field areas as documented in the Environmental Impact Statement.

"Marine Environment" includes the physical, chemical, geological and biological and genetic components, conditions and factors which interact and determine the productivity, state, condition and quality and connectivity of the marine ecosystem(s), the waters of the seas and oceans and the airspace above those waters, as well as the seabed and ocean floor and subsoil thereof.

"Mining Area(s)" means that part or parts of the Contract Area allocated to a Contractor for Exploitation, defined by the coordinates contained in the exploitation contract.

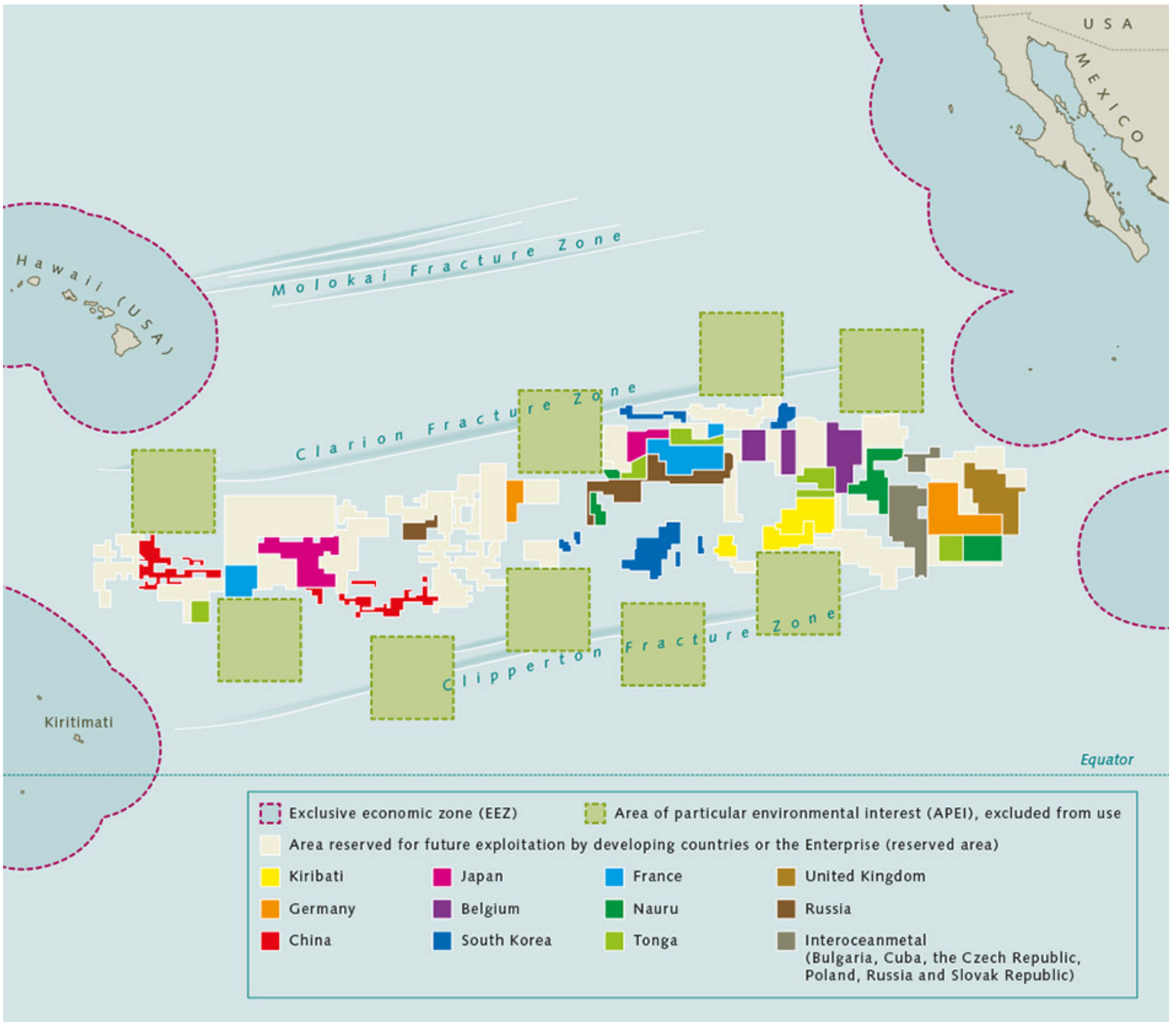

Figure 1. Picture showing the areas for the exploration licences that have been issued by the International Seabed Authority (ISA) in the Clarion-Clipperton Zone (CCZ) in the Pacific. Further the designation of the reserved areas and areas of particular environmental interest (APEIs) are shown. The CCZ covers an area approximately the size of Europe. https://worldoceanreview.co

"Mining Discharge" means the disposal, dumping as defined in Article 1 1(5), of the Convention, or release, disposal, spilling, leaking, pumping, emitting, or emptying of sediments, wastes and other effluents, including water evacuated from Minerals during shipboard processing, into the Marine Environment made as an integral part of, or as a direct result of activities in the Area or from shipboard processing immediately above a Contract Area.

"Monitor" or "Monitoring" means the systematic sampling and assessment of the Marine Environment in order to observe, study, detect or measure the Environmental Effects against, where practicable, quantitative and qualitative environmental targets.

"Serious Harm to the Marine Environment" means any Environmental Effect from activities in the Area on the living or non-living components of the Marine Environment and associated ecosystems beyond that which is negligible, or which has been assessed and judged to be acceptable by the Authority pursuant to these Regulations and the relevant rules and regulations adopted by the Authority.

These definitions are important because they delineate the areas of the exploitation project, i.e. the working areas for the contractor and the areas where environmental effects are likely to occur.

What shall be monitored?

Currently the seafloor with its benthic life where the seabed mining takes place and where the strongest environmental impact is expected is under a special focus of all involved stakeholders in seabed mining. Therefore, the main target of this paper is to describe threshold levels of a possible sediment plume with the accompanying environmental impact around the activities at the seafloor.

Where should the environmental monitoring take place?

Based on a plume model prepared for the planned seabed mining activities considering the data collected by exploration and verified by testing an assessment on the possible spreading of sediments shall be made. This outlook shall consider all possible variations that can occur during the exploitation activities (including seasonal variations)

As a minimum environmental monitoring should include the Environmental Impact Area (the Mining Area, adjacent, surrounding and far-field areas). To avoid conflicts with the mining activities the fixed monitoring stations can be placed on the boundaries of the mining area. The monitoring locations should be based on anticipated current directions, obtained from measurements and plume modelling in the planning phase of the project considering all possible current variations e.g. depending on the season. If there is a prevailing current direction, this should be taken into consideration as well. The monitoring setup shall have the necessary flexibility to adjust for changes in current velocity and direction. Figure 2 shows an example of a setup for monitoring.

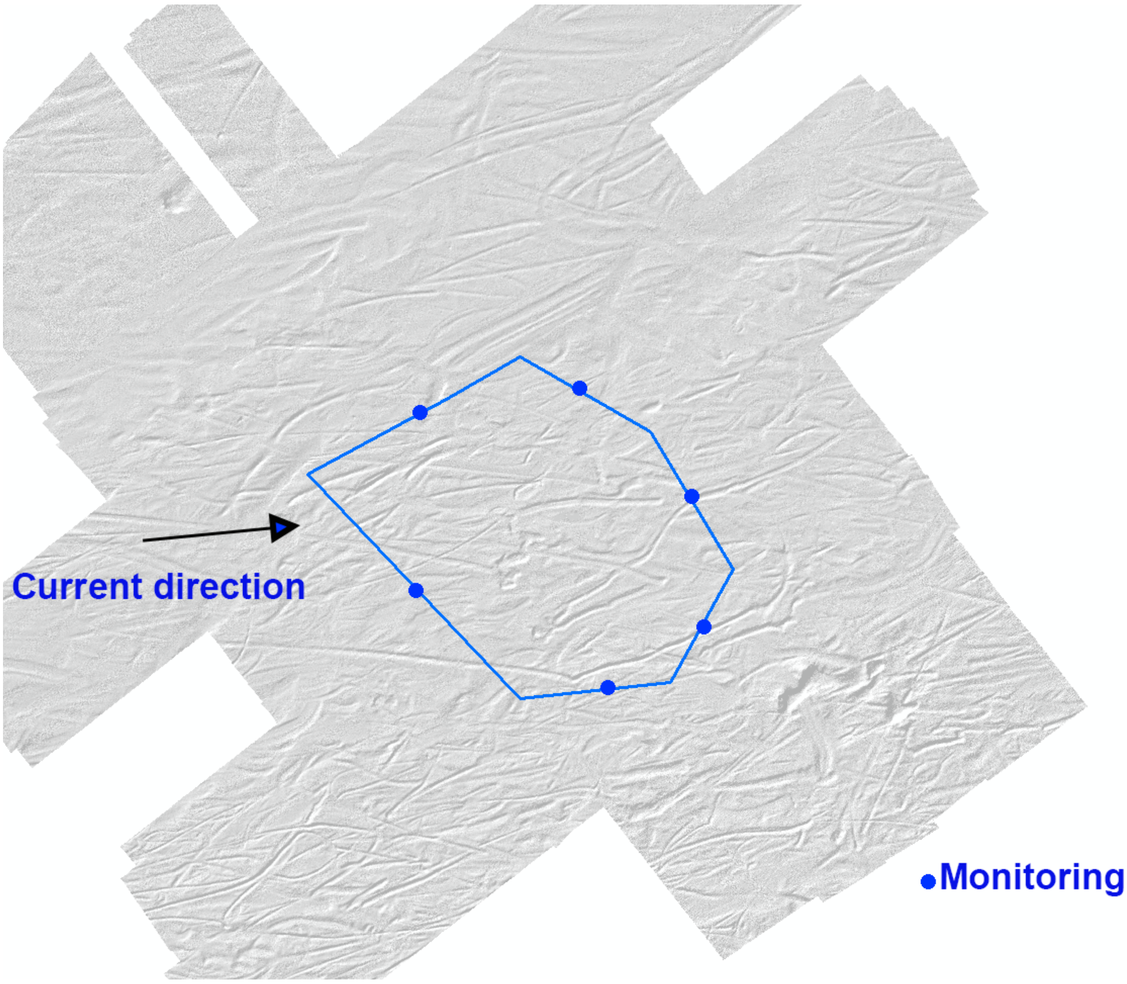

Figure 2. An example of a setup for monitoring a mining area, the blue line representing the boarder of the mining area, and the blue points representing the monitoring stations.

If any endangered species have been registered in the preliminary investigations they have to be included in the monitoring program.

Which monitoring equipment and parameters should be included and how frequently should they be measured?

The most important monitoring is related to control the spreading of particles from the mining activities. Measurements to control spreading should be real-time to be able to implement mitigating measures immediately.

Turbidity meters (particles)

Online turbidity measurement is an indirect method to measure suspended solid particles by light emission and how the light is reflected. These measurements should be done continuously during the project.

Current meters

Online current meters will give regular measurements on current speed and direction in the water column (profiling meters) or at specific depth (point meters). The current data are used for anticipating spreading of particles and can be used for real-time modelling.

Contaminants

In addition to turbidity it is important to know if the particles are contaminated or not. This should be done regularly by carrying out water sampling and chemical analyses. The sampling should reflect the concentration in the sediment plume, the extent of the sediment plume should be determined by turbidity profiles (horizontal and vertical measurements). Parameters that should be analysed in the water should minimum be heavy metals and other possible contaminants generated by the mining equipment.

CTD instrument

In addition to stationary real-time instruments, CTD (Conductivity, Temperature, Depth (pressure)) measurements should be performed. This data will give valuable additional information to interpret water samples and turbidity monitoring data. The CTD can be deployed on a carousel together with water samplers and other instruments such as turbidity meters.

Sediment traps

With sediment traps long-term effects of spreading of sediments can be studied. Sediment traps collect settling particles. Traps can be placed set up to measure for shorter periods or the whole length of the mining activity. If the traps have been collecting sediments for the whole length of the mining activity they will indicate the total amount of sediments settled at the trap location. The sediments in the trap can also be chemically analysed to indicate of there has been spreading of contamination.

What should be the threshold levels?

Turbidity monitoring: The threshold levels for turbidity should be based on measured background levels. In other operations that can cause elevated turbidity such as for example dredging the threshold level for stopping the operation is the background level plus an additional turbidity of for example 10 NTU. There is normally a time limit for the exceedance of the turbidity threshold, for example 30 minutes, to take into account that the amount of particles spread is the particle density (turbidity) multiplied with the time that the spreading takes place.

Water sampling: For water the EU has through the EU Water Framework Directive described how to set "threshold values" for marine water quality. Such values have for example been set by the Norwegian Environment Agency.

Sediment traps: Sediment traps are useful to check the total amount of particles that are spread outside the mining area. This can be calculated as the total amount that is spread per day (in kg) multiplied with the total amount of mining days. The threshold level should be set at a level where no harm is done to the environment.

Method for estimating the particle transport out of the mining area

For the calculation of spreading of contaminants from the mining area, the mining area is modelled as a polygon as shown in Figure 3 (defined by the blue line). On each of the line segments of the polygon there is a monitoring station in the middle of the line. The data collected from each monitoring station represents the information on particle transport (flux) going out of that segment. By adding up the sediment transport out of each segment the total sediment transport out of the mining area can be calculated. To be able to do this also the height of the plume going out of each segment has to be known. This is done by measuring vertical turbidity profiles in each segment.

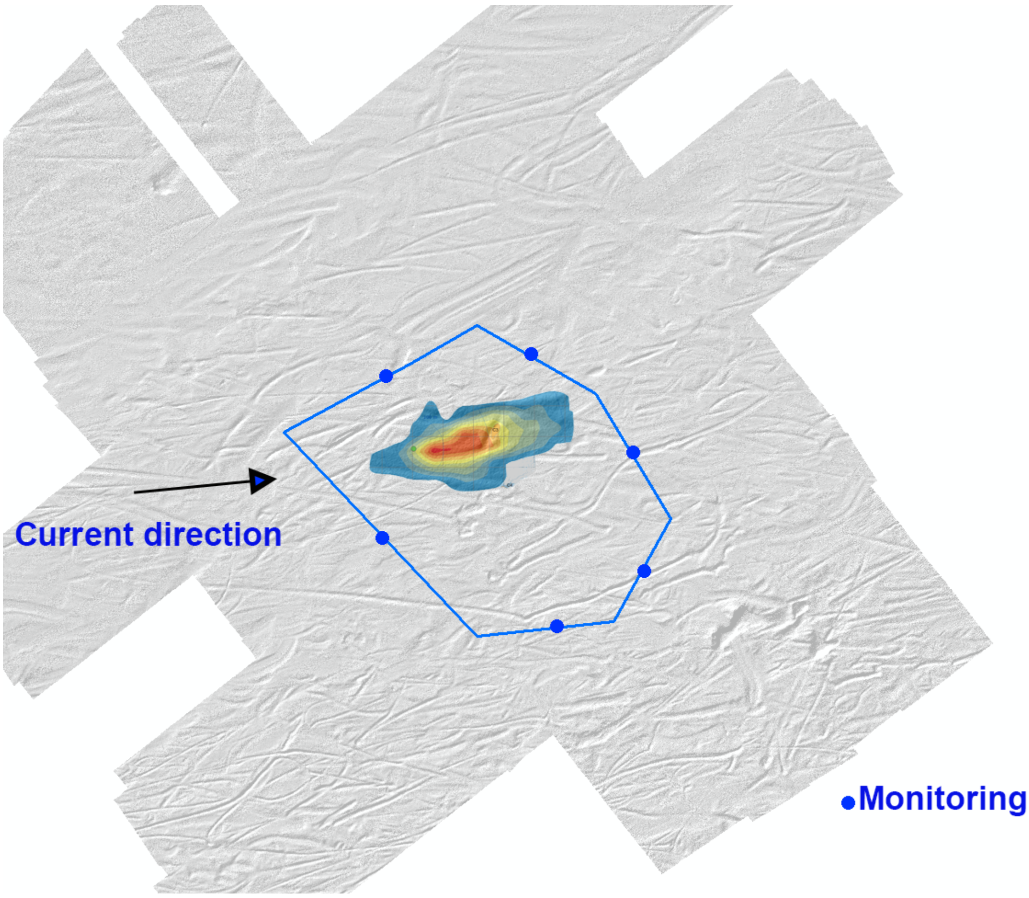

Figure 3. The polygon that encloses the mining area (blue line). Inside the polygon the turbidity plume from an ongoing activity on the seabed is visualized.

Exceedance of threshold levels due to rapidly increasing current velocities

There will be a risk for periodic sudden changes in current velocities due to eddies, a natural phenomenon that is well known in the southern Pacific. Such eddies can reach to reach to very large water depths and influence deep sea mining. In worst such eddies can cause spreading of particles far beyond normal conditions on the seabed. This could also lead to exceedance of threshold levels for the actual mining site and cause stop in the activities.

Early warning mechanisms are important to avoid excessive spreading of particles during strong eddies. This means that not only current measurements are important but also models based on predictions from measured meteorological and hydrographical data.

Further information can be obtained by local current monitoring networks, for example have current meters 1 km away from the mining should be able to give an early warning (about an hour before with typical current velocities).

Other environmental impacts

There are also other environmental impacts related to the operations of the surface vessel or the transport system, examples of such are:

- Release process water at the surface
- Release of transport water from deep sea (if a riser system with a fluidized transport is used)
- Return of mine tailings to the seabed (if separation of tailings takes place on the vessel)

All these planned impacts have to be monitored as well in a suitable way.

Conclusions

Operational environmental threshold levels for exploitation of mineral resources in the deep sea are needed. This is a first proposal trying to identify environmental threshold levels for seabed mining.

The threshold levels are based on experiences from other maritime industry activities than seabed mining where there are already existing and accepted threshold levels.

References

DNV GL (2016). Recommended Practice - Managing environmental aspects and impacts of seabed mining. DNV GL-RP-O601.

International Seabed Authority (2017a). Draft regulations for exploitation for mineral resources in the Area. ISBA/23/LTC/CRP.3*. http://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/ISBA23-LTC-CRP3-Rev.pdf

International Seabed Authority (2017b). Developing a regulatory framework for mineral exploitation in the Area. A Discussion Paper on the development and drafting of Regulations on Exploitation for Mineral Resources in the Area (Environmental Matters). https://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/DP-EnvRegsDraft25117.pdf

Keywords: environmental threshold levels, environmental impact, exploitation, mineral resources, deep sea mining

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He is currently the leader of DNV GLs project group for Seabed Mining.

Free-Hanging vs Free-Standing Seabed Mining Vertical Transport Systems

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ABSTRACT

Deepsea Mining will soon become a reality with Nautilus Minerals getting their equipment ready to mine SMS at Solwara 1 off the coast of Papua New Guinea.

The vertical transport system (VTS) adopted by Nautilus consists of a riser hanging ‘freely’ from the mining production vessel with a lifting pump unit suspended at its lower end. A compliant jumper connects the pump to the seabed crawler without restraining its movements. In this free-hanging VTS arrangement, the vessel can be re-positioned to follow the crawler should it want to extend the mining area and start stretching the jumper.

A recently proposed alternative to this is a free-standing VTS whereby the riser is grounded on the seabed with a base and maintained in an upright position by distributed buoyancy modules or a buoyancy tank at the top. A compliant jumper connects the seabed crawler to the riser base, and another connects the riser top to the vessel. In this free-standing arrangement, the entire VTS can be lifted clear of the seabed for relocation to a new mining area.

This paper will describe the important features of the two options and discuss the advantages and disadvantages in respect of riser dynamic behavior, water depth, weather and mining windows, pump maintenance, installation and retrieval, continency measures, etc. The two systems will also be appraised separately for mining SMS and SMnN deposits.

Keywords: Deepwater, Mining, Riser

Frank Lim

Frank Lim was a Global Director of 2H Offshore, a company that has pioneered technologies for riser systems that are now deployed in deepwater regions around the world. He now assumes the role of Principal Advisor and is also a professor at the China University of Petroleum in Beijing.

Frank's offshore engineering career began in 1983 upon gaining a PhD in the UK, and continued through numerous oil and gas projects in the North Sea, Gulf of Mexico, West Africa and Brazil, until about a decade ago when he turned his interests to deepwater projects in the Asia Pacific, supporting them from the 2H Kuala Lumpur and Beijing offices he set up in the region.

Since 2007, he has been leading all 2H projects in seabed mining riser design in different parts of the world, including Papa New Guinea, Pacific Ocean, Black Sea and South Indian Ocean.

A fellow of the UK Institution of Mechanical Engineers and Royal Institution of Naval Architects, Frank is a regular author of technical papers and speaker at conferences.

Draft Exploitation Regulations: Commercial Viability

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ABSTRACT

An examination of the draft Exploitation Regulations from an investor's perspective. We will look at the commercial requirements of the investment community (debt and equity) in order to provide funding to a deepsea mining project, and contrast this with the position put forward in the draft Exploitation Regulations. We will then recommend suggested amendments to the Exploitation Regulations to assist future investment on this growing industry.

Keywords: Legal, Financing, Commercial, Economical, Investment, Debt, Equity

Eleanor Martin

Eleanor Martin is a banking and finance lawyer based in London. She has detailed experience in advising on offshore equipment (including FPSOs and drilling rigs) financing, whether of a project finance, asset finance, project bond or corporate nature.

Eleanor has structured and completed financings of offshore equipment operating in the North Sea, offshore Brazil, Norwegian Continental Shelf, offshore Nigeria, offshore Western Australia and offshore Angola.

Eleanor currently sits on the advisory board of Blue Nodules and has advised a number of deep sea mining companies on structuring investments into projects for harvesting activities in the clarion clipperton zone in the Pacific Ocean.

Eleanor has spent time on secondment with two major European banks (including the offshore desk of one of them). She is recognised by *Chambers UK 2017* as a leading individual for offshore finance who has "expertise in financing offshore assets including FPSOs, drilling rigs and support vessels" and impresses clients with her "sharp, pragmatic and thinking outside of the box" approach.

The Nauru Ocean Resources NORI D Campaign 3 Survey: meeting client needs in a new market- Fugro's first commercial AUV, geotechnical, and resource survey for polymetallic nodules in the CCZ

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INTRODUCTION

Fugro completed its first project supporting deep-sea polymetallic nodule exploration under a contract awarded by seafloor mineral company Nauru Ocean Resources Inc., (NORI), a subsidiary of DeepGreen Metals Inc., in June 2018. The project area is located in the prolific, nodule-rich, Clarion Clipperton Zone (CCZ) in the Pacific Ocean, approximately 1,300 km south of San Diego, California. A milestone for Fugro, the work represents one of the first commercial AUV surveys in the CCZ.

Prospecting for deepwater marine minerals in a commercial (non-research) market is not easy or cheap. This is why, in part, much of the work in this new frontier has been done with subsidized scientific and academic vessels and equipment. As the industry eventually shifts to a commercial market, the challenge for private sector marine site characterization companies is to offer technical efficiencies and new value-added custom technologies in a cost-efficient package.

The NORI survey of the NORI D area was the first survey for polymetallic nodules for which Fugro had been approached to offer competitive solutions using our deep water marine site characterization assets, data interpretation, and geoscience capability. Rather than perform the survey from one of our own vessels, Fugro was asked to prepare solutions that would be deployed off the deepwater anchor handling tug supply vessel, OSV *Maersk Launcher*. Fugro offered the Fugro *EchoSurveyor VII* AUV geophysical and photogrammetric survey platform (Figure 1) and operations team, along with personnel for survey, offshore data processing and management, geotechnical testing, data interpretation, and field mineral sampling.

The survey mobilized out of San Diego, California in early April 2018. The transit for sea trials commenced on April 14. The *Maersk Launcher* arrived back in San Diego for demobilization after survey completion on June 3rd, 2018.

The NORI D Campaign 3 Geophysical, Geotechnical, and Resource Assessment Survey

Background

NORI has been collecting data and conducting studies that will ultimately contribute to a feasibility study for a deep-sea polymetallic nodule mining project in the NORI D area. NORI conducted exploratory vessel-based (hull-mounted) multibeam echosounder (MBES) survey and bulk sampling activities over NORI D during 2012. This work confirmed the presence of nodules and supported historical grade and nodule abundance data documented by Pioneer Contractors during the 1970's.

The purpose of the program was to use ultra-high resolution geophysical data and camera imagery to select a collector test site in the NORI D tenement, collect mineral samples to support an updated mineral resource assessment, obtain geotechnical measurements, and opportunistically acquire environmental data.

The resolution of vessel-based bathymetric and acoustic backscatter data, together with historical seafloor sampling data was sufficient to define broad areas with a combination of suitable topography, geological substrate and evidence of nodule abundance. From these data, a number of sites were provisionally identified as suitable candidates for future collector trials.

AUV survey methods were identified as the best technological fit for follow-up investigation at a site-survey scale, with the capability of providing co-registered multi-sensor datasets at the appropriate resolutions necessary to confidently select the most suitable trial-site and provide a framework on which to build associated ongoing engineering and environmental studies.

Campaign 3 was the third marine investigation of the NORI D area by NORI. The survey was designed by NORI, Margin, and AMC Consultants, and adapted in consultation with Fugro to fit the survey timeline and technical objectives.

Simultaneous Operations with AUVs

Fugro has been offering commercial AUV surveys since the late 1990s for the deepwater oil and gas sector. Typically, these surveys were performed for deepwater oil and gas site characterization and for archaeological surveys. For more than a thousand dives, the mode of operation has been to deploy the AUV to the mission and follow the AUV with the vessel to provide the AUV with the required position corrections to adjust for eventual drift in the AUV inertial navigation system. Fugro had not, to date, ever left an AUV to perform a mission while the vessel engaged in another activity.

It was seen that value could be added to this project if Fugro could operate the AUV within an array of underwater transponders that could give the AUV the needed corrections to counter navigational drift for precision AUV data collection. Fugro had past experience with setting up underwater beacons for deepwater construction survey needs but had not used beacons with its AUV fleet.

As the scope and needs developed, Fugro offered the AUV to NORI in truly autonomous mode that would allow an expansion of the scope of work that NORI could accomplish within this survey campaign. Fugro, at the time, was looking at this mode of operating the AUV as an internal innovation and improvement initiative. In preparation for this survey, sea trials were run in the Gulf of Mexico for this mode of operation, so that the capability could be offered in the remote CCZ for NORI.

This mode of operation allowed the AUV to do detailed mapping of the collector test site, while simultaneously collecting large box core samples that could provide the basis for an indicated resource assessment.

Survey Objectives

The key objectives of the AUV survey program were to conduct detailed bathymetric, sonar imaging - MBES backscatter and side scan sonar (SSS), and photogrammetry surveys to help facilitate:

- Identification and selection of a suitable area for subsea collector test trials. This required mapping of nodule distribution and detailed topographic mapping to identify areas conducive to mining system design constraints.
- Collection of sufficient geological and geotechnical data to ensure future sampling and collector test programs are appropriately designed and that trial mining performance can be assessed.

- Collection of appropriate seafloor imagery to assist with selection of suitable environmental monitoring sites – particularly for physical oceanographic mooring studies.
- Identification of environmental baseline reference zones. An important consideration is that the habitat of these reference sites is similar in character to the site that will be selected for the mining trial.

There were four main AUV survey focus areas with different acquisition parameters:

- Reconnaissance lines were collected at a 35 m AUV altitude to assess geological and near-surface conditions prior to acquiring low-altitude camera data. These data were also used to select the collector test site location and to assess the designated Preservation Reference Zone (PRZ) areas within the NORI D tenement.
- Camera lines were run at a 6 m AUV altitude to map the distribution and abundance of the nodules. These data were also used to select the collector test site location.
- Within the collector test area, data were collected at a 22 m altitude and were used to evaluate geologic and near-surface conditions for future collector test activities.
- Within the mooring sites, data were collected at a 90 m altitude and were used to evaluate geologic and near-surface conditions for future metocean data mooring locations.

The distribution of the survey focus areas is shown in Figure 2. An example of the increased resolution of the AUV geophysical data over the existing good quality 12 kHz hull-mounted multibeam echosounder is shown in Figure 3 and AUV camera data showing individual nodules is shown in Figure 4.

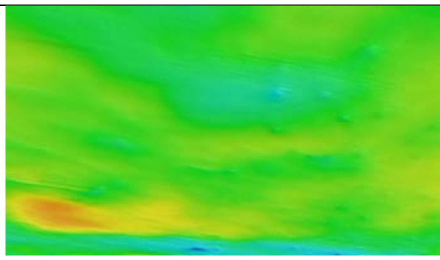
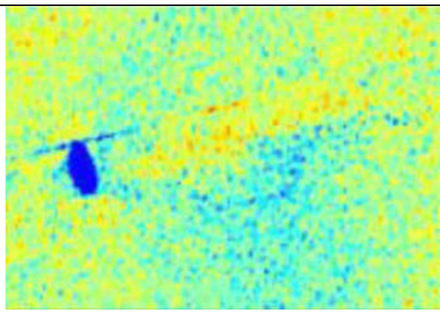
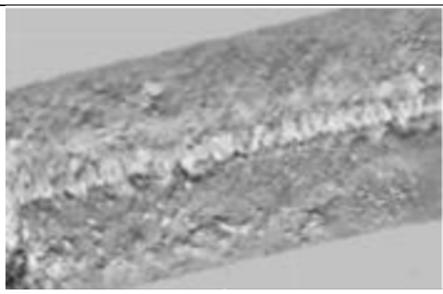
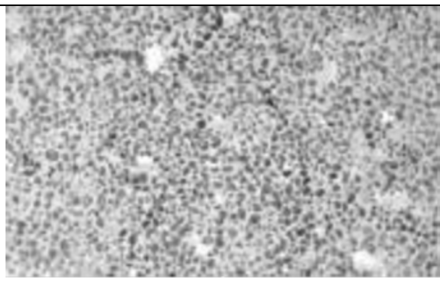
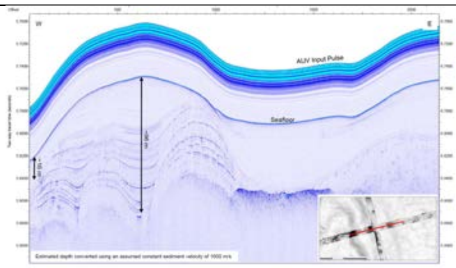
Equipment Used

The Fugro *EchoSurveyor VII* Autonomous Underwater Vehicle (AUV) is a Hugin 1000 rated to 4500 m depth (Figure 1). The payload deployed in the NORI D Campaign 3 was:

AUV Payload	
Kongsberg EM 2040 Multibeam Echosounder (MBES)	200-400 kHz frequency; 0.7° by 0.7° array; 160° swath angle
Edgetech 2205 Side Scan Sonar (SSS)	240 kHz, 540 kHz, and 1600 kHz frequencies.
Edgetech DW-106 and 424 Full Spectrum Chirp Sub Bottom Profiler (SBP)	1-6 kHz and 4-24 kHz frequency modes
Allied Vision GE4000 Digital Camera system	35 mm digital equivalent format; 5 frames per second

Figure 1. Fugro EchoSurveyor VII Autonomous Underwater Vehicle being recovered onto OSV Maersk Launcher during the NORI D Campaign 3 AUV and Geotechnical Survey.

The main data outputs and uses from *EchoSurveyor VII* are listed on the following table.

Main Data Outputs	Uses	Example
Bathymetry (water depth) in meters	- Assess seafloor morphology - Identify geologic features	
Backscatter (acoustic energy scatter) in decibels or relative intensity	- Identify hard or soft areas of the seafloor - Define nodule types and indicative abundances	
Side scan sonar	- Identify geologic features - Assess relative hardness or softness of the seafloor	
Camera imagery	- Identify the distribution and abundance of polymetallic nodules	
Subbottom profiler (ultra-high resolution) seismic data	- Penetrates to depths up to 100 m below seafloor - Assess buried stratigraphy and structural geology	

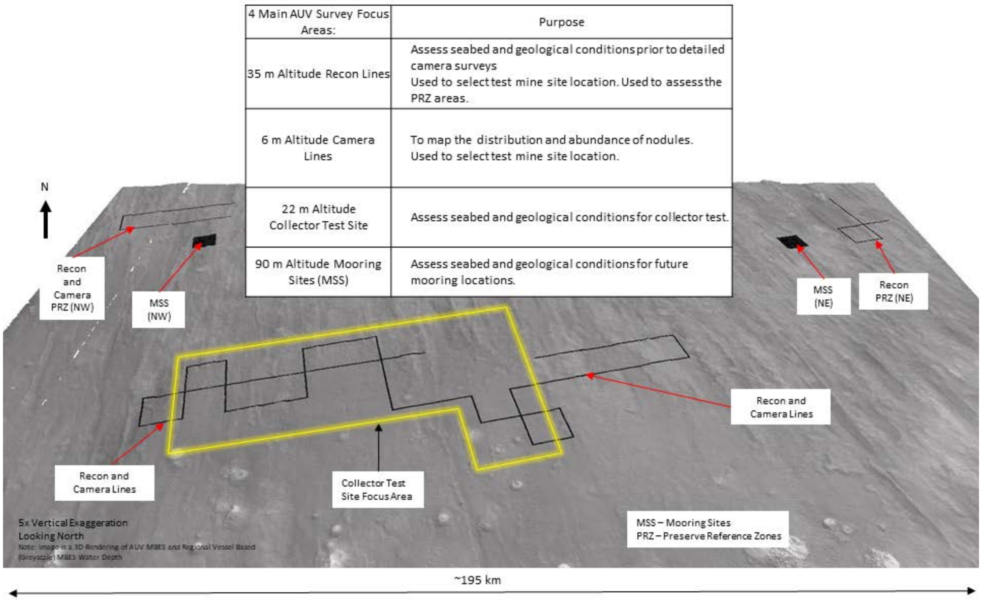


Figure 2. Perspective view of NORI D Campaign 3 geophysical program showing reconnaissance and camera lines, mooring site surveys, Preservation Reference Zone (PRZ) reconnaissance and camera surveys, and collector test focus area.

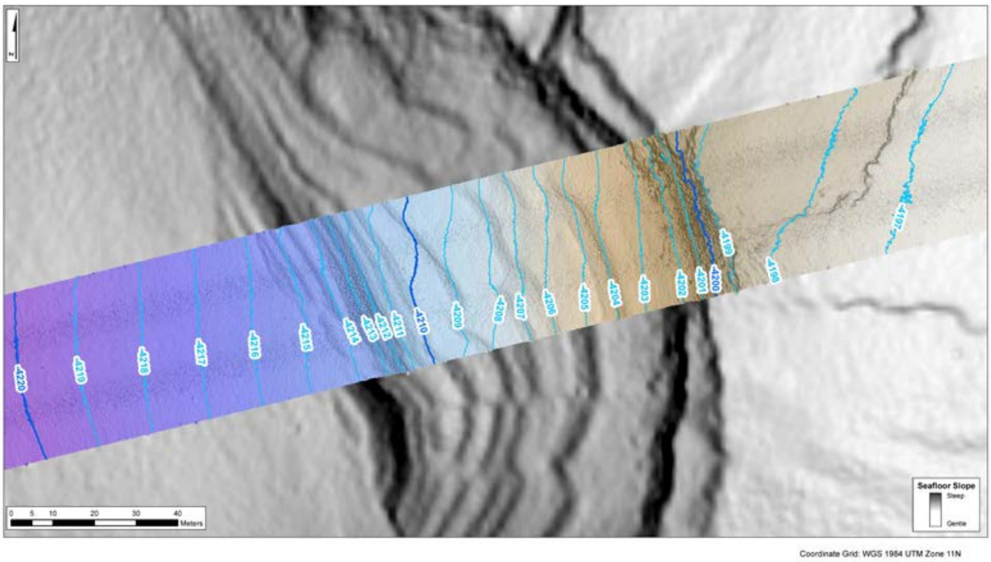


Figure 3. Image shows the resolution difference of shaded relief high-resolution AUV bathymetry (purple to brown) acquired from Fugro EchoSurveyor VII draped over 12 kHz regional hull-mounted bathymetry (greyscale).

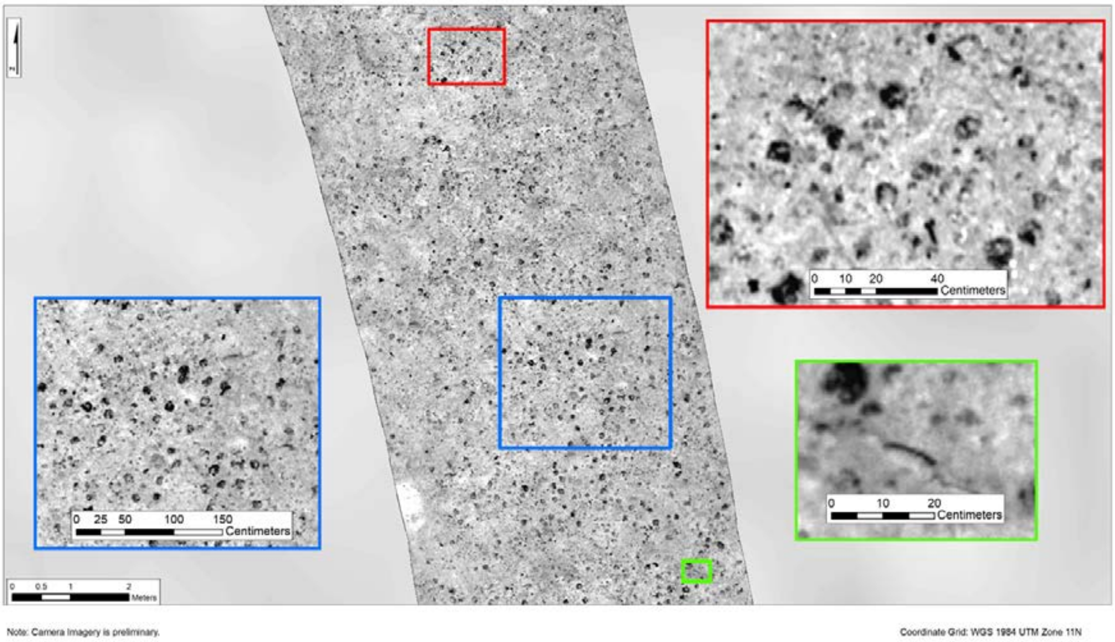


Figure 4. Preliminary camera imagery from reconnaissance camera lines processed in the field showing high quality, high resolution imagery of polymetallic nodules and biologic features.

Mineral Sampling and Geotechnical Program

The seafloor sampling program was designed to collect nodule samples to support an updated mineral resource assessment. Forty-five (45) grid points were selected for box core samples based on a regular 7 km grid across detailed survey area (Figure 5). An ultra-short base line (USBL) transponder was fixed onto the box core (Figure 6). Box cores were then navigated to the pre-defined grid points as efficiently as possible and dropped to the seafloor if the navigation position fix was within 35 m of the grid target location. Photographic or geophysical information regarding nodule abundance was specifically not used during selection of the landing sites in order to avoid biasing the samples towards nodule-rich locations. For the 45 box cores, the mean distance between the grid target location and actual box core position was 18.4 m plus or minus 7.9 m.

Opportunistic box coring was utilized en route to the survey areas depending on nodule processing time, AUV downtime, and transit time. However, most of the box cores were acquired during simultaneous operations, in which the AUV would be deployed for a ~21 hour mission during which box cores would be taken and processed before returning to retrieve the AUV.

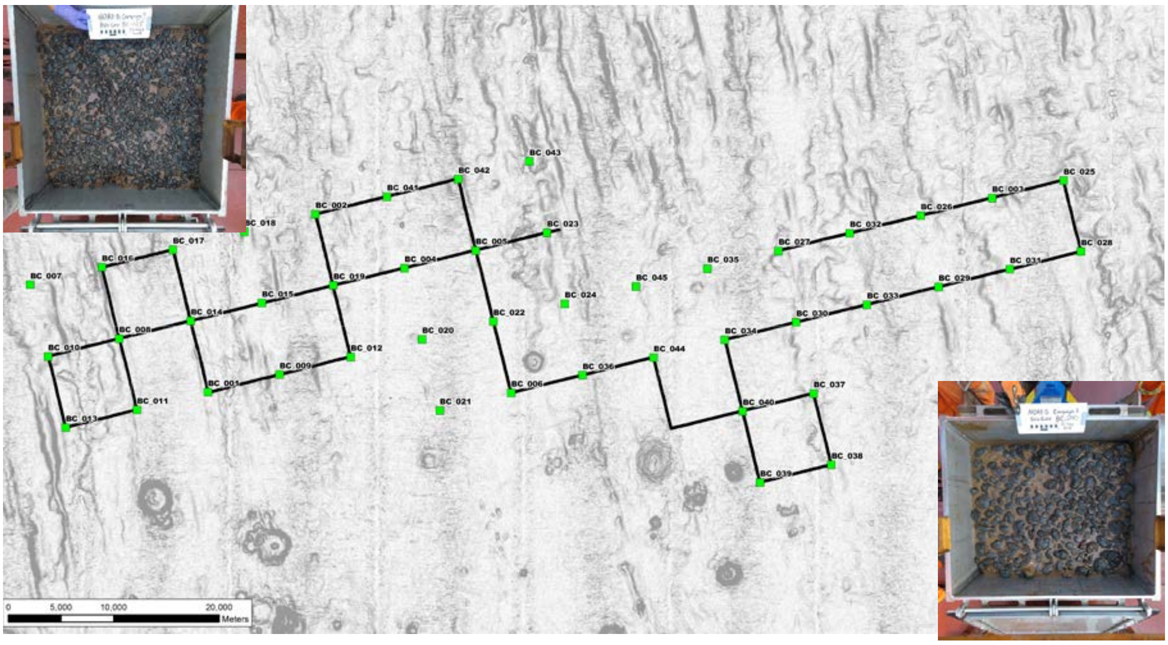


Figure 5. Forty-five box core samples taken during NORI D Campaign 3. Background imagery is 12 kHz multibeam echosounder. AUV lines are also shown. Inset photographs show typical box core in situ polymetallic nodule distribution.

Sampling Equipment

The box core is the preferred marine soils sampling device for taking representative in situ samples of the seabed for shallow geotechnical studies and the best method for retrieving polymetallic samples for resource evaluation and environmental studies. For the NORI D Campaign 3, the samples were acquired with a large-form 0.75 m^2 box core built by K.C. Denmark A/S (Figure 6). The box core used in NORI D Campaign 3 is unusually large. The most common size for box core sampling is a 0.25 m^2 corer whereas the corer used in the campaign obtains a sample three times the area (0.75 sq m). This was selected based on analysis of expected nodule size and determination of the required sample size to obtain an adequate sample for determination of nodule abundance.

Figure 6. 0.75 m^2 Box Core manufactured by K.C. Denmark A/S used for mineral sampling, geotechnical tests, and opportunistic environmental sampling for NORI D Campaign 3. Photo on right shows USBL transponder attached to box core frame.

Geotechnical Testing

The geotechnical program consisted of obtaining box cores to provide a sampling of the near-seafloor soils. Basic offshore index and strength laboratory tests, comprised of soil descriptions, wet density measurements, and undrained shear strength index tests (torvane tests and intact and residual miniature vane tests) were conducted on the geotechnical subsamples obtained from the box cores. It is important to note that the target for geotechnical sampling was the soil matrix and purposefully excluded the mineralized nodules at the seafloor. For most box cores, nodules were removed before taking geotechnical samples. The field laboratory tests were performed in general accordance with ASTM (2017).

The samples were brought back to Fugro's geotechnical laboratory for further testing. The field test results and further laboratory testing will be used to establish geotechnical parameters at the proposed collector test site.

Environmental Sampling

Thirty-five (35) box cores were sampled for environmental parameters and biology. A biology team from ERIAS Pty. Ltd., was contracted by NORI and coordinated box core processing with the Fugro geoscience team during the survey. Characterization of the environmental and biologic sampling results are not integrated into this conference paper. The box cores were processed for nodule biota and megafauna and chemical samples were taken. It should be noted that the high-resolution camera imagery worked well to image megafauna that would not be captured within a box core. Transects through Protected Reference Zones (PRZ) were surveyed with the AUV.

Mineral Sampling

A mineral sampling and onboard processing protocol was developed so that the good quality mineral samples could be used to estimate mineral resources for the NORI D area. Sampling methods and documentation were designed to meet international mineral resource reporting standards. To this end, the mineral sampling program for Campaign 3 produced a complete record of the samples collected in the box core program including abundance (kg/m^2), vertical distribution (i.e. at surface or buried), wet weight, wet density, dimensions and morphology, and a photographic record of all nodules collected.

Each nodule was individually counted per depth layer and described based on the following characteristics: shape, texture, fragmentation, and development of botryoidal texture.
Two electronic scales were set up with reference weights on dynamic mode to compensate for the movement on the vessel. Nodules were weighed in batches to reduce random error from low mass samples and to reduce processing time. Five (5) dynamic weights were taken per batch and averaged for the final batch weight represented in the data sheet. Wet density of the nodules was determined by weight and volume displacement.

All nodules from the box core were photographed by layer using a graticule with color calibrations to have a complete photographic record of the nodules (Figure 7).

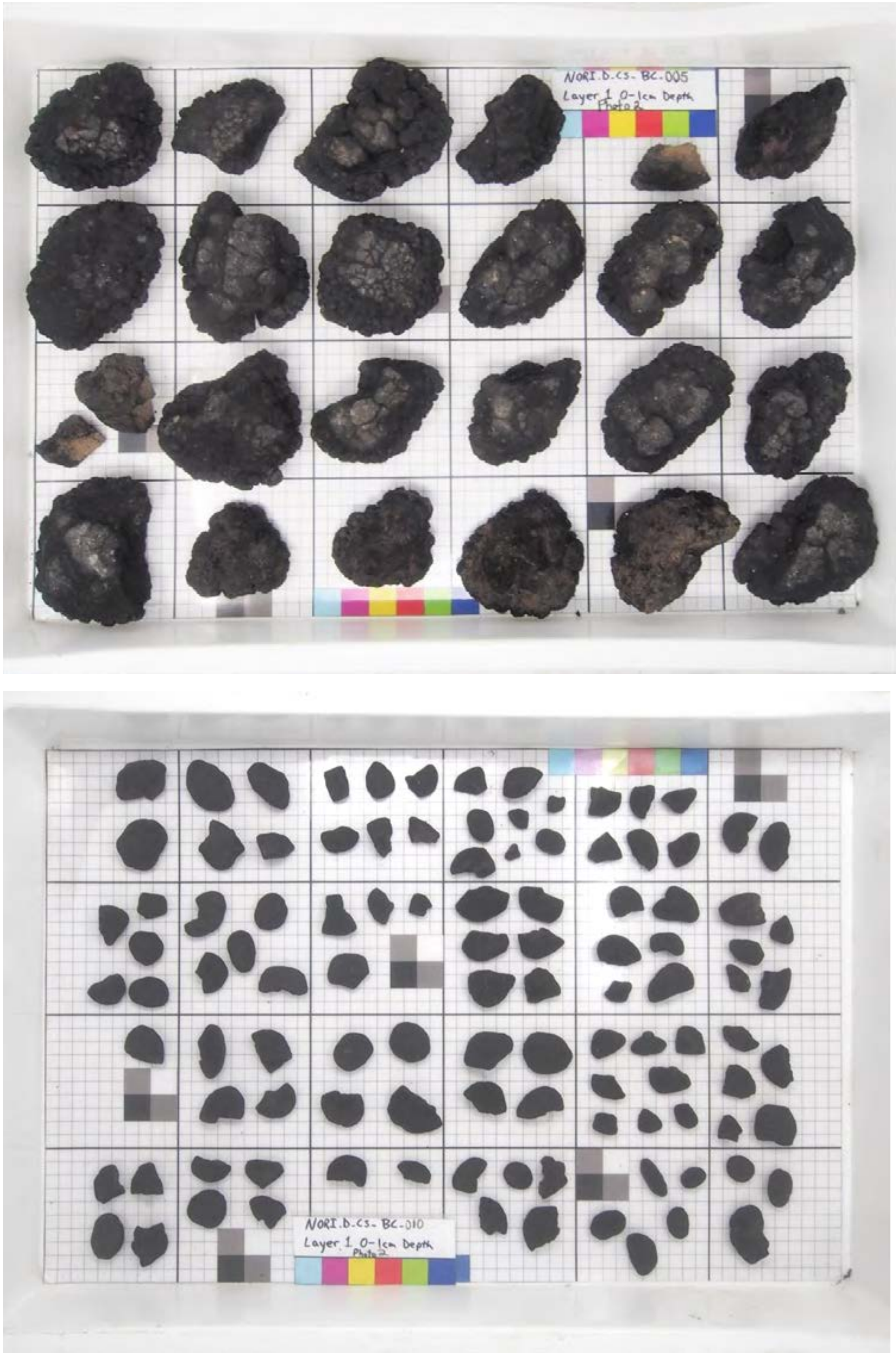


Figure 7. Examples of the photographic record of the nodules taken during NORI D Campaign 3.

After careful data QC (principally a comparison of the nodule count to the count in the photographic record and reweigh of the surface nodules) the nodules were recombined by box core location and split for laboratory assay (Figure 8). If the yield was high enough, and almost all were, the mineral samples were coned and quartered to produce a reference sample and an assay sample. The assay sample was then recombined and large nodules were crushed to uniform size. The sample was then coned and quartered to produce four splits for resource assessment: primary lab, secondary lab, duplicate primary lab, and duplicate secondary lab.

Figure 8. Cone and quarter of samples for distribution for laboratory analysis.

A bar code system was developed to track the samples. Samples were tagged, bagged, and heat sealed. Samples were weighed offshore and reweighed on land upon arrival in San Diego. The weights of the samples made offshore compared to those made on land were, on average, within 0.12%.

Onboard Data Processing and Interpretation with Geoscience Support

An additional mission critical service that added value to the NORI D Campaign 3 survey was the ability to process and interpret the massive amount of camera and geophysical data (over 15 TB) while building a high quality interpretational GIS database, so that NORI could develop and make an informed decision about where to locate an optimal collector test site during the survey. To this end, Fugro deployed a team of specialist marine site characterization geologists and used new methodologies for automatic nodule detection and high-resolution feature-based navigation correction.

Relationship of Nodule Type and Abundance to Camera and Geophysical Data

Relationships between physical measurements of nodule abundance and size and the photographic and geophysical data were developed after the fact, and in predictive mode for the planned locations. Individual nodules were not resolvable by either the 12 kHz or 200 and 400 kHz multibeam echosounder data but areas with distinct 12 kHz backscatter and 200 kHz backscatter do appear to correlate with nodule abundances and size variations found in the 45 box core samples.

Meeting the Campaign 3 Objectives

A total of 2,286 line-km of data was acquired with the AUV, covering an approximate 375 km^2 area of the seafloor.

Initial reconnaissance AUV traverses were conducted over the candidate collector test sites using MBES, SSS and Sub-Bottom Profiler payloads to provide confirmation of topographic and geological features observed in the vessel-based MBES dataset, but at a much higher level of detail and confidence. These traverses were then followed by low-altitude surveys using the AUV’s camera payload to provide visual confirmation of nodule distribution.

The reconnaissance traverses were also designed to provide continuity between proposed sampling sites based on a non-biased rectilinear sampling grid. A key component to the success of the campaign was the ability to conduct simultaneous operations while the AUV was underway with detailed survey of the selected collector test site through use of a UTP (Underwater Transponder Protocol) seafloor acoustic positioning array. This enabled the collection of a total of 45 box cores over the sampling grid throughout the campaign. This data is currently being used to update the resource estimation and for geotechnical assessment purposes.

Onboard data processing and preliminary data interpretation of the reconnaissance dataset enabled a rapid decision-making process with respect to identifying the most appropriate area for the detailed site-survey. A high-resolution full-coverage MBES, SSS, and SBP survey, supplemented with camera transects, was acquired over this site at <30 cm bin size.

Insights

- The AUV camera payload data enabled the continuity of nodule distribution to be mapped between physical sampling locations.
- Of note was the density of distribution of the nodules observed within the field-of-view of the camera transects, showing a dominantly closely-packed nodule distribution.
- There was also good correlation between both visual and physical sample nodule distribution and high-resolution AUV MBES backscatter acoustic facies.
- Both AUV camera and MBES backscatter data also showed notable nodule distribution in areas previously interpreted from vessel-based MBES backscatter data to be of lower-potential.

Key Results

- Successful selection and mapping of trial mining site.
- Acquisition of 45 box cores with visual continuity (AUV camera survey data) provided between physical sample locations.
- Selection of environmental baseline reference zones with similar bathymetric morphology as the trial mining site.
- AUV bathymetric data confirmed that the vessel-based MBES was of sufficient resolution to enable siting for oceanographic moorings to be used in a long-term environmental monitoring study.

Disclaimer

The purpose of this extended abstract is to provide supplemental information about the NORI D Campaign 3 survey to accompany the oral presentation at the 2018 Underwater Mining Conference and should not be used for any other purposes.

Acknowledgements

The authors would like to thank Anthony O'Sullivan, NORI, for supporting this survey, this conference submission and for permission to show data examples as well as Samantha Smith and Jon Machin of NORI for their guidance and contributions to the survey design. The authors would also like to thank: Scott Wilson, Morten Frostholm Larsen, and the crew of the *Maersk Launcher* for operations support; Tim Farrow, Chad Pastor, Bruce Aucoin, Melissa Jeansonne, among others in Houston and Lafayette at Fugro for shoreside support; Jeff Croucher and Will Blalock for data processing and management during the field program; Larry Fluke and K.C. Gan for offshore and onshore geotechnical work. Finally, a well-deserving thanks to the survey and AUV technical specialists on the Fugro field crew.

Keywords: AUV, AUV operations, box core, CCZ, polymetallic nodules, high resolution geophysics, data integration.

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Dan is a marine geologist with over 20 years of experience with main areas of interest in seafloor mapping and geochemistry surveys, deepwater site characterization, marine mineral exploration, and methane hydrate exploration. He has authored or co-authored over 40 articles about marine geochemical survey methods, site characterization, and methane hydrate characterization and exploration. Dan participated in the site selection and science party in the landmark Chevron-US Department of Energy gas hydrate drilling expedition in the Gulf of Mexico in 2009. Dan serves on the U.S. Department of Energy Methane Hydrate Advisory Committee. In 2016, Dan was able to go offshore on the MarMine seafloor massive sulfide exploration cruise on the Arctic Mid-Ocean Ridge, and recently lead the geoscience team on the NORI 2018 Geophysical and Geotechnical Survey in the CCZ.
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Christine Devine is a supervising geoscientist with experience in geohazard identification and risk assessment for various subsea site characterization projects. She possesses over 15 years of experience interpreting geological, geophysical, and geotechnical data and has a background in the mineral exploration and mining industry. Christine participated as a member of the geoscience team on the NORI D Campaign 3 Geophysical and Geotechnical Survey in 2018. She has a B.Sc and M.Sc in Geology and is registered as a professional geoscientist in both Newfoundland, Canada and Texas, USA.

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Ian provides expertise to the Seafloor Minerals industry, with a focus on innovation development and knowledge creation from exploration through to mining phase.

He has over 29 years industry experience in the Seafloor Minerals Exploration and Mining Industry, and has extensive experience with various commodities including: sea floor massive sulphides, marine diamonds, marine placer gold, polymetallic nodules, base metal and bulk-commodity marine minerals. During his career he has held the position of Innovation Lead – Exploration and Chief Geophysicist at Nautilus Minerals, Chief Geophysicist at Neptune Minerals, and Global Exploration Targeting Manager and Technical Lead – Geophysics at De Beers Marine. He has been engaged as a freelance consultant to the marine minerals industry for the past 6 years, and was the NORI Client Representative on the NORI 2018 Survey

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AMC Consultants

Ian Lipton, Principal Geologist and Geometallurgy Practice Leader, has more than 30 years of experience in mining geology, resource evaluation, and exploration. Ian's mining expertise includes resource estimation, feasibility studies, technical audits and reviews, due diligence studies, Independent Technical Specialist Reports, and valuations. Ian completed the first publicly-reported estimate for a seafloor massive sulphide deposit (Solwara 1, Papua New Guinea) and has been a consultant for a number of seafloor projects, including polymetallic nodule projects in the northeast Pacific Ocean and sea floor sediments in the Black Sea. Ian has a B Sc. Geological Sciences from the University of Birmingham, UK and is a Fellow of the Australasian Institute of Mining and Metallurgy.

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Kathryn Rovang is a geoscientist and GIS analyst with experience in integrated site characterization involving interpreting geophysical, geological, and geotechnical data using various software packages. She possesses 3 years of experience in various GIS applications, specifically in the realm of database management, high resolution data manipulation and analysis, python scripting for automated tool workflows, and developing multiple software suite workflows for data processing both in web-based and desktop platforms. Kathryn participated as a member of the geoscience team on the NORI D Campaign 3 Geophysical and Geotechnical Survey in 2018. She has a B.S in Anthropology and a B.S in Geology and Geophysics; as well as, a GIS Analyst II certification.

A Comparison of Terrestrial and Seabed Mineral Resources for Cobalt

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ABSTRACT

Recent focus by terrestrial mineral explorers (and investors) on cobalt has increasingly highlighted the future critical need for this metal, with new-age batteries being the primary utilisation.

We present an overview of the world's current terrestrial cobalt resources and put this in perspective of currently known seabed resources, particularly polymetallic nodule and crust deposits. We focus on comparison of the key exploration, development and exploitation risks for such deposits, and provide a framework for financial evaluation and appraisal.

Keywords: cobalt, seabed resources, dredge sampling, grab sampling, box core, gravity core, piston core, vibrocore, surface drilling, seabed drilling, representative sampling.

World's First Lifting Test for Polymetallic Sulphides in the EEZ of Japan

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ABSTRACT

Seafloor polymetallic sulphides are distributed in the EEZ of Japan, including substantial deposits in the Okinawa Trough and Izu-Bonin back-arc basin. In this new frontier, the successful development of these resources in Japan is expected to bring about a new domestic supply of mineral resources. The initial stages of this development are authorized by the Basic Plan on Ocean Policy, approved by the Japanese Cabinet on April 26, 2013, and the Plan for the Development of Marine Energy and Mineral Resources, formulated by the Ministry of Economy, Trade and Industry (METI) on December 24, 2013.

In 2008, the Japan Oil, Gas and Metals National Corporation (JOGMEC), commissioned by METI, began a survey and technological development programme for the development of the seafloor polymetallc sulphides (PMS) based on these Plans. The examination of four different fields: the evaluation of the amount of the resource, environmental assessment, mining technology, and processing & smelting technology, are concurrently promoted, aiming for commercialization as soon as possible.

Based on the results of research for properties of geomorphology and marine environments of the target test sites in the Okinawa trough, which have been ongoing for several years, the preparation of the pilot lifting test included an in-situ excavation and crushing test conducted using test excavating and crushing systems.

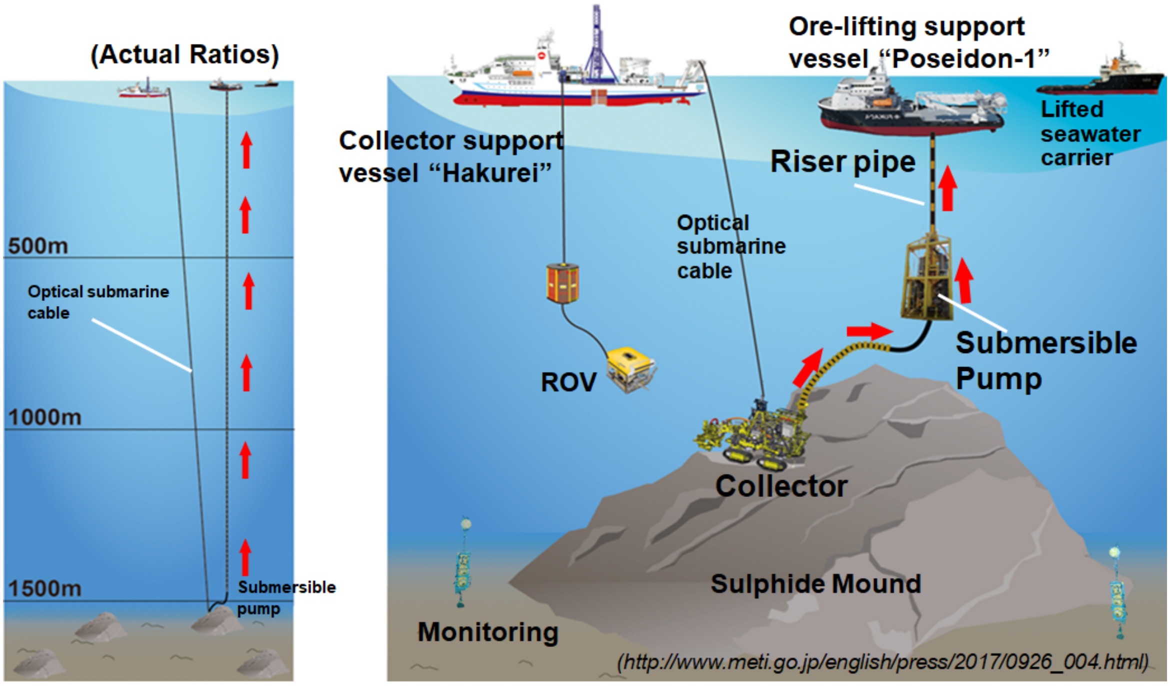
Following this, and taking the opportunities of good weather conditions during the period prior to late September 2017, they collected the crushed ore, and then, continuously lifted the ore to above sea level from a depth of approximately 1,600m and onto the ore-lifting support vessel (Poseisdon-1) using a submersible pump and an ore-lifting riser pipe, thereby providing technical verification and data acquisition concerning a series of steps of this system. A total of about sixteen wet tons of sulphide ore and artificial ore were collected on the ore lifting support vessel.

Thus, the objectives of the test, to verify the technologies for continuous ore lifting together with slurry water from the deposit site and to acquire extensive monitoring data from these operations were successfully accomplished. To this end, JOGMEC meticulously organized conditions according to the purposes of the test, including crushing ore to the appropriate size distribution to prevent clogging of the pump, manual adjustment of the density of target ore to seawater, and conducting the test only during the period when established hydrographic threshold conditions were met.

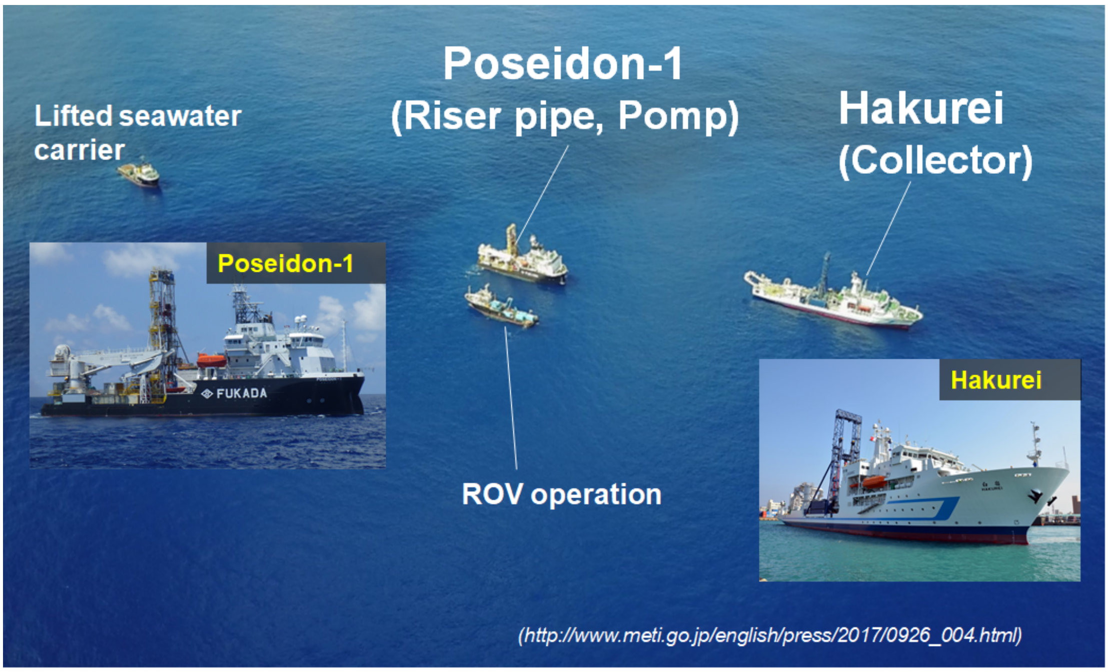
Prior to the test, environmental assessment was carried out including environmental baseline surveys, development of prediction model and analysis of genetic connectivity using biological samples. In addition, even during and after the test, JOGMEC also conducted environmental monitoring to measure and evaluate the impact of the test on the environment.

In conclusion, the ore-lifting test was successful, and this success constitutes a big step toward proving the viability of future deep-sea mining. However, it is only one of many steps necessary for the establishment of deep-sea mining. Issues still to be addressed in commercial mining include technical and environmental fields such as a buffer system for a better controlled slurry concentration, in-situ crushing and separation technologies for control of grain size for the lifting of the ore, the development of an internationally acceptable EIA procedure, and other technical and regulatory challenges.

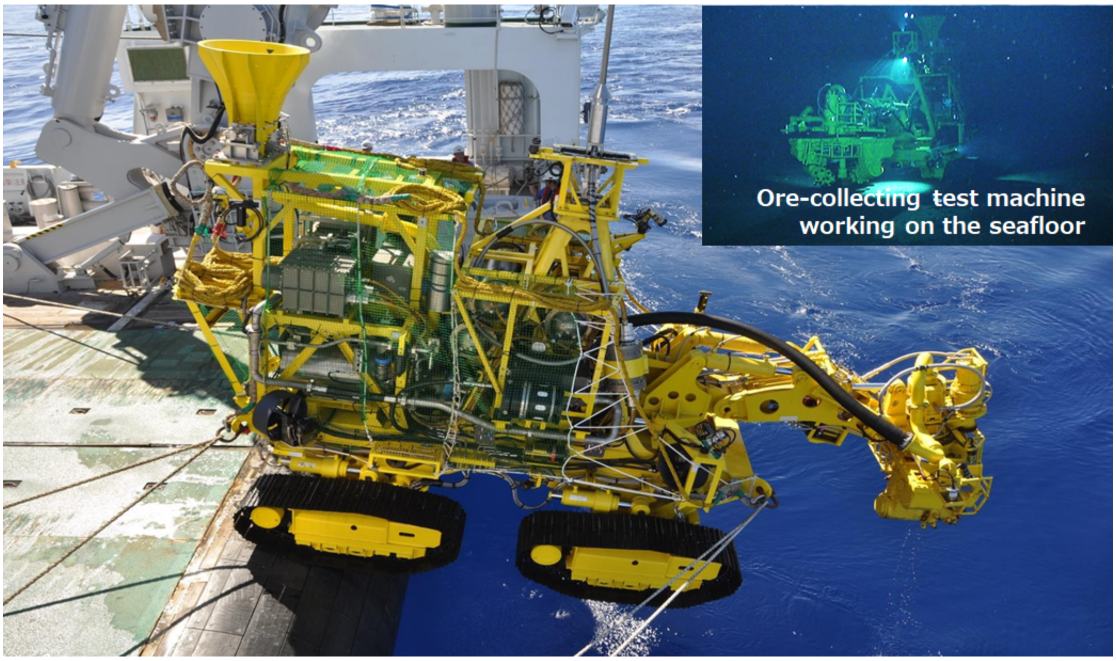
Keywords: polymetallic sulphides, seabed mining technology, ore lifting operation



Ore lifting test diagram



Vessel operation during test



Ore-collecting test machine launched from the deck of vessel

Lifted ore at ore lifting support vessel

REFERENCES

Basic Plan on Ocean Policy (Cabinet decision), March, 2008

Ministry of Economy, Trade and Industry (METI), "Plan for the Development of Marine Energy and Mineral Resources", March 2009 *(in Japanese)*.

Basic Plan on Ocean Policy (Cabinet decision), April, 2013

Ministry of Economy, Trade and Industry (METI), "Plan for the Development of Marine Energy and Mineral Resources", December 2013 *(in Japanese)*.

N. Okamoto, "Current Status of Japanese Deep-sea Mining Technologies", World NAOE Forum 2017, Realizing Deep-Sea Mining: Approaches and Solutions, 11th December 2017

N. Okamoto, S. Shiokawa, S. Kawano, H. Sakurai, N. Yamaji and M. Kurihara, Current status of Japan's activities for deep-sea commercial mining campaign, OCEANS'18 MTS/IEEE Kobe, 2018.

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Weathering of sulfides in a deep-sea environment: A case study

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Weathering of sulfides and the generation of acid mine drainage (AMD) is a well-known environmental issue in on-land mining. The process can release potentially toxic compounds and heavy metals to the environment and is highly influenced by microbial activity. However, the weathering of sulfides in deep-sea environments is not well studied. In 2014 we therefore deployed two titanium incubators filled with freshly ground pyrite grains into an inactive part of the hydrothermal sulfide mound of Loki´s Castle vent field, aiming to study the in-situ seafloor weathering of the freshly exposed sulfides. Each incubator had five chambers placed in a depth profile, where the upper chamber was exposed to the bottom seawater. After one year of exposure, one incubator was collected and analyzed for weathering features and microbial colonization and community composition. In addition, one sediment core (25 cm deep) was collected from the sulfide mound in close vicinity to the incubators, and another core (45 cm deep) was collected from the (hemi)pelagic sediment just outside the sulfide mound. The cores were analyzed for geochemical composition of the solid material and porewater, and the microbial community composition aiming to define the redox zoning and dominating geomicrobiological processes in the natural deposits, and to unravel how these processes influence the mobility of heavy metals during sulfide weathering.

Scanning electron microscopy (SEM) revealed development of Fe-oxyhydroxide weathering rims on the pyrite grains in the incubator chambers. Spalling of the rims on the most weathered grains, exposing fresh pyrite surfaces to oxidation, was commonly observed. The SEM investigation also revealed a positive correlation between weathering degree and microbial community density. Preliminary results from the microbial community analysis show a high relative abundance of putative sulfide oxidizers, suggesting that the community is governing the degradation of pyrite.

Geochemical analyses of the sediment revealed a ten times higher concentration of heavy metals in the sulfide mound compared to the (hemi)pelagic sediment except for in one layer that was clearly affected by hydrothermal activity. However, despite the large difference in heavy metal concentration in the sediment between the two environments, the geochemical analyses of porewater revealed nearly similar concentrations of heavy metals. The porewater from the sulfide mound showed an exhaustion of oxygen, followed by a decrease in nitrate, and alternating patterns of dissolved Mn and Fe, indicating an exhaustion of terminal electron acceptors with a higher energy yield than sulfate. A low organic carbon content suggests that this is connected to the oxidation of sulfides in the upper part of the sediment. Microbial groups known to utilize other components than oxygen while oxidizing sulfide were detected in the sediment. In addition, despite no clear sign of sulfate reduction from the porewater composition, a community of sulfate reducers was detected with a high relative abundance indicating that sulfate reduction is occurring in the mound sediment. The microbial reduction of sulfate to hydrogen-sulfide likely results in precipitation of secondary sulfides, a process that removes heavy metals dissolved during the oxidation of the sulfide minerals. In the (hemi)pelagic sediment a continuous presence of oxygen throughout the core is explained by the low organic carbon content and the general low content of hydrothermal sulfides. In addition, there was no indication of microbial groups known to reduce sulfate, but other groups which thrives in an oxygenated environment were detected at all depths.

The surprisingly similar concentration of dissolved heavy metals in the two environments, despite the large difference in the solid sediment, reveal the importance of sulfate reduction as an efficient geomicrobiological immobilization process. During seafloor mining activities sulfide minerals are expected to be exposed to oxic conditions, resulting in similar processes to those observed in the (hemi)pelagic sediment and the pyrite in the incubators. A potential effect of this is an increased concentration of heavy metals in the surrounding waters. Together with a sediment plume containing fine particles of sulfides, this can impact the ecosystems in the area.

Hydrothermal activity and deep-sea mineral deposits at ultraslow spreading ridges: examples from the Arctic Mid-Ocean Ridge system

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The extension of the Mid-Atlantic Ridge north of Iceland has collectively been referred to as the Arctic Mid-Ocean Ridges (AMOR). The AMOR extends from the northern shelf of Iceland, to the Siberian shelf in the Laptev Sea, passing *en route* through the Norwegian-Greenland Sea, the narrow gateway of the Fram Strait, and across the Eurasia Basin. The AMOR is 4000 km long and is divided into six super segments: 1) the Kolbeinsey Ridge, 2) the Mohns Ridge, 3) the Knipovich Ridge, 4) the Molloy Ridge, 5) the Lena Trough, and 6) the Gakkel Ridge.

After continental rifting at 60-50 million years ago, around 2.5 million km^2 of oceanic seafloor has formed by seafloor spreading - resulting in the formation of the Norwegian-Greenland Sea and the Eurasian Basin. This northernmost part of the global ridge system is anomalous in several ways: The seafloor spreading takes place at an ultraslow rate (less than 2 cm/y) with spreading rates decreasing northward to around 1 cm/y at the Gakkel Ridge - which is the most slow-spreading ridge on Earth. As a result, the volcanic activity along the northern part of the AMOR is low, the oceanic crust is unusually thin (around 3,5 km at the Knipovich Ridge, Kandilarov et al.2010), and the rift valley is deep (average water depth > 3 km). In the southern part of the AMOR, the ridge system is affected by the Icelandic plume and a hot spot below Jan Mayen. The ridge-plume interaction results in higher volcanic productivity, unusually thick oceanic crust (9-11 km, Kandilarov et al. 2012) and shallow ridge segments (1500-100 m). The AMOR also display contrasting spreading regimes, whereas some super segments are dominated by orthogonal spreading (Kolbeinsey and Gakkel Ridge) others are characterized by highly oblique spreading (Mohns and Knipovich ridges). Some ridge segment displays asymmetric spreading, like the Mohns Ridge where core complexes preferentially form along the northwestern flank. Together these variations in ridge characteristics results in large diversity of hydrothermal systems and associated mineral deposits.

During the last decades, more than 20 confirmed and potential vent sites have been identified along the AMOR. Among these are eight active vent fields that has been located at the seafloor and investigated in more or less detail using autonomous and remotely operated vehicles. At the northern, magmatically starved segments of the ridge system (i.e. north of central Mohns Ridge) only two active vent fields have yet have been studied (Loki's Castle and Ægirs kilde). Both are located at the Mohns Ridge, and both occurs at approximately 2400 m depth in the central parts at large axial volcanic ridges that are typical for this super segment. Whereas the Ægirs kilde appears to be a young developing vent field with only small mineral deposits, Loki's Castle has been active for around ten thousand years, during which a large composite hydrothermal mound has developed. At the surface the mound consists of altered chimney fragments and fine-grained debris where the first is composed of pyrrhotite, pyrite, and chalcopyrite with sphalerite, and minor galena, and non-sulfide phases consist of anhydrite, oxyhydroxides and phyllosilicates such as gypsum, talc, smectite and serpentine-group minerals. The average Cu contents is relatively low. In addition to these active fields, several ancient mineralization areas have also been located at inner rift fault walls and at core complexes. Some of the samples recovered from this setting are richer in copper.

The hydrothermal fields that are located at the shallow, hot-spot influenced part of the AMOR typically emanate 270-200°C hydrothermal fluids that are at or close to the boiling point. These vent fields also undergo degassing, mainly of CO_2, which gives rise to distinct gas flares above the vent fields. The white to clear vent fluids are relatively metal-depleted, and the hydrothermal deposits that develop around the vent sites are in general small. Mounds that are up to 20-30 meters across and 5-10 m high are present at some vent sites. Due to boiling and degassing it is believed that sulphides precipitate at depth.

The mineral deposits vary markedly with tectonic setting and water depth. At the Jan Mayen vent fields, which are located at or near the ridge axis at 700-500 m depth, the deposits are Zn-dominated with sphalerite as the main sulphide mineral. This is followed by chalcopyrite, pyrite, marcasite and minor galena (Cruz, 2016). Chimneys and flanges can here be extremely enriched in Zn (up to 34.5 wt% Zn) but with low Cu (max 1 % Cu). They are also relatively Au-rich (up to 2.6 ppm). Compared to Loki's Castle, the shallow Jan Mayen vent fields depicts higher Au contents, higher Zn, and lower Cu/Zn ratios.

The Grimsey vent field, situated in a sedimented graben in the Tjörnes Fracture zone just north of Iceland, show contrasting style of mineralization. Venting here occurs at around 400 m depth with fluids temperature reaching the boiling point at 250 °C (Hannington et al. 2001). Unlike the Jan Mayen vent fields, chimneys and mineral deposits are here predominantly composed of anhydrite and talc.

At the northern Kolbeinsey we recently discovered, a shallow, hybrid, seafloor hydrothermal system (known as the Seven Sisters Vent Field) (Marques et al., submitted). Unlike the Jan Mayen and Grimsey fields, this display mineralization with some epithermal-style characteristics. Barite is ubiquitous and is replaced by pyrite, which is the first sulfide to form, followed by Zn-Cu-Pb-Ag bearing sulfides, sulfosalts and silica. The mineralized rocks contain appreciable amounts of 'epithermal suite' elements such as Tl, As, Sb, and Hg. The unusual vent field is hosted by a flat-topped volcano composed of mafic volcaniclasts. Water depth is ~130 m where 200°C, phase-separating fluids vent from unique pinnacle-like edifices. Sulfide and secondary alteration mineralogy, fluid and gas chemistry, as well as $\delta^{34}S$ and $^{87}Sr/^{86}Sr$ isotope values indicate that mineralization at Seven Sisters is sustained by the input of magmatic derived fluids with seawater contribution.

It was predicted that the hydrothermal activity along ultraslow spreading ridges would be low or absent. The last 20 years of exploration of various parts of the AMOR and other ultraslow spreading ridges has shown that this is not the case. However, despite the many plumes that has been identified along the Gakkel Ridge (Edmonds et al. 2003), the ^{3}He contents of the deep water reveal that the total hydrothermal flux is low compared to ridges spreading at faster rates (Jean-Baptiste and Fourré, 2004). An ongoing study of hydrothermal fluxes along the Mohns Ridge suggests that the hydrothermal fluxes in magma-starved part of the ridge system is very low (Stensland et al, this volume).

On the other hand, contrary to fast-spreading ridges that have the highest hydrothermal fluxes and therefore initially were considered more prospective for the presence of significant massive sulfides, slow to ultra-slow systems are capable of sustaining long-lived hydrothermal activity at a site, and therefore the potential to form larger, and perhaps richer ore-metal sulfide accumulations (e.g. Hannington et al. 2005; Rona 2008; Hannington et al. 2011). The discovery of the Loki's Castle vent field in 2008 demonstrated that large metal-sulphide deposits can be present at ultraslow spreading ridges (Pedersen et al. 2010a). Presently, we are carrying out systematic high-resolution surveys of axial volcanic ridges similar to the one hosting Loki's Castle in order to clarify the abundance and size range of mineral deposits.

The total amount of base-metal sulphides that are associated within oceanic crust are likely to be huge. The total resources that may be accessible at the seafloor are debated, and studies to constrain the metal inventory of the ridges are ongoing. Seafloor sedimentation rate define the width of the ridge axis corridor where mineral deposits may be located and mined with current techniques. Along the AMOR the sedimentation rates are high due the proximity to continental margins that have been repeatedly glaciated during the last 4 million years. Sediment coring along the central part of the ridge system (Mohns & Knipovich Ridge) show sedimentation rates above 5 cm/Ka. Oceanic crust that is older than one million years will therefore in general be covered by at least 50 meters of sediments. Furthermore, as one million years old seafloor typically will be present only 10 km from the spreading axis with a full spreading rate of 2 cm/year, accessible resources will therefore primarily be limited to the youngest parts of the inner rift valley and steep slopes along the flanks where sediments do not accumulate at this rate.

Large parts of the Arctic Mid-Ocean Ridge system remain unexplored. The known diversity of hydrothermal activity along this ridge is large and will likely expand as new parts of the ridge system are explored in the coming years. In progress are also a range of more in-depth studies that aim to advance our knowledge on the distribution, nature, systematics and economic potential of massive sulfide accumulations in these settings.

REFERENCE

Cruz MI (2016) Mineralogy and Geochemistry of contrasting hydrothermal systems on the Arctic Mid Ocean Ridge (AMOR): The Jan Mayen and Loki's Castle vent fields. PhD thesis, Universidade of Lisboa.

Edmonds HN, Michael PJ, Baker ET, Connelly DP, Snow JE, Langmuir CH, Dick HJ, Mühe R, German CR, Graham DW (2003). Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic Ocean. Nature 421(6920):252.

Hannington M, Herzig P, Stoffers P, Scholten J, Botz R, Garbe-Schönberg D, Jonasson IR, Roest W (2001) First observations of high-temperature submarine hydrothermal vents and massive anhydrite deposits off the north coast of Iceland. Marine Geology. 2001 Jul 15;177(3-4):199-220.

Hannington M, Jamieson J, Monecke T, et al. (2011) The abundance of seafloor massive sulfide deposits. Geology 39: 1155–1158.

Hannington MD, de Ronde C, Petersen S (2005) Sea-floor tectonics and submarine hydrothermal systems. Economic Geology 100th Anniversary Volume: 111–141.

Jean-Baptiste P, Fourré E (2004) Hydrothermal activity on Gakkel Ridge, Nature 428, 36.

Kandilarov A, Mjelde R, Pedersen, Hellevang B, Papenberg C, Petersen CJ (2012) The northern boundary of the Jan Mayen microcontinent, North Atlantic determined from ocean bottom seismic, multichannel seismic, and gravity data. Marine Geophysical Research 33:55-76.

Kandilarov A, Landa H, Mjelde R, Pedersen, Okino K, Murai Y (2010) Crustal structure of the ultra-slow spreading Knipovich Ridge, North Atlantic, along a presumed ridge segment center. Marine Geophysical Researches 31:173-195.

Marques AFA, Roerdink DL, Baumberger T, deRonde C, Ditchburn RG, Denny A, Thorseth IH, Okland I, Lilley MD, Whitehouse MJ, Pedersen RB (xxxx) Seven Sisters Hydrothermal System: First record of epithermal-type mineralization hosted in mafic volcaniclasts on a shallow flat top volcano on the slow spreading Arctic Mid-Ocean Ridge, submitted.

Mozgova NN, Efimov A, Borodaev YS, et al. (1999) Mineralogy and chemistry of massive sulfides from the Logatchev hydrothermal field (14 degrees 45'N Mid-Atlantic Ridge). 8: 379–395.

Pedersen RB, Rapp HT, Thorseth IH, et al. (2010a) Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge. Nat Comms 1: 1-6.

Pedersen RB, Thorseth IH, Nygård TE, et al. (2010b) Hydrothermal Activity at the Arctic Mid-Ocean Ridges. In: Rona P, Devey CW, Dyment J, Murton B (eds) Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges. American Geophysical Union, pp 67–89

Rona P (2008) The changing view of marine minerals. Ore Geology Reviews 33:618–666.

Rolf B. Pedersen

My current research focuses on seafloor spreading, formation of oceanic lithosphere, hydrothermal systems and deep-sea geobiology. My expertise is in geochemistry, petrology and marine geology. Deep marine research is currently focused on ultraslow spreading ridges and exploration of the Arctic Mid-Ocean Ridges (AMOR). This ranges from studying volcanic crust-forming processes and the architecture of oceanic lithosphere - to water-rock-microbe interaction in hydrothermal systems. Exploration of the AMOR to clarify the extent and diversity of hydrothermal activity is an important part of my current research activity. For this, I have organized a number of international deep-sea expeditions, and I collaborate widely with marine technology institutions and companies to develop marine robotics and sampling tools for this research. More recently I have become involved in CO_2 storage related research that is focused on sequestration of CO_2 in the oceanic lithosphere, and on seafloor leakage scenarios and their environmental consequences.

Seafloor backscatter data: a cost and time-effective method for exploration of seafloor massive sulfide deposits? - A case study at the TAG district

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ABSTRACT

With the world's growing demand for metals, seafloor massive sulfides (SMS) deposits are now seen as a possible mineral resource that could contributes to secure metal supply for human needs. SMS deposits are characterized by high concentrations of base metals and at some place high contents of precious and rare metals. Since 1977 and the discovery of the first high temperature (HT) hydrothermal vent and its sulfide mineralization and high biodiversity, more than 300 sites are known today. If the exploration strategy for detection of active hydrothermal sites is now robust, their associated mineralization will not (and must not) constitute a potential target for deep-sea mining due to environmental concerns and technical limitations. Recent studies on SMS deposits are rather focused on extinct and buried mineralized sites characterized by a lower biomass. Several geophysical techniques to explore and detect extinct SMS (eSMS) and buried SMS (bSMS) have been developed (e.g. Kawada and Kasaya, 2017; Szitkar et al., 2017, 2014) using different approaches (e.g. regional or local scale; ship-based or using underwater vehicles) with several degrees of success or limitation. Here we present results from acoustic surveys performed on the TAG hydrothermal district during the BICOSE (2014) and LEVE-SMF

(2016) cruises and direct observation provided by HOV (Nautile) dives carried out during HERMINE cruise (2017). Acoustic data were acquired using two different multibeam echosounders (MBES): the hull-mounted Kongsberg EM122 (12 kHz, R/V L'Atalante) and the ROV-mounted RESON SeaBat 7125 (400 kHz, ROV Victor) (Figure 1). After processing, acoustic seafloor backscatter data from both MBES provides complementary qualitative results in relation to the seafloor composition.

The analysis of the seafloor backscatter data obtained by near-seafloor surveys with the high-resolution 400 kHz MBES shows a clear relationship between low backscatter strength values and areas covered with pelagic and hydrothermal sediments whereas high backscatter strength values are associated to pillow lavas and basaltic scree. Intermediate backscatter strength values are rather related to old and younger eSMS as well as to mineralization on TAG active mound.

Low backscatter strength values obtained with the 12 kHz hull-mounted MBES are related to large surfaces of old, strongly oxidized eSMS while high backscatter strength values are associated to younger eSMS deposits, to the TAG active mound and to sediment-covered basalt (Figure 1). Several areas dominated by low backscatter strength values and associated to mound morphologies were investigated and sampled with the HOV Nautile. All of these mounds were found to be very old and strongly oxidized eSMS deposits. Atypical backscatter strength values of these eSMS deposits will be discussed.

Only couples of hours of surveys are required to cover a surface of more than 70 km^2 with the 12 kHz vessel hull-mounted MBES, compared to the time needed by an ROV to cover such a surface. Therefore, hull-mounted MBES acoustic backscatter survey is a promising approach for cost and time-effective exploration and detection of eSMS deposits.

Keywords: Exploration, Extinct Seafloor Massive Sulfides, Acoustic backscatter data, 12 kHz hull-mounted multibeam echosounder, 400 kHz ROV-mounted multibeam echosounder, HOV Nautile.

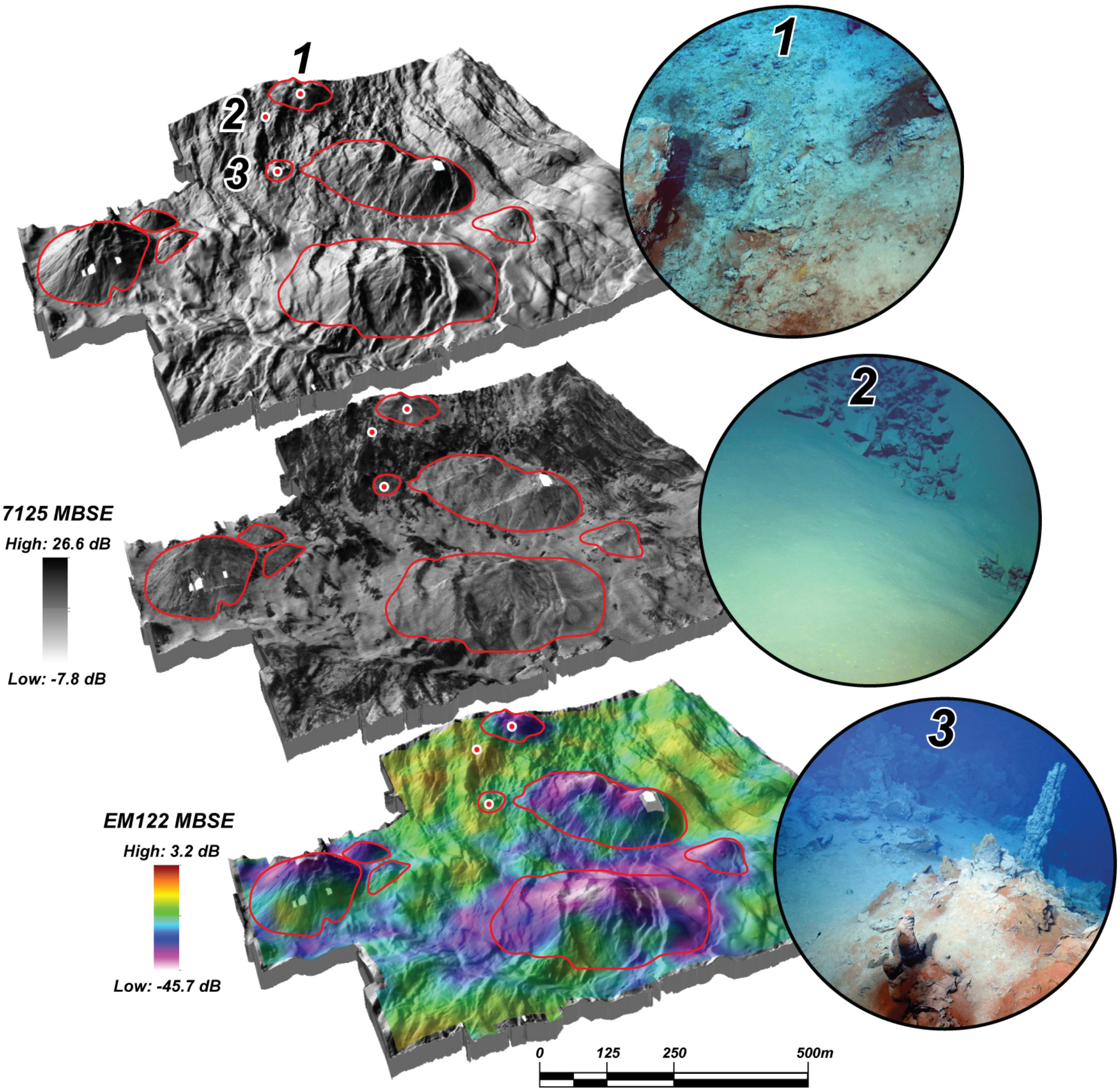

Figure 1 : Acoustic data from the Alvin mounds (TAG district) Top: Oblique view of gray-shaded high resolution bathymetric map (near seafloor mapping using ROV Victor); Middle: near seafloor backscatter data obtained using the ROV Victor (RESON SeaBat 7125 high resolution MBES); Bottom: Kongsberg EM122 MBES backscatter data (colored area) obtained from the ship (R/V L'Atalante) and plotted on the high resolution bathymetric map. Red lines outline the extension of seafloor massive sulfide (SMS) deposits. 1: Old and strongly oxidized extinct SMS with no visible sulfides chimneys; 2: Basalt scree covered by thick pelagic sedimentary cover; 3: Young extinct SMS with sulfides chimneys (Relic Mound).

REFERENCES

Kawada, Y., Kasaya, T., 2017. Marine self-potential survey for exploring seafloor hydrothermal ore deposits. Sci. Rep. 7, 13552. https://doi.org/10.1038/s41598-017-13920-0

Szitkar, F., Dyment, J., Fouquet, Y., Honsho, C., Horen, H., 2014. The magnetic signature of ultramafic-hosted hydrothermal sites. Geology 42, 715–718. https://doi.org/10.1130/G35729.1

Szitkar, F., Tivey, M.A., Kelley, D.S., Karson, J.A., Früh-Green, G.L., Denny, A.R., 2017. Magnetic exploration of a low-temperature ultramafic-hosted hydrothermal site (Lost City, 30°N, MAR). Earth Planet. Sci. Lett. 461, 40–45. https://doi.org/10.1016/j.epsl.2016.12.033

Ewan Pelleter

Ewan Pelleter received a Ph.D. in Earth Sciences from the University of Lorraine at Nancy in 2007. Then, he spent few years in Canada (Geological Survey of Canada, Québec) and France (French Geological Survey, Orléans) working on Iron Oxide Copper Gold Deposits (ICOG). Ewan has been a marine geologist with the Ifremer since 2010 and he started working on seafloor massive sulfide deposits as a member of the FUTUNA project, a public-private partnership dedicated to the exploration for seafloor massive sulfides in the French EEZ of Wallis and Futuna. Since 2010, Ewan has participated in 6 research cruises, was chief of the LEVE-SMF cruise (2016) and co-chief of the HERMINE cruise (2017) focused on the French exploration area in the Mid-Atlantic Ridge. His research focuses on understanding the metallogenic processes related with the formation of deep-sea mineral resources.

The Vertical Mining Approach for SMS Deposits – Chances and Challenges

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Abstract

The Company Bauer Maschinen is very well known in the field of specialist foundation equipment. In the diaphragm wall market, we have experiences both in manufacturing and executing projects all over the world since 1984. We have a population of more than 300 units working all over the world in all climate and soil conditions. Especially for hard soil and rock conditions, we have developed several cutting tools and systems to optimize the performance, e. g. the “flipper tooth”

Besides the execution of land based foundation projects, we have performed our firs offshore project with the trench cutter in 1994. Our task was to take samples out of the alluvial soil off the coast of Namibia in a water depth of max. 200 m. We converted a drill vessel and launched the cutter thru the moon pool. The samples had a cross section of 3,40 m² and a max. depth of 5 m. They were used to estimate the content of diamonds.

The first time, we reached the seabed of the deep sea was together with our seafloor exploration rig MeBo, where we can take cores up to a length of 160 m in a maximum water depth of 4000 m. With our customer MARUM, we have done several expeditions since 2005. The last expedition took place in the Black Sea to explore gas hydrates.

With the experiences, we have gathered both in the foundation business and the deep sea exploration, we have developed a new method for taking big volume samples from SMS deposits up to a water depth of 2500 m. We work in cooperation with an experienced offshore company, Harren & partner, who brings in their offshore experiences. This new approach can minimize the technological risk and reduce both the investment and operating costs. We will equip an existing offshore construction vessel with a modified trench cutter, lower the cutter to the seabed and take 100 tons of SMS material per trench. The transportation from the seabed to the vessel will be done with a patented hopper system.

To test the equipment, we are in contact with the German Ministry of Economics, who owns an exploration license for SMS deposits in the Indian Ocean, which is a ISA license. The first sampling results of such SMS ores show a high value of metals.

The discontinuous ore transport with a hopper offers many advantages, such as the energy demand. As we are just lifting the hopper with the ore, we do not have to transport a huge amount of seawater, which we have to bring back to the seabed. The theoretical calculations show here a huge benefit. As we are also working in a closed circuit system, we minimize the environmental impact.

On the other hand, we have to investigate for underwater separation systems. In our market research, we found again some existing technologies for land based usages, which we can adopt to the seabed

As a conclusion, we can say, that this new approach for samplings seems to be an economic system for the later deep-sea mining and, due to the vertical approach, suitable also for small deposits.

Keywords: Seaflor Massive Sulfides, vertical mining approach, trench cutter, flipper tooth, hopper system

Leonhard Weixler

Leonhard Weixler was born in September 1963 in Germany.

He studied mechanical engineering at the University of Applied Science in Augsburg.

He graduated as Dipl.-Ing. (FH) in September 1985.

Mr. Weixler started his career in BAUER Maschinen GmbH, which is now world marked leader for special foundation equipment.

Until end of 2010 he was responsible for the mechanical design and development of BAUER Maschinen GmbH.

Now he is responsible as an executive director for the business unit Maritime Technologies.

Since April 2014 he is also president of the newly formed DeepSea Mining Alliance (DSMA), based in Hamburg, Germany.

Navigating marine management regimes under the New Zealand Exclusive Economic Zone Act 2012

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Managing sediment plumes under multiple jurisdictions

Management of activities in the New Zealand EEZ can be characterized as a distributed basis of decision-making with each independent and separate decision-maker focused on specific elements of a proposal (environmental, work place safety, wildlife management, fisheries, navigation, oil spill).

The New Zealand EEZ Act 2012 was intended as gap-filling legislation to address the lack of an environmental assessment lens for permissions to undertake certain activities in the New Zealand EEZ. These activities relate mostly to marine scientific research, dumping and discharges, oil and gas exploration and development, and seabed mining.

The regulatory decision-maker for most EEZ Act marine consents is the New Zealand EPA. Since 2013 when this gap-filling legislation took effect, the EPA and its decision-making committees have processed three seabed mining applications. Two consents were refused, one consent was granted in 2017.

A common feature of all consents has been the assessment and consideration of the scale, significance and effects of sediment plumes arising from the activity.

One consent is for irons and mining in about 40m of water where the plumes reach the nearby coastal waters and shoreline, the second consent is far offshore but plumes extend far beyond the mining area (850 km^2) in to rare coral habitats and in to a significant offshore fishery.

A significant consideration for decision-makers is how the assessment and management of plumes under the EEZ Act interact with, and potentially overlap, management of such plumes under other legislation (Resource Management Act, Marine Mammals Protection Act, and Wildlife Act). This is in a statutory context where the EEZ Act requires explicit consideration of the nature and effect of other marine management regimes over the matter under consideration.

This presentation will traverse the statutory landscape in New Zealand and within the EEZ. It will draw on the three marine consents to show how the statutory framework came in to play with respect to sediment plumes. It will critically examine how well this framework serves the interest of environmental protection, and the sustainable management of natural resources. This plays out in the somewhat conventional industry assessments based on western world science, models and data. However, a specific feature for New Zealand is the role and views of its indigenous Maori people. They have rights protected under the Treaty of Waitangi, and the interplay of those rights with the obligations of the Crown come under tension in the EEZ Act's treatment of existing interests and cultural rights where sediment plumes are seen to adversely impact on and affect the relationship of these people with their traditional resources. At the heart of this issue is not science, but a Maori world view and matauranga Maori (the Maoril knowledge system). The role of indigenous knowledge systems in assessing effects of sediment plumes far afield from the site of seabed mining activity is an important issue worldwide where commercial interests come up against traditional knowledge and views about management of the marine environment.

The presentation will look at how the EEZ Act manages this overlap of jurisdiction and expectations.

Keywords: New Zealand EEZ Act, seabed mining consents, sediment plumes, overlapping jurisdictions, indigenous peoples

Siobhan Quayle
General Manager, Climate, Land & Oceans

As the EPA's former General Counsel, Siobhan is a valued member of the Environmental Protection Authority's Executive Leadership Team.

Her significant experience across the legal and regulatory landscape means she brings a sound cross-organisational perspective to the role of General Manager, Climate, Land and Oceans.

She has been a part of the EPA since it was established in July 2011. Before that she was a senior solicitor with the Ministry for the Environment and also has worked as part of a specialist environmental law team at Chapman Tripp.

Siobhan has studied at the International Tribunal for the Law of the Sea in Hamburg, holds a Bachelor of Laws and a Bachelor of Science from Victoria University and also holds a post graduate Diploma in Education. She has also held leadership positions in secondary school education and is currently the Deputy Chair for the Board of Land Search and Rescue NZ.

STAKEHOLDERS' PERSPECTIVES ON DEEP SEA MINING: A CASE STUDY IN GERMANY

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ABSTRACT

Scientists show that polymetallic nodules and massive sulfides from deep sea mining contain valuable metals. These metals have the potential to overcome future shortages of supply. Hence, companies, government agencies and industrial associations increasingly evaluate deep sea mining as a promising supplement of land mining. Technologies to extract, exploit, transport and smelt polymetallic nodules and massive sulfides industrially are still in conceptual stage and not sufficiently advanced for operation. According to the International Seabed Authority, large scale exploitation would require a successful pilot mining test in order to demonstrate e.g. the technological feasibility but also the conservation of environmental systems services. At the same time, NGO´s and a some scientists point out that large scale extraction of polymetallic nodules and massive sulfides could disturb the habitat of benthic organisms, with unknown long-term effects. Aside from the direct impacts of mining, indirect consequences about leakage are likely.

In the oral presentation I will show how companies, government agencies, scientists and association/interest groups perceive and assess economical/technological, social and environmental risks and opportunities of deep sea mining. In order to analyze the perspectives of each stakeholder group on deep sea mining, we conducted 15 interviews with four stakeholder groups and a

large scale survey (n = 500, return rate = 13 %) in Germany. We used the concept of sustainability with its economical/technological, ecological and social dimensions for the interpretation of the results. The empirical research shows the following core results:

1. Economical/technological dimension: The majority of stakeholders expect the first pilot mining test for Germany within the next 10 years. Still, companies lack legal certainty whereas government agencies criticize companies´ marginal investment activities. Surprisingly the primary objective of the stakeholders is not to secure access to raw materials for German industries but rather to market German technologies worldwide. This may be relevant for policy makers regarding innovation and industrial policy.

2. Social dimension: Deep sea mining is expected to have a high scale of automatization. Hence, deep sea mining should not have large scale impact on the labour market. While education and training will be of minor importance, monitoring will play a central role in deep sea mining.

3. Ecological dimension: It will most likely not be the direct environmental impacts that will be the most challenging risks of deep sea mining, but rather the societal resistance due to ecological impacts. All stakeholder groups agree that societal resistance may impede deep sea mining. Furthermore scientists demand evidence from ecological tests before industrial mining starts.

Keywords: Industries, stakeholder perspectives, survey, sustainability

Main Author

Tina Schneider (Dr.) is currently a senior researcher at the Institute Labour and Economy (iaw) at the University of Bremen (Germany). In her research she has a strong orientation towards sustainability economics and management supplemented by empirical research methods. Her present research project "Innovation network for deep sea mining in Germany", she presents at the conference, is funded by the University of Bremen and the Hans-Böckler-Foundation.

Germany's exploration for seafloor massive sulfides in the Indian Ocean

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INTRODUCTION

Germany has a long history in marine research in the Indian Ocean. The first German scientific cruise started in 1964, followed by a series of state-sponsored research cruises between 1983 and 1995 leading to the first finding of polymetallic sulfides in the Indian Ocean. The research included regional bathymetric, geological, structural, volcanological, petrological and hydrothermal investigations along the Carlsberg Ridge and the Central Indian Ridge (CIR). Early environmental base line studies covered oceanographic and sedimentology aspects. In 2010, BGR took the initiative for the preparation of a license application for the exploration of polymetallic sulfides with the International Seabed Authority (ISA), and prospecting started in 2011 along the southern Central (CIR) and the northern Southeast Indian Ridge (SEIR) in the southwestern Indian Ocean (cruises INDEX 2011 on board R/V Sonne), INDEX 2012 (R/V Fugro Gauss), INDEX 2013/1-2 (R/V Sonne) and INDEX 2014 (R/V Pelagia). After three years of resource-oriented and environmental base line studies, BGR, in order for the Federal Ministry for Economic Affairs and Energy (BMWi), applied for an exploration license which was approved by and subsequently signed with the ISA in 2015. The license gave permission to start a detailed exclusive resource-oriented exploration program in the license area. The program includes the outline of potential ore deposits and a resource assessment but also extensive and detailed base line studies for the sustainable protection of the marine environment in the license area. The license contract has a fifteen years lifetime and may allow the application for a subsequent mining license. The exploration aims at the identification of inactive polymetallic sulfide deposits, formed below former discharge zones of hot hydrothermal fluids on the ocean floor ("black smoker" systems), by advanced and modern exploration techniques.

Exploration Activities

The exploration cruises INDEX2015 (R/V Pelagia), INDEX2016_1 (N/O Pourquoi Pas?), INDEX2016_2 (R/V Maria S. Merian) and INDEX2017 (R/V Sonne) performed detailed bathymetric measurements, site evaluations, exploration for vent site and inactive sulfide fields, volcanology, geophysical measurements and attendant environmental surveys including biodiversity base line studies and habitat analysis, oceanography and sedimentology. For area definition and first geological characterization, BGR carried out a detailed bathymetric mapping program. In total, 505 km of the southern Central Indian Ridge and 475 km of the northern Southeast Indian Ridge were mapped with an average width of 70 km. As a prime exploration target area, a total of 57.000 km² was covered by new overview swath bathymetry with a resolution better than 40 m. In 2012 to 2014, the first sulfide blocks and clusters required for BGR's application were mapped in much greater detail using ship-based and deep-towed swath bathymetry. The program included the collection of geophysical (magnetics, electromagnetics, gravimetry) and geological data as well as the testing and implementation of successful exploration program strategies.

The license area covers an area of 10 000 km², divided in 100 sulfide blocks each 10 x 10 km in size. The blocks are confined in 12 clusters along the southern Central Indian Ridge and the northern Southeast Indian Ridge (Fig. 1).

The prospecting cruises included a rock and sediment sampling program, measurements of oceanographic parameters and the study of biodiversity and habitats along the southern Central Indian and northern Southeast Indian Ridge spreading centers as well as, and in much greater detail, in areas close to known active hydrothermal vent fields and inactive sulfide sites. The INDEX exploration program started with cruise INDEX 2015. The cruise included intense geophysical measurements and the use of the Canadian ROPOS. The new ALPHA site and the EDMOND-GAUSS-SCORE site with a combination of active vents and inactive sulfide fields were identified, mapped and sampled for the first time.

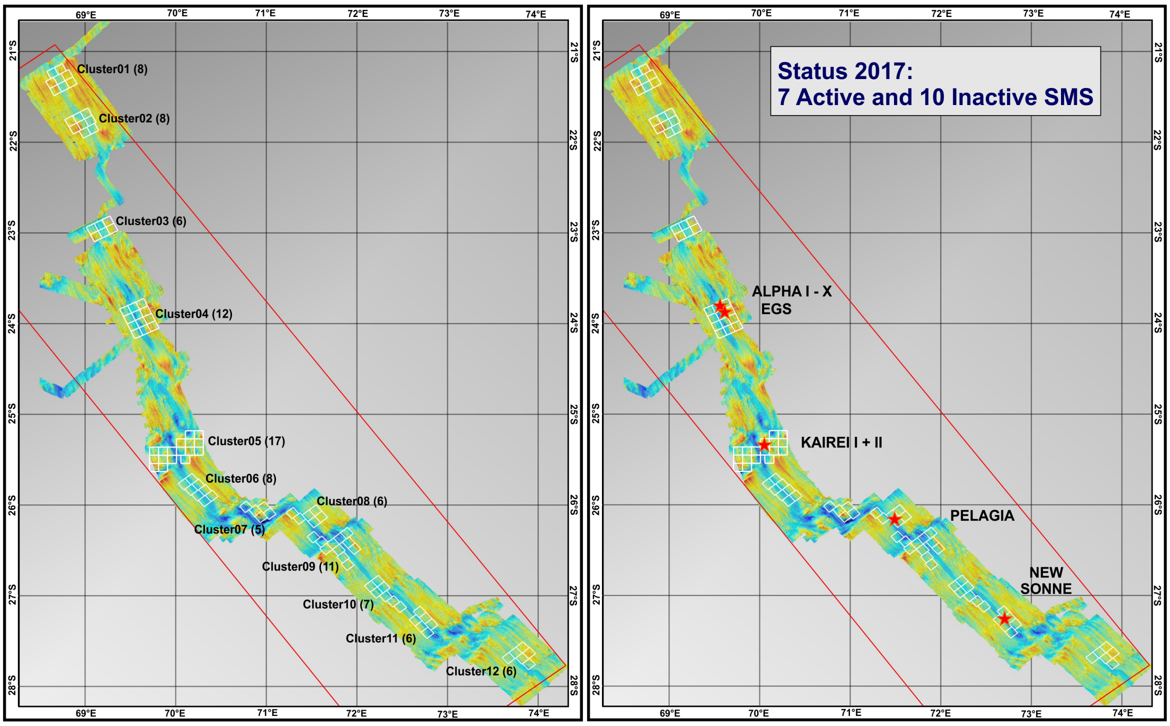

Fig. 1. Location of the German exploration license area along the southern Central and the northern Southeast Indian Ridges. Left: Distribution of the 100 sulfide blocks and location of the 12 exploration clusters. Right: Current status of BGR`s exploration program with locations of the known vent fields and inactive sulfide sites.

Cruise INDEX 2016 followed in January-February 2016 and mapped and sampled for the first time the new vent field PELAGIA, the first vent site along the entire Southeast Indian Ridge. Cruise INDEX2016_2 aimed at the first 3D seismic measurements on the EDMOND-GAUSS-SCORE site (cluster 4) during leg 1 and the detailed exploration of license clusters 1-2-3 including an intense sedimentary and oceanographic program for environmental base line studies (leg 2). The scientific program during cruise INDEX2017 included enhanced petrological sampling and the deployment of oceanographic and sediment moorings. Special emphasis was laid on the evaluation of the potential for (1) inactive sulfide sites partly or completely buried by pelagic and volcano-clastic sediments, (2) the electromagnetic characteristics and (3) the potential information about the enrichment of sulfides below the seafloor. The main work focused on the very first exploration of the southern license clusters 10-11-12 with respect to petrogenesis, ridge development, structural interpretation, hydrothermal activity, particle analysis and sedimentology, paleoceanography and biodiversity. Following intense plume hunting and deep-towed high resolution bathymetric mapping, a second active vent field along the northern Southeast Indian Ridge (NEW SONNE) was identified in cluster 11. A number of plume indications, bathymetric, volcanological and heat flow evidences suggest additional prospective areas in the three clusters.

Current State of Sulfide Exploration

The exploration for polymetallic sulfides in the BGR license area identified a total of five polymetallic sulfide sites, partly associated with active hydrothermal venting and with extensive inactive sites. The identification of venting also characterizes potential areas and zones of former hydrothermal activity and may facilitate the delineation of inactive sulfide sites. The areas include a number of 7 active vent fields and 10 inactive sulfide sites. The active hydrothermal vent fields are named EDMOND, KAIREI I, $ALPHA_{1-3}$, PELAGIA and NEW SONNE. The inactive sites include $ALPHA_{4-10}$, GAUSS, SCORE and KAIREI II (Fig. 1). The vent fields and sulfide areas can be represented by a model shown in Figure 2. The hydrothermal vent fields and sulfide sites are localized by ridge parallel and ridge perpendicular faults. The faults controlled early volcanism along the ridge axis and away from the ridge axis. They were continuously reactivated resulting in uplift and unroofing of earlier volcanic edifices which led to the development of extensive talus deposits, fault scarps and uplift of oceanic core complexes typical of slow spreading centers.

The SONNE (not in BGR`s license area), ALPHA, EDMOND, GAUSS, SCORE, KAIREI and NEW SONNE sulfide sites essentially formed in the same time frame, and the ALPHA, EDMOND, KAIREI, PELAGIA and NEW SONNE fields continue to be active. The SONNE field formed on a young, composite pillow volcano immediately following active basalt volcanism. The PELAGIA vent field is associated with the axial graben. At SONNE and PELAGIA, the coincidence of volcanic and hydrothermal vents is typical of most ancient VMS deposit settings and of magmatic controlled venting (magmatic heat at the ridge axis).

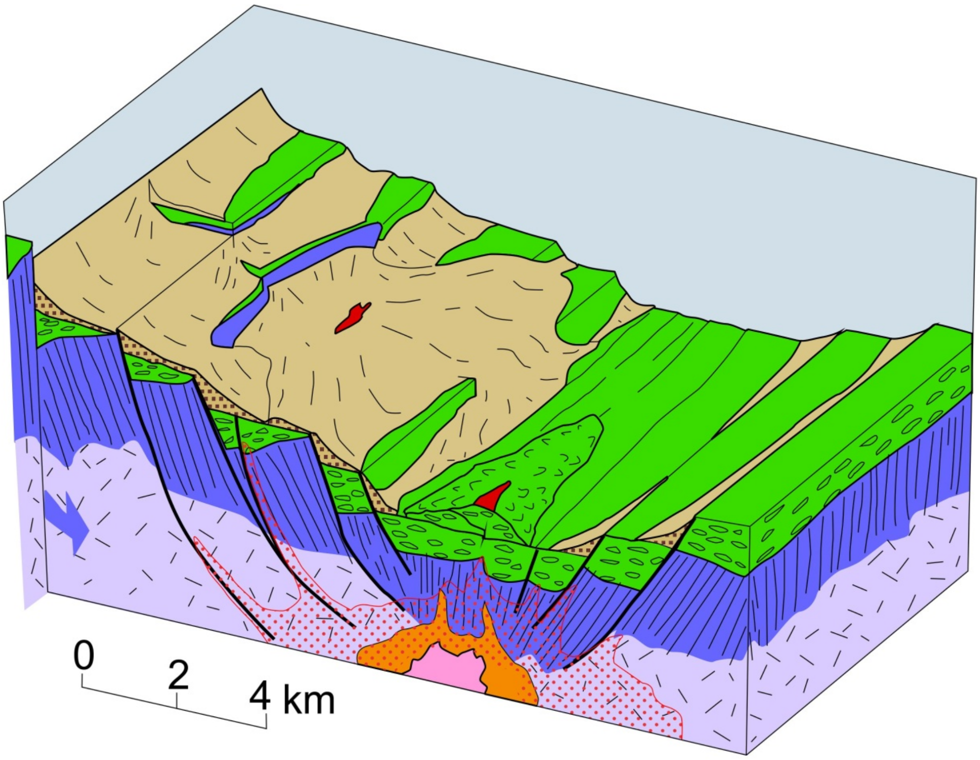

Fig. 2. Diagrammatic illustration showing two different environments for the SMS deposits in the Indian Ocean. The SONNE SMS deposit as well as the active PELAGIA vent field are located on pillow volcanoes immediately adjacent and elongated parallel to the CIR and SEIR, respectively. The KAIREI, EDMOND, GAUSS, SCORE, ALPHA and NEW SONNE sulfide sites are not associated with active volcanism, but with tectonically active faults and talus deposits up to 7 km from the spreading axes.

The association of ALPHA, EDMOND, GAUSS, SCORE, KAIREI and NEW SONNE with off-axis tectonically active but volcanically inactive settings, their formation on talus deposits that may unconformably overly volcanic and intrusive rocks, and their association with long-lived, continuously reactivated and deep penetration faults is typical of tectonic controlled venting common to slower spreading ridges. Long lived, deep penetrating faults acted as conduits for hydrothermal fluids derived from reservoirs that may have interacted with volcanic and mafic/ultramafic intrusive rocks.

The largest contiguous zone of massive sulfide are identified in the ALPHA and EDMOND-GAUSS-SCORE Zones. The surface dimensions are approximately 1,600 x 600 m and 1,600 x 200 m, respectively. It is discussed that the different sulfide sites are associated with two different substrates; typical mid-ocean ridge basalt versus gabbroic and ultramafic rocks. It is believed that sulphides with a gabbroic-ultramafic substrate are often distinctly enriched in Cu, Au and Sn, reflecting petrological controls on fluid compositions (e.g., reaction with gabbros, serpentinized peridotite, plagiogranites). The KAIREI and EDMOND hydrothermal fields are also chemically distinct from each other in their vent fluids; this is reflected in the compositions of the sulphides. The EDMOND, PELAGIA and ALPHA fluid compositions are within the range of values previously observed in mid-ocean ridge hydrothermal fluids whereas the KAIREI fluids may have been affected by the serpentinization of ultramafic rock exposed near the field (Kumagai et al., 2008; Nakamura et al., 2009). The surface association of all three vent fields is entirely MOR-type basalt. All fluids analyzed from active vents in the license area are hypersaline brines. Fluids from the EDMOND field are some of the hottest brines yet sampled. The high temperature coupled with the high chlorinity leads to enhanced metal transport. The composition of hydrothermal fluid end-members from the ALPHA vent field resembles those from EDMOND suggesting similar alteration processes. Metal concentrations are in a similar range but high Fe concentrations cannot be found. The KAIREI and PELAGIA fields have lower temperature ranges and lower chlorinities, and the vent fluids contain less metal.

It is not possible to make generalizations about the bulk compositions of the CIR and SEIR sites at this state of exploration. However, different possible models for a resource assessment were applied to the neovolcanic zones of the Central and the Southeast Indian Ridges. Typically, there is insufficient data to determine the deposit densities. This can be resolved by making simple assumptions about the spacing between occurrences or by comparisons with ridges or ridge segments that have been more completely mapped. Another approach is to use deposit density data from ancient analogues of SMS deposits.

An assessment for the license area at the southern CIR and northern SEIR resulted in a larger number of identified seafloor massive sulfide sites than what was suggested and extrapolated when prospecting and exploration started. The current state of CIR exploration identified six (including SONNE) sulfide sites including active vents and inactive sulfide fields, and a number of plumes were recorded so far. The overall average spacing between the known sulfide sites and the plume recordings is 54 km. The sulfide site spacing for the CIR has a very similar average of 57 km. This is twice the sulfide occurrence density as suggested from the global average by Hannington and Monecke (2009) and also from early plume data (Baker, 2007) but lies within the actual estimate by Baker (2017). The northernmost SEIR hosts two active vent fields. The distance between PELAGIA and NEW SONNE is 176 km. Taking the identified axial plumes into account, the overall average spacing between the known sulfide sites and the plume recordings is 46 km. The average spacing of all sulfide sites along the southernmost CIR and the northernmost SEIR equals to 90 km. With the addition of the identified plumes, the spacing reduces to 50 km.

Based on a theoretical assessment, the entire German license area has potential for about nine seafloor massive sulfide (SMS) deposits. The current state of exploration has identified seven sulfide sites, 11 plume recordings (10 axial, 1 on flank) and two not yet reconfirmed recordings from former research cruises along the CIR and SEIR (one sulfide outcrop, one plume). These numbers include the SONNE and YOKONIWA sites outside the German license area. The estimations for potential sulfide tonnages range from 1 to 8

million tonnes in the neovolcanic zone and up to 17 million tonnes for the area including off-axis deposits up to 15 km from the ridge axis.

The ongoing exploration program continues the efforts to define new inactive seafloor massive sulfide occurrences, the estimation and measurement of the orebody dimensions, the analysis of metal concentrations and subsequently the identification of potentially economically feasible deposits. Additional objectives are the conceptual development of mining techniques and the design of an optimized and zero-waste metallurgical process.

Here we present the exploration concepts and results from our investigations after three years of exploration in the German license area for polymetallic sulfides in the Indian Ocean.

Keywords: sulfide exploration, Indian Ocean.

Ulrich Schwarz-Schampera

Dr. Ulrich Schwarz-Schampera is an economic geologist graduated from the Universities of Clausthal, Aachen and Freiberg. He is working in the field of ore deposit research with all aspects of geochemistry and mineralogy since 1991. Special emphasis is laid on trace elements and the added value to their recovery from base metal deposits including resource and environmental assessments. He works on marine metal deposits since 1994 and conducted a series of research cruises to hydrothermal vents in the arc environment. Since joining the Federal Institute for Geosciences and Natural Resources (BGR) in 2003, the focus was laid on terrestrial ore deposits and gold mineralization in the Tonga-Kermadec island arc system. Since 2011, Dr. Schwarz-Schampera is leading BGR`s program for the prospecting for polymetallic sulfide deposits including the application for the first German exploration license for marine polymetallic sulphides in the Indian ocean with the International Seabed Authority. He is leading the 15-years exploration activities in the German claim since the contract was signed in 2015.

Studies on the properties and environmental impacts of deep seabed mine tailings in Korea

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INTRODUCTION

One of the major concerns for deep seabed mining is its environmental impact, from the disturbance of benthic communities due to the mining activity to the disposal of mine tailings back to the ocean. Yet a significant amount of waste materials would be produced from the on-deck processing on the mining platform, all the materials that produced on the mining platform are to be shipped to the land unless the related regulation and guidelines are developed by IMO and ISA (ISA, 2018). Still, ecotoxicology data for the deep seabed minerals from case studies in deep-sea tailings disposal (DSTD) and submarine tailings disposal (STD) sites are lacking and all other related aspects are also largely unknown. This year, the Republic of Korea has started a research project for the more comprehensive understanding of chemical and physical properties of mine tailings from the on-deck processing and the possible environmental impacts on the marine organisms after its disposal. Based on the scientific data collected from this project, Korea would be able to make recommendations for the methods and technical standards for the deep seabed mining discharges. The subjects of this project are threefold: to understand the physical/chemical properties of the tailings, to model the dispersion of particulates after the disposal, and to assess its impact on the marine ecology.

Laboratory Experiments Producing Mine Tailings

First, the possible waste materials are produced by mimicking the collecting and dressing processes at sea. The polymetallic nodules (PN) would be mined by using a collector lifting the crushed nodules out of the bottom sediment, and the bottom water, accompanying sediment, and the fine nodule particles which are too small to be recovered would be discharged to the ocean and thus are considered as tailings (Schriever and Thiel, 2013). In the laboratory, PN is crushed into the fragments smaller than 2 cm, abraded in the water using the rock mill, and then sieved to obtain the fine particles to be disposed.

The tailings for seabed massive sulfides (SMS) consist of such materials, but they also include the rock fragments of with no resource value that would increase the shipping expenses significantly. The on-deck ore dressing would likely take place to increase the profit for the commercial development, which produces other tailings such as acid, slags, etc. Therefore, the development of environment-friendly on-deck ore dressing process should be preceded to understand the properties of SMS mine tailing and minimize its environmental impact from the discharge.

At-Sea Experiments For Assessment of Environmental Impact

During the cruises for the exploration of mining sites of Korea in the Pacific and Indian Ocean, seawater and living zooplanktons were sampled. A portion of seawater samples was stored and/or preserved for the analyses of elemental chemistry and chlorophyll a. The size-separated fragments of PN and SMS are subjected to the elution experiments by using seawater collected from the surface and the bottom ocean. The mixture of seawater and ore fragments was stirred for 10 days, and eluted water samples were periodically extracted and centrifuged to separate particulates (Figure 1). The chemical and isotopic composition of the samples will be analyzed to evaluate the toxicity and to develop the isotopic tracer of mine tailings.

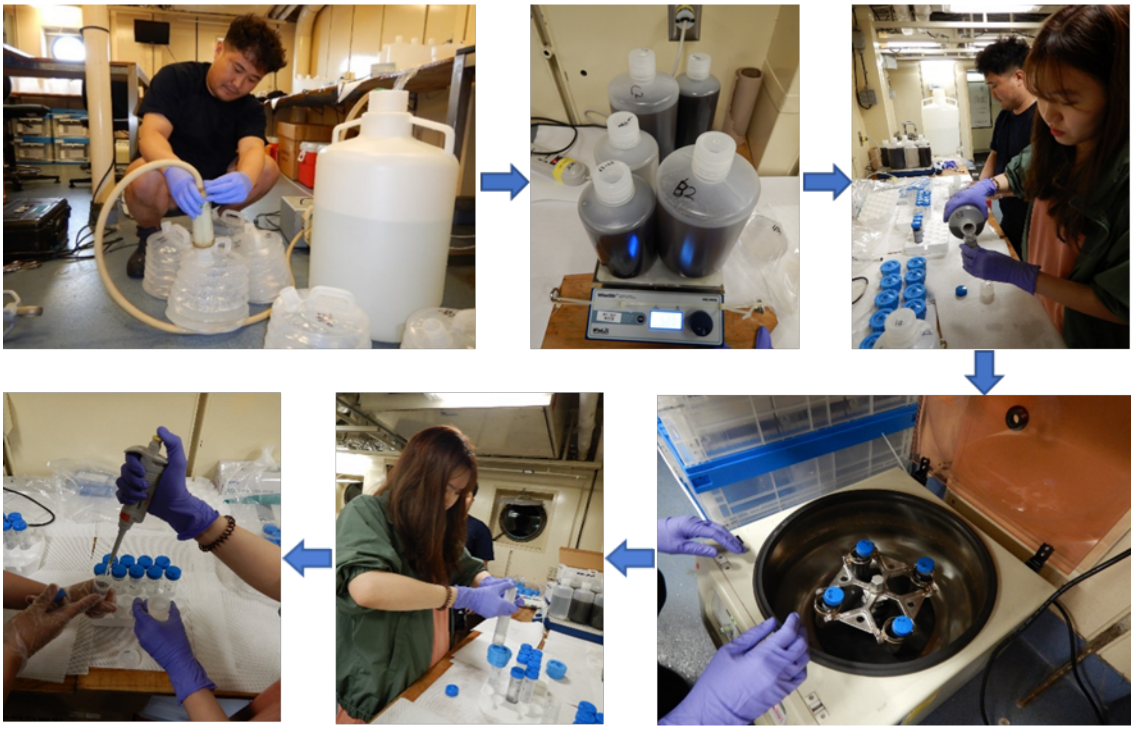

Figure 1. Elution experiments

To assess the effect of mine tailings on phytoplankton and microbial activities, the phytoplankton were collected with a conical net by vertical towing during the Pacific cruise and the on-deck culturing experiment has been made during the Indian Ocean cruise. Communities of phytoplanktons and microbes were analyzed from the seawater samples. Seawater samples were placed in a 6L PE bottles and the ore particles of PN and SMS were added in six different concentrations (10, 20, 50, 100, 200, 1000 ppm). The mixtures with surface water were incubated in a water pool stirring with hydro-pump for living in surface water at night or morning to prevent negative effects done on phyto-plankton activity due to excessive sunlight and high temperature. The water mixtures with water collected at 1,000 m were incubated in a refrigerator to maintain the water temperature for living 1000 m depth, respectively. Samples were taken in 5 different sampling times (at 0, 1, 3, 6, 12 hours). Unfiltered samples were collected and fixed with the addition of Lugol and formaldehyde solution for taxonomical analysis via flow-cytometer and flow-cam at the laboratory. After 12 hours of incubation, the mixtures were filtered with 0.2 µm pore-sized and 0.45 µm pore-sized superfilter for DNA and RNA collection.

The minimum and maximum fluorescence (F_0 and F_m) are proportional to the amount of chlorophyll a and the photosynthetic activity when saturated. In the culturing experiment, the decrease in photosynthetic ability is occurring immediately in two samples with highest concentration (200 and 1000 ppm), and eventually in other samples as time goes by (Figure 2). The decreases in F_0 and F_m are positively related to the incubating time and the particle concentration, indicating the negative influence of ore particles on the phytoplankton communities.

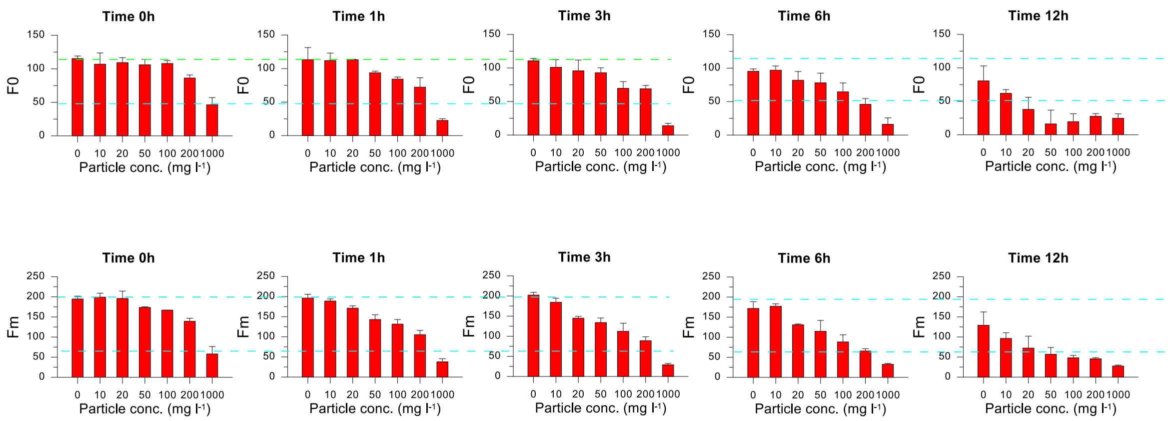

Figure 2. F0 and Fm measured from the on-deck incubated seawater from the Indian Ocean after adding PN particles (<20 µm)

Future Works

Our project has launched in 2018, and thus much of our works are still ongoing and only the preliminary results have been made so far. The toxicity of tailings is being assessed from the mortality and hatching rates of zooplanktons and the RNA analyses. The particulate diffusion after the disposal would be modelled, by using dataset of current, particle concentration and grain size, the amount and the duration of disposal. The impact on benthic ecosystem should be carefully examined and the on-site experiment is required. Although industry is almost ready for the mining operation, they should also be prepared to minimize the potential environmental impact following the environmental guidelines and regulations to be made. Our project would be an important milestone for the future deep seabed mining.

REFERENCES

International Seabed Authority, 2018. Draft Regulations on Exploitation of Mineral Resources in the Area, https://www.isa.org.jm/document/isba24ltcwp1.

Schriever, G. and Thiel, H., 2013. Tailings and their Disposal in Deep-Sea Mining, Proceedings of the Tenth (2013) ISOPE Ocean Mining and Gas Hydrates Symposium, Szczecin, Poland, September 22-26, 2013.

Keywords: deep seabed mining, mine tailings, deep-sea tailings disposal, at-sea ore dressing

Inah Seo

Dr. Inah Seo is a senior researcher working in the Global Ocean Research Center at KIOST. After joining to the deep seabed mining project since Dec 2015, she has worked on the geochemistry of bottom sediment and its origin. Her main focus is a better understanding of the nature of the bottom sedimentation and its oceanographic significance. From those interests, assessment of the resource potential of deep sea sediment and the environmental impact of sediment disturbance by seabed mining is her long-term goal. She is also interested in the sedimentology and paleoceanography to understand the past ocean dynamics.

EVA a robotic vehicle for underwater mining operations support

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ABSTRACT

Underwater intervention operations have been supported by robotic systems such as remotely operated vehicles (ROV) for a long time. In particular challenging scenarios such as the deep sea, the use of ROV systems for environment awareness is in fact the main tool of choice.

With the technical advances in autonomous robotics, there is an increased effort in substitute ROVs whenever possible for autonomous underwater vehicles (AUV). These systems don't have tether and thus provide large advantages from the operations and logistic point of view. However the limited options for underwater communications render them impracticable for many tasks were real time environment awareness and direct human control is needed.

Emerging applications in underwater mining, both at sea [1] and in inland flooded mines [2] pose additional requirements in terms of operation support needs and environment restrictions.

Two main tasks are to be addressed by assisting robots in these underwater mining operations: providing adequate environment awareness for human operators and obtain precise realtime 3D environment modelling (particularly relevant for the mining planning).

The use of ROVs with umbilical cable, has in this case large limitations due to the nature of the mining cutting (performed by dedicated systems) that limit manoeuvrability and pose high risk of cutting the cable or damaging the vehicle.

In this paper we present EVA (Exploration VAMOS AUV) an innovative hybrid ROV/AUV system developed for operations support in inland underwater mining operations. This robot is always operated without tether, and the can be used in a wireless ROV tele-operation mode using very short range high bandwidth underwater communication systems and in autonomous AUV mode.

The system is developed in the context of the VAMOS [2] European H2020 research project. This project aims to develop robotic systems for the exploitation of flooded open pit mines.

In the VAMOS system concept, the mining vehicle (MV) is deployed by a support launch and recovery vessel and is tele-operated from the surface (receiving power, and sending the ore to the surface). The system is assisted by the HROV/AUV that communicates wirelessly (using short range radio) with the MV or the surface support vessel when within range.

The HROV/AUV is used for two tasks: to provide increased awareness, with sensing (visual and acoustical) from another point of view (different from the MV) to the cutting operations and for precise 3D environment modelling. For these tasks the system has full 6DOF manoeuvrability (see Fig. 1) allowing controlled motion in the restricted space and adequate positioning.

Both vision based systems and sonar (either imaging or multibeam profiling) are commonly used in ROVs [3], [4], [5] to provide both operator awareness and mapping information. When the water is clear enough it is possible to use laser based systems to provide high bathymetric precision at close range [6].

This system is equipped with a laser based multiple structured light system for precise modelling when the water turbidity conditions allow (mainly in pre-survey missions and when the MV is not operating) and a 3D multibeam sonar (Coda Octopus Echoscope) or a imaging/proiling multibeam sonar. The former sonar provides a depth image of the environment acting as a 3D depth acoustic camera. This sonar is required not only to obtain fast 3D point cloud measurements from a free vehicle but also to provide depth perception information for the virtual reality environment used in the VAMOS system to supervise and plan the mining operations.

The use of a full 3D multibeam when compared with the use of standard line multibeam sonars is advantageous since in a single ping a 2D image (with depth information) is provided thus eliminating the requirement of scanning with a standard multibeam sonar. This even more relevant considering that the sensor is mounted in highly manoeuvrable underwater vehicle and thus there are strong limitations for the use of pan mounted line sonars (due to speed of data acquisition and vehicle dynamics effects)

In this work the developed vehicle architecture (Fig. 2) and system development and implementation are described. The perception and awareness system for the vehicle is presented in the context of the overall VAMOS system. Validation tests in tank and in relevant operational scenarios are also presented and discussed.

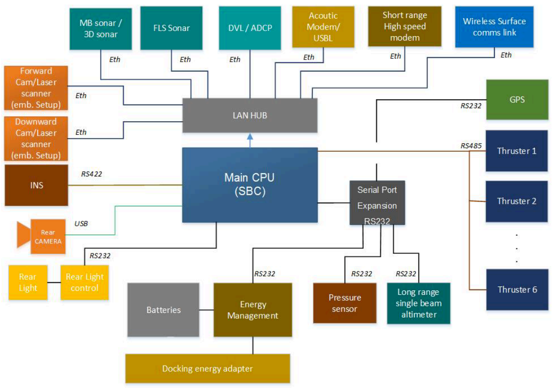

Figure 1. EVA HROV/AUV in tests on Lee Moor Mine, UK Figure 2. VAMOS AUV system architecture

References

[1] NI 43-101 Technical Report 2011 PNG, Tonga, Fiji, Solomon Islands, New Zealand, Vanuatu and the ISA" Nautilus Minerals Incorporated

[2] VAMOS website, http://vamos-project.eu

[3] A. Plotnik and S. Rock, "Visual Servoing of an ROV for Servicing of Tethered Ocean Moorings," in OCEANS 2006, 2006, pp. 1–6.

[4] A. D. Bowen, D. R. Yoerger, C. Taylor, R. McCabe, J. Howland, D. Gomez-Ibanez, J. C. Kinsey, M. Heintz, G. McDonald, D. B. Peters, B. Fletcher, C. Young, J. Buescher, L. L. Whitcomb, S. C. Martin, S. E. Webster, and M. V. Jakuba, "The Nereus hybrid underwater robotic vehicle for global ocean science operations to 11,000m depth," in OCEANS 2008, 2008, pp. 1–10.

[5] N. Palomeras, M. Carreras, P. Ridao, and E. Hernandez, "Mission control system for dam inspection with an AUV," in 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 2551–2556.

[6] G. Inglis and C. Roman, "Sonar constrained stereo correspondence for three-dimensional seafloor reconstruction," in OCEANS'10 IEEE SYDNEY, 2010, pp. 1–10.

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Metalliferous sediments in the Red Sea deeps: from resource to reserve

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ABSTRACT

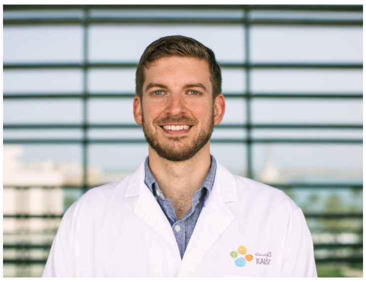
Annual metal consumption per capita has increased several orders of magnitude worldwide since the turn of the 19th century, yet grades of terrestrial ores are decreasing as reserves dwindle. Consequently, deep sea metal deposits are gradually transitioning from identified resources to economically viable reserves.

Deposits in the Red Sea deeps along the axial trough result from tectonic and local hydrothermal processes. Continental rifting and ocean floor spreading produce fresh oceanic crust; concurrently, seafloor evaporites flow into the spreading zone and form isolated deeps. The deeps are often filled with hot stratified brines maintained by locally discharged fluids during hydrothermal circulation. Metalliferous sediments precipitate from the brines within the deeps.

The ongoing multipronged study at KAUST involves: (1) acoustic characterization of the metalliferous accumulations using advanced signal processing techniques that capture the physics of granular materials; (2) comprehensive mineralogical and textural characterization of sampled sediments using SEM, EDS, XRD, XRF, and ICP-OES; (3) multiphysics instruments deployed to measure undisturbed sediment properties in-situ; (4) development of a distributed seafloor observatory for monitoring field operations; (5) innovative concentration and separation technologies; and (6) new strategies for proper tailings disposal purposely conceived for the unique field conditions in the Red Sea deeps.

Keywords: Red Sea deeps, Atlantis II, seafloor metalliferous sediments, deep sea mining

JOSHUA E. SMITH



Joshua Smith Ph.D. joined KAUST (King Abdullah University of Science and Technology) in November of 2017 as a Postdoctoral Fellow. He obtained his MSc and PhD degrees from Georgia Tech, with emphasis on geology and geophysics. His expertise extends into the quantification of hydrothermal discharge along mid-ocean ridges. His doctoral dissertation explored fluid flow in deformed porous media using a combination of analytical and numerical techniques. Josh's research at KAUST addresses the formation of metalliferous sediments within the Red Sea and the potential for mining operations.

I, Joshua E Smith, provide my permission to archive the abstract with OneMine.org at the conclusion of the UMC.

Offshore mineral resources in the Norwegian sea: latest developments

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ABSTRACT

The Norwegian Petroleum Directorate, which is the Government agency for the management of offshore geo-resources including seabed minerals, is about to finish this year's marine data acquisition cruise in the Norwegian Sea. We would very much like to present the preliminary results of that cruise, including the discovery of a new black smoker and surrounding sulphide deposits.

Hydrothermal Fluxes along the Mohns Ridge - implications for mineral resources at ultraslow spreading ridges

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Venting on ultraslow spreading ridges is far more abundant then previously predicted, and the discrepancy between observed and predicted vent field density may imply that non-magmatic heat sources are common along these ridges (Baker and German, 2004; Escartin et al., 2008; Rona et al., 2010; German et al., 2016).

In this study we have estimated the flux from two hydrothermal vent sites situated on the slow to ultraslow spreading Mohns Ridge at the Arctic Mid-Ocean Ridge system (AMOR). The flux estimates have been made using the primordial isotope ^{3}He in the non-buoyant plume above the Loki's Castle vent field at the northern termination of the Mohns Ridge, and from the Jan Mayen vent fields area situated close to the southern termination of the ridge.

Primordial ^{3}He enters the oceans through degassing and mixing with hydrothermal fluids eventually to be discharged at the ocean floor primarily at hydrothermal vent sites and submarine volcanic eruptions (e.g. Clarke et al., 1969; Lupton and Craig, 1981; Lupton, 1998). Once introduced into the water column the concentration will only decrease by dilution due to its conservative behavior in the water column.

Water column samples were collected using a CTD (conductivity, temperature, depth) probe (911plus Seabird) with a Niskin water bottle rosette. The water column above the Jan Mayen vent fields (JMVF) was sampled in the years 2006, 2011, 2012 and 2013 (82 samples) and the water column above the Loki's Castle vent field was sampled in the years 2007, 2008 and 2009 (116 samples).

By utilizing helium isotope measurements in the plume one can make an estimate of the ^{3}He flux from the vent sites in the region. To make this estimate some assumptions needs to be made, specifically in regards to the rift valley water flux. Although many studies of ocean currents and their fluxes has been conducted in the Nordic Seas, no studies have yet focused on the deep current fluxes in the rift valley. However, the water flux in the rift valley further south on the Mid-Atlantic Ridge has shown a remarkable stability with a flux of 0.07 Sv (1 Sv = 10^6 m^3/s) (Thurnherr et al., 2002). Although these measurements were obtained far from our study area the similarity of topography allows us to assume that the flux is in a similar range.

The average δ^3He in the plume (the water column below 1900 m water depth) of Loki's Castle is 11.74 % and the average of the JMVF plume (the water column below 300 m water depth) is δ^3He 17.3 %. The ^3He flux transported by the plume has been expressed as $Q_{3He}=\Phi x[^4He]xR_a x (\delta-\delta_{BG})/100$ (Jean-Baptiste et al., 2004a), where ^4He is the helium concentration measured in the deep sea background; 1.84 μmol/m^3 and the δ^3He in the background (δ_{BG}) is 5 %, R_a is 1.38 x 10^{-6} and is the atmospheric ratio. This gives a $\boldsymbol{Q_{3He}}$**=12 nmol/s** for the plume from Loki's Castle and $\boldsymbol{Q_{3He}}$**= 21.9 nmol/s** for the Jan Mayen vent fields. This flux can be described as a flux per kilometer of ridge per spreading rate. The spreading rate of the Mohns Ridge is about 15 mm/year. The average spacing between vent fields at ultraslow spreading ridges has been estimated to be slightly above 1/100 km ridge (Baker and German, 2004). This gives a flux of **0.22 mmol/km/mm/yr** from Loki's Castle and **0.40 mmol/km/mm spreading rate** from the JMVF. Whereas the flux for Loki's Castle is below the worlds average of 0.33 mmol/km/mm/yr (Farley al., 1995; Dutay et al., 2004), the flux of the Jan Mayen vent field is above this average.

Although these estimates of the hydrothermal flux along the Mohns Ridge yet have a high uncertainty the value for Loki's Castle area correspond to values calculated from the Gakkel Ridge by Jean-Baptiste et al. (2004b) (0.15 – 0.32 mmol/km/mm spreading rate) and to fluxes estimated in the same region by Bönisch and Schlosser (1995). They observed through their calculations that the flux of ^3He from the ridge below was indeed lower than the world average. The northeastern part of the Mohns Ridge, where Loki's Castle is located, seems to share this feature. This is consistent with the fact that from the central Mohns Ridge and northeastwards the crustal thickness of the AMOR is below the world average of 6-7 km (see Pedersen et al, this volume).

The flux estimate of the Jan Mayen vent field area is comparable to fluxes calculated for the Rainbow vent field and the Lucky Strike vent field further south on the Mid-Atlantic Ridge (Jean Baptiste et al., 2004a). These estimates reveal a flux of 0.5 mmol/km/mm spreading rate for Rainbow and 0.45 mmol/km/mm spreading rate for Lucky Strike, both estimates well above the global average. The high flux in this area has been attributed to more intense hydrothermal activity along the ridge segment that is affected by the Azores hotspot. The high values obtained for the Jan Mayen vent fields area can also be explained by ridge hotspot-ridge interactions and unusual thick oceanic crust at the south-western part of the Mohns Ridge.

The site frequency (F_s= sites/100 km ridge segment) of the Mohns Ridge has overall been estimated to be 1.27 (Stensland et al., in prep), comparable to the F_s of the ultraslow spreading Gakkel Ridge (1.1 -1.2) (Baker et al., 2004) and that of the eastern South West Indian Ridge (1.3) (Baker et al., 2004) and correlates to a linear function of F_s versus spreading rate reported by Beaulieu et al. (2015) and German et al. (2016). The crustal thickness range along the Mohns Ridge from up to 10-11 km in the hot-spot influenced part in the south, which is well above the global average of 6-7 km, to 3-4 km in the central and northern parts of the ridge. The hydrothermal site frequency seems to reflect variations in magma supply along the ridge, and to increase from the magma starved segments in the north to the hotspot influenced segments in the south.

Direct measurements of heat and metal fluxes at individual chimneys are currently being carried out at the Loki's Castle vent field and the initial data from this long term monitoring will be reported. Combined with the plume data these results will further advance our understanding of hydrothermal fluxes and potential metal inventory at the Mohns Ridge and other ultraslow spreading ridges.

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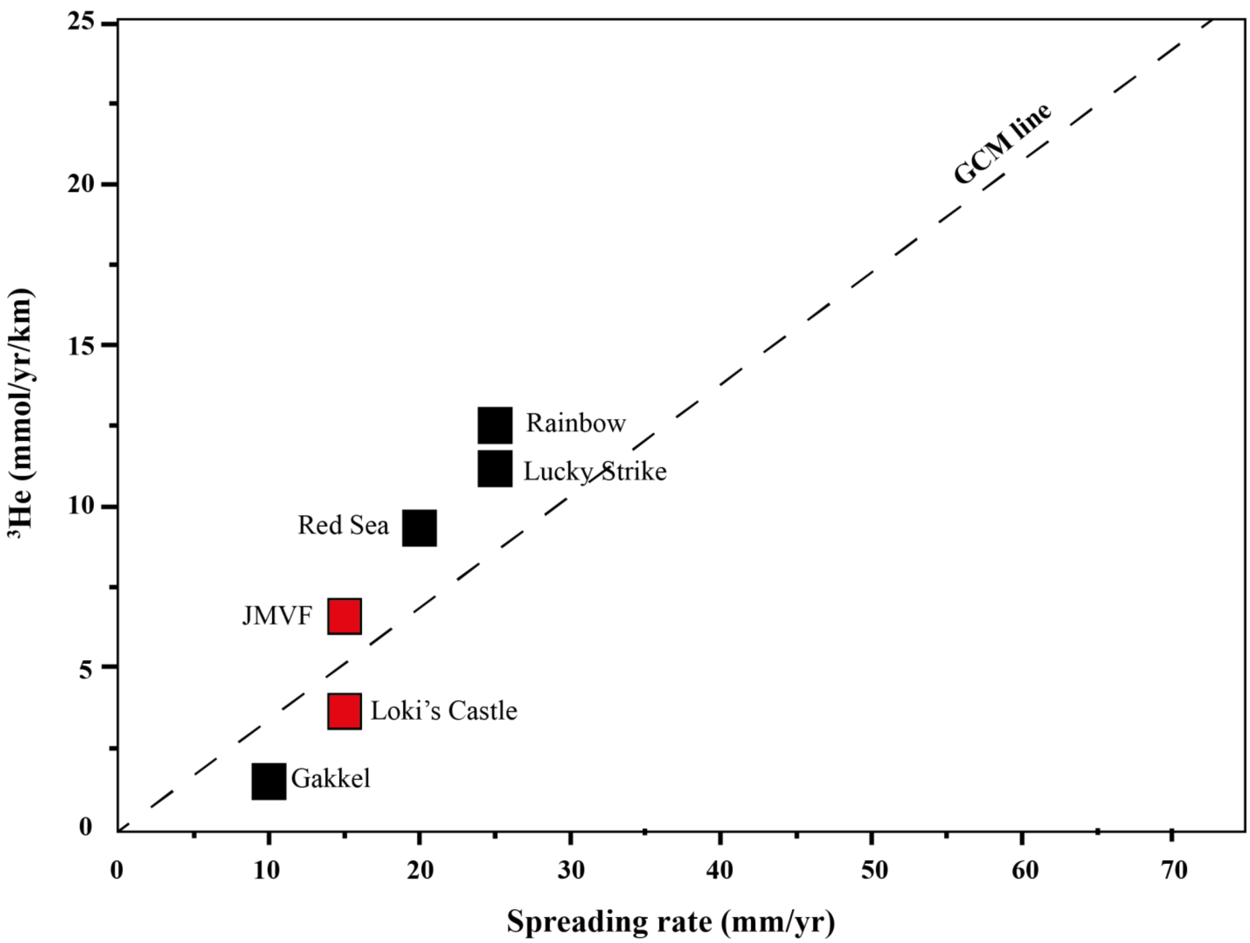

Figur 1:The annual flux of ^3He per kilometer of ridge as a function of spreading rate. The dashed line gives the global average of 0.33 mmol/km/mm/yr (Farley et al., 1995; Dutay et al., 2004). The calculations and data for the Lucky Strike, the Red Sea, the Rainbow site and the Gakkel Ridge can be found in Jean-Baptiste et al.(1998), Jean-Baptiste et al. (2004c), Jean-Baptiste et al. (2004b) and Jean-Baptiste et al. (2004a). This figure is modified from Jean Baptiste et al (2004a).

References:

Baker, E.T, Edmonds H. N, Michael P.J, Bach W, Dick H.J.B, Snow J.E, Walker S.L, Banerjee N.R, and Langmuir C.H. 2004. Hydrothermal venting in magma deserts: The ultraslow-spreading Gakkel and Southwest Indian Ridges, Geochem. Geophys. Geosyst., 5, Q08002, doi:10.1029/2004GC000712.

Baker E.T and German C.R. 2004. On the global distribution of hydrothermal vent fields. Geophys. Monogr. Ser. Volume 148, Pages 245-266.

Clarke W.B, Beg M.A and Craig H. 1969. Excess ^{3}He in the Sea: Evidence for terrestrial primordial helium. Earth and Plan. Sci. Lett, 6, 213-220.

Dutay J.C, Jean-Baptiste P, Campin J.M, Ishida A, Maier-Reimer E, Matear R.J, Mouchet A, Totterdell I.J, Yamanaka, Rodgers K, Madec G, Orr J.C.2004. Evaluation of OCMIP-2 ocean models' deep circulation with mantle helium-3. Journal of Marine Systems 48, 15–36.

Escartin, J., Smith, D.K., Cann, J., Schouten, H., Langmuir, C.H., Escrig, S., 2008. Central role of detachment faults in accretion of slow-spreading oceanic lithosphere. Nature, 455, 790–794. http://dx.doi.org/10.1038/nature07333.

Farley K.A, Maier-Reimer E, Schlosser P and Broecker W.S. 1995. Constraints on mantle ^{3}He fluxes and deep-sea circulation from an oceanic general circulation model. Journal of geophysical research, vol. 100, no. B3, 3829-383

German C.R, Petersen S, Hannington M.D. 2016. Hydrothermal exploration of mid-ocean ridges: Where might the largest sulfide deposits be forming? Chemical Geology, vol. 420, pp. 114–126

Jean-Baptiste P, Bougault H, Vangriesheim A, Charlou J.L, Radford-Knoery J, Fouquet Y, Needham D, German C. 1998. Mantle ^{3}He in hydrothermal vents and plume of the Lucky Strike site (MAR 37°17N) and associated geothermal heat flux, Earth Planet. Sci. Lett. Vol. 157, pp. 69-77.

Jean-Baptiste P, Fourre E, Charlou J.L, German C.R, Radford-Knoery J. 2004a. Helium isotopes at the Rainbow hydrothermal site (Mid-Atlantic Ridge, 36°14`N). Earth and Planetary Science Letters, vol. 221, pp. 325-335.

Jean-Baptiste P, Fourré E. 2004b. Hydrothermal activity on Gakkel Ridge. Nature, vol.428, p. 36.

Jean-Baptiste P, Fourré E, Metzl N, Ternon J.F, Poisson A. 2004c. Red Sea deep water circulation and ventilation rate deduced from the 3He and 14C tracer fields.Journal of Marine Systems, Vol. 48, Issues 1–4, pp. 37-50

Lupton J.E. 1998. Hydrothermal helium plumes in the Pacific Ocean. Journal of Geophysical Research, vol. 103, no. C8, pp. 15,853-15,868.

Lupton J. E and Craig H. 1981. A Major Helium-3 Source at 15° S on the East Pacific Rise. Science, New Series, Vol. 214, No. 4516, pp. 13-18.

Rona, P.A., Devey, C.W., Dyment, J., Murton, B.J., 2010. Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges. Geophys. Monogr. Ser., vol. 188. AGU, Washington, DC.

Stensland A, Baumberger T, Mork K. A, Thorseth I.H, Pedersen R.B.2018. ^{3}He along the ultraslow spreading AMOR in the Norwegian and Greenland Seas. In press.

Thurnherr A.M, Richards K.S, German C.R, Lane-Serff G.F and Speer K.G. 2002. Flow and Mixing in the Rift Valley of the Mid-Atlantic Ridge. American Meteorological Society, vol 32, pp. 1763-1777

Use of Autonomous Technology for mapping Seabed Minerals

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ABSTRACT

Swire Seabed is dedicated to being at the forefront of the Autonomous Subsea Revolution. The company is currently working along and developing operational, technical and market strategies where autonomous technology is the driving force. Swire Seabed's vessel Seabed Constructor is currently mobilized and operating eight Hugin AUVs and 6 Surface going USVs. This significant and revolutionary spread is owned by Ocean Infinity. Ocean Infinity and Swire Seabed is currently involved in the search for the missing MH370 – in about 3 months the vessel and autonomous spread have fine combed an area of deep sea floor spanning over more the 100 000 km^2 . With such a considerable spread with a depth rating of 6000 meter – Swire Seabed and Ocean Infinity is challenging long held paradigms in subsea mapping and resource surveys. Highly accurate and precise data can be acquired for large areas in record time, and at a comparatively much reduced cost. As one earlier required several vessels and associated crews and logistical support – Swire Seabed and Ocean infinity are now able to operate a large number of AUVs and USVs, through technological advances in automatic data-processing and interpretation, from a single offshore vessel. This opens up vast possibilities for emerging markets such as subsea-minerals.

Swire Seabed is also developing strong collaborative relationships with academic institutions. Along with UIB Swire Seabed is developing methodology for deep sea geological and geophysical resource searches applying AUVs at an industrial scale – this work is based on UIBs groundbreaking work and significant experience in the same fields. In particular Swire Seabed and K.G Jebsen Centre for Deep Sea Research (UIB) have developed methodologies for conducting detailed Seep-Searches at a large geographical scale. UIB and Swire Seabed is further pursuing a formalized long term relationship for academic and industrial cooperation and exchange in AUV operation and methodology development. Whilst K.G Jebsen Centre for deep sea research have been involved in basig deep sea research for years, Swire Seabed have specialized in cost-effective heavy duty

operations in water depths greater the 3500 meters. This collaboration affords the subsea mining community a unique pool of both insight and operational capacity.

This presentation will be given jointly by Jan Arvid Ingulfsen from Swire Seabed and Lars-Kristian Trellevik from K.G Jebsen Centre for Deep Sea Research

Keywords: Autonomous seabed mapping, Multiple AUV operations, Efficient Mapping for minerals.

Lars Kristian Trellevik

The initial spreading of turbidity plumes – Dedicated laboratory experiments for model validation

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ABSTRACT

One of the obstacles during the initial phases of project development is the assessment of the environmental impact. Mining residue, consisting of fine seafloor sediments, are to be discharged subsea to mitigate the impact of these suspended particles. In order to test the effectiveness of discharging in proximity of the seabed, a numerical model is developed within the open source software package OpenFoam. Dedicated laboratory experiments for numerical model validation are discussed within this paper.

INTRODUCTION

Siltation is considered one of the major pressures on the environment for a seabed mining operation. Siltation is defined as the pollution of water by a high concentration of suspended sediments like clay or silt. This can be caused by two main activities during the mining process: the spill loss during the excavation and the return flow of undesired seafloor sediment after ore filtration on the ship. In a concentrated cloud, these fine particles form a so-called turbidity plume. Prediction of the size of these plumes and the created layer thickness of deposited sediment is a crucial part of the environmental impact assessment.

The challenge in predicting the behaviour of these plumes is found in the wide range of scales involved in the process. At the point of origin, the turbidity plumes spread mainly under the influence of turbulent whirls created by an initial momentum and a buoyancy difference due to the presence of the suspended sediment particles. If carried by ambient currents, these plumes can spread for several kilometres before blending in the background.

The usual approach for the prediction of turbidity plumes is to model this initial discharge stage (near-field) by a one-dimensional integral model (*e.g.* Lee and Cheung, 1990 or Jirka, 2004), and integrate this near-field model with a far-field model (*e.g.* Delft3D). These 1-D integral models are reliant on basic turbulence models which limit to boundary-free water columns; influence such as an impact with the seabed cannot be taken into account in an accurate way.

An alternative approach is to use a 3D CFD model (*e.g.* Wit, 2015 and Decrop, 2015). This alternative approach has been successfully tested and validated for turbidity plumes caused by dredging activities. Validation for seabed mining applications is however lacking.

As an accurate prediction of plumes created by the excavation process are mining tool and operator dependent, it is thought best to first focus on the development of a general model for the discharge of returned sediment out of a vertical discharge pipe.

One of the main design parameters which can be used to control the size of this plume, is the water depth at which the plume is released. Legislation developments are currently moving towards discouraging a discharge in the upper water column up to 1km of water depth (Spearman, 2016). The arguments are to avoid influences on the various depth-zones which are significant to local organisms. Remaining options are to discharge close to the minimum depth, deeper down, or even close to the seafloor.

Discharging close to the seafloor would have the advantage of a short deposition distance, which would mean that the plume would deposit quickly before the currents have a chance to carry it away for long distances. A model to properly investigate this option is however lacking. There is also no measurement data available to validate such a model.

The goal of the research described in this paper is to develop a predictive model and to investigate the influence of discharging close to the seafloor on the turbidity plume.

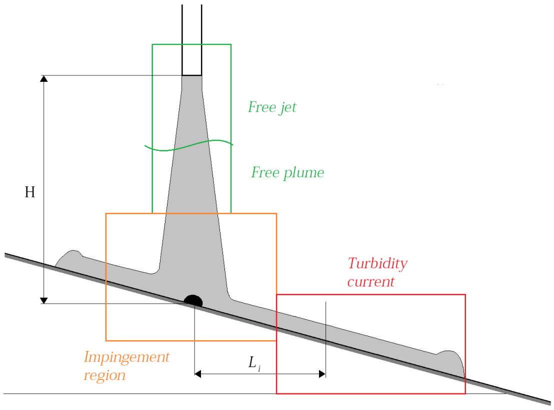
The main questions of the research programme are:

- What is the relation between the depth of discharge and the deposition rate?
- What is the relation between the depth of discharge and the turbidity dilution rate?
- What is influence of the bed slope; can a slope cause unstable turbidity currents?

SHORT DESCRIPTION OF THE TURBIDITY PLUME BEHAVIOR

The particle sizes of the returned sediment are expected to be in the order of 64 μm and smaller (roughly the thickness of a human hair). The presence of cohesive particles such as clay could create flocs, which are larger as they form a cluster. Thus, when the flow of sediment waste and other effluents leaves the discharge pipe, it behaves as a mixture of sediment and water. The fluid density difference and discharge momentum will drive the initial flow, defined in literature as a dense turbulent jet. The jet will lose its momentum as it progresses downwards, growing in volume due to the entrainment of surrounding water (see Figure 1a). It is the process within the initial meters of the discharge that achieve the highest dilution rates.

After a transition distance, the jet is driven mainly by the fluid density difference which defines it as a plume. Under the influence of ambient currents, the plume might deflect in the direction the current (Figure 1b). However, if the plume reaches the seabed before deflecting, it will impinge on the seabed. In this case, the plume will radially spread and continue flowing as a turbidity current on top of the seabed. Within this process, the larger particles will settle close to the source, whereas the smaller particles will be carried for longer distances before depositing on the sea floor.



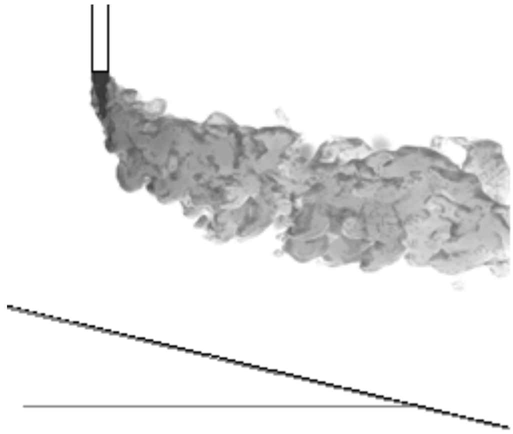


Figure 1(a) The three regions of a particle-laden impinging jet (b) bend plume.

Depending on the velocity of this current, the shear stress on the seabed could be sufficient to erode the top layer and suspend sediment particles. Considering a negative inclination angle of the seafloor below, it might even initiate an avalanche if the erosion is higher than the deposition and the weight of the current increases thereby accelerating it.

REGIMES OF INTEREST

Figure 2 shows the relation between the buoyancy force of the discharged plume (B_{j0}) and the deflection of the plume for different crossflow velocities (U_{cf}). The y-axis shows the influence of stand off distance on a logarithmic scale. Currents in the deep sea (< 1km water depth) are on average roughly 0.05 m/s and fluctuate roughly between 0 and 0.15 m/s. Values for B_{j0} are roughly expected between 0.015 and 0.04 m^4/s^3, based on a suspended sediment concentration (SSC) range of 5 - 15 g/l, a discharge pipe diameter of 0.4 m and a velocity of 4 m/s.

This graph can be used to indicate that under average conditions, a discharge height of roughly 100m from the seabed could ensure an impingement on the seafloor before bending off under the influence of ambient currents (green lines). However, if ambient currents would reach 0.15 m/s, the plume would bend off if the discharge standoff distance would be higher than 10 m (purple lines). These values are used for reference to simulate the discharge scenarios in the laboratory.

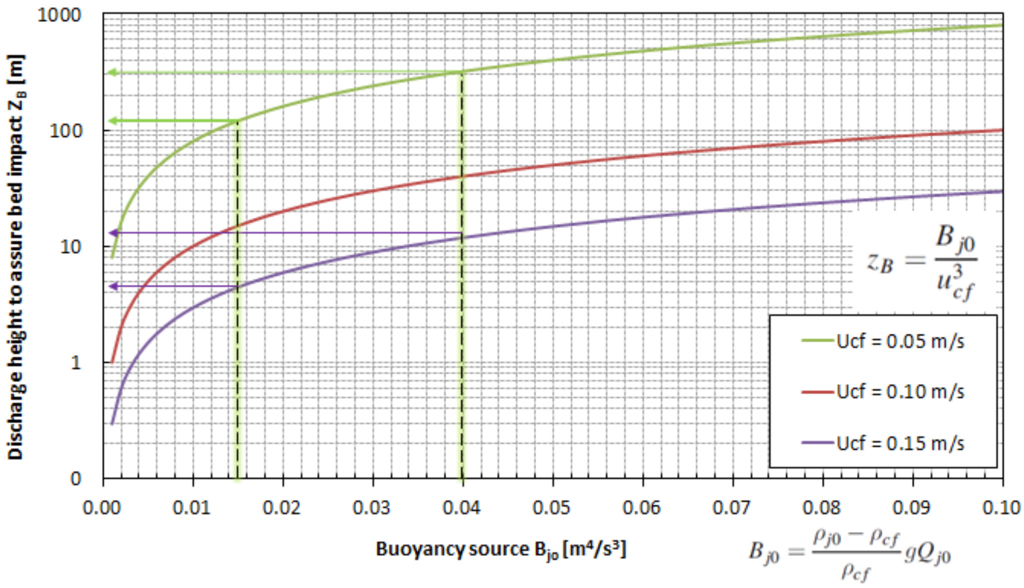


Figure 2. Required discharge distance to ensure bed impact for various ambient currents.

LABORATORY EXPERIMENTS

The main goal of the experiments is to simulate various seabed mining discharge scenarios in a controlled laboratory environment, in order to quantify the near-field behaviour of the turbidity plume for numerical model validation. The emphasis is on the inclusion of settling particles inside the submerged plume. The effect of ambient currents is not studied within these experiments. Instead, the plume will impinge vertically on a boundary and spread out horizontally into a current.

Within this laboratory study, the aim is to measure the velocity and concentration changes along the centreline of the turbidity current under steady conditions, after it has transitioned along the horizontal wall. In order to keep the experiments under controlled conditions, a Froude scale of 1:50 was chosen.

For this purpose, a rectangular tank with glass panels was constructed in the Delft University dredging laboratory (see Figure 3). The tank measures 5.0 m in length, 2.5m in width and 2.0 m in height. These sizes are chosen to represent a near-field water column of 250x125x100 meters. On the bottom of the tank, a large table measuring 4.5 x 2.0 m was placed to represent a simplified seafloor which can be inclined to represent bed slopes. An interface of sliding profiled aluminium beams is fitted to the top of the tank to mount a round discharge pipe (ID = 10 mm) and measurement equipment or cameras.

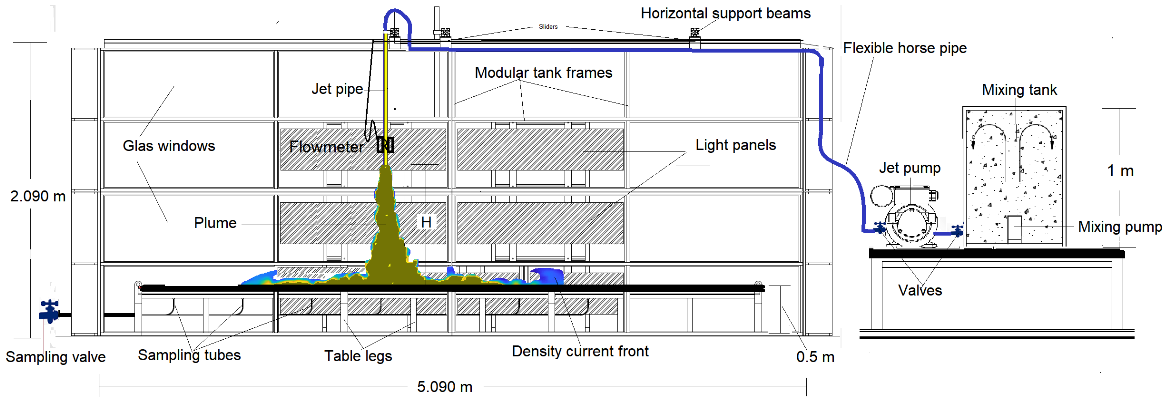


Figure 3. Experimental set-up (Byishimo, 2018)

A reservoir is placed next to the tank in order to create the sediment-water mixture. The used sediment consists of fine grinded quarts particles (Millisil M10). These particles provide a small particle size (4 – 60 µm) and cannot flocculate. Practically all non-settling particles (< 15µm) were filtered out to keep visual access and be able to re-use the 25.000L water for several measurements. A submerged pump keeps the small particles continuously mixed and suspended. A small pump is added after the reservoir to pump the mixture via a flexible hose to the discharge pipe submerged in the tank. An acoustic sensor measures the mixture velocity before leaving the discharge pipe. This velocity can be controlled by setting a ball valve between the pump and the jet pipe. It was fixed during all measurements at a velocity of 0.7 m/s.

A camera can observe the discharged plume through the glass walls and log the overall development of the plume. Via nine flexible sampling tubes connected along the centreline of the table, the turbidity current can be drained when passing with a sampling valve at the front of the tank, and analysed with an infrared turbidity sampler. An submerged infrared turbidity sensor and acoustic velocity sensor can measure the centreline changes of the plume over height and distance travelled. This data is gathered by a data logger and stored on a PC.

RESULTS

Plume development

A total of nine different experiments were performed for a bed without inclination, and these experiments were repeated for an inclined bed with an angle of 10º. Initial concentrations were varied between 5, 10 and 20 g/L. Discharge heights varied between 0.25, 0.50 and 1.00 meter. The big dataset is not fully analysed yet, however some of the results are treated in the following section.

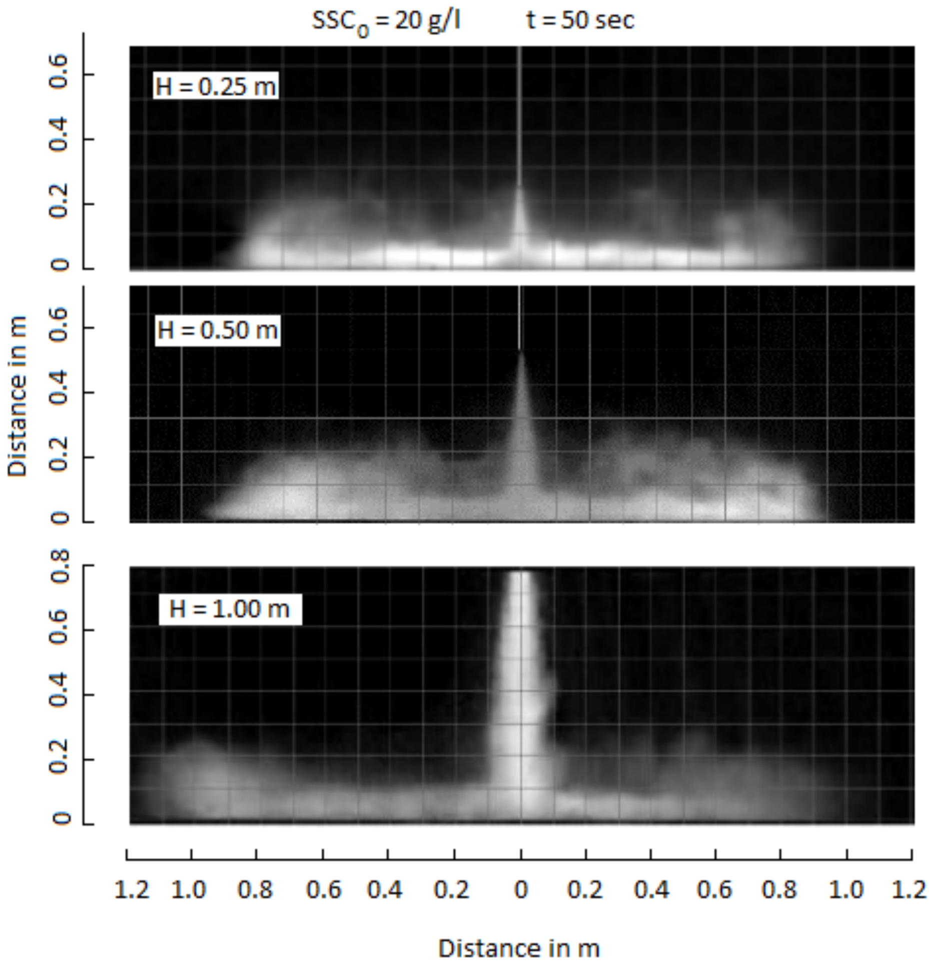


Figure 4. Snapshots of the created laboratory turbidity plumes after 50 seconds. Adapted from Warringa (2017).

Figure 4 shows the snapshots of the developed turbidity plume impinging on the bed, creating a horizontal turbidity current. These images were created by adding a few millilitres fluorescent ink to the discharged mixture in combination with a high powered UV-canon to enhance contrast. The tank and camera were fully covered by a black sheet to further increase contrast.

Measurement data from the velocity and turbidity sensors was taken along the central axis of the current, in x- and y-axis. Measurement data was logged after an initial 5 minute break to create a time-average steady turbidity current above the table. After these 5 minutes, ab ADV sensor would log a vertical velocity profile by gradually measuring 13 points for ~67 seconds at 15 Hz.

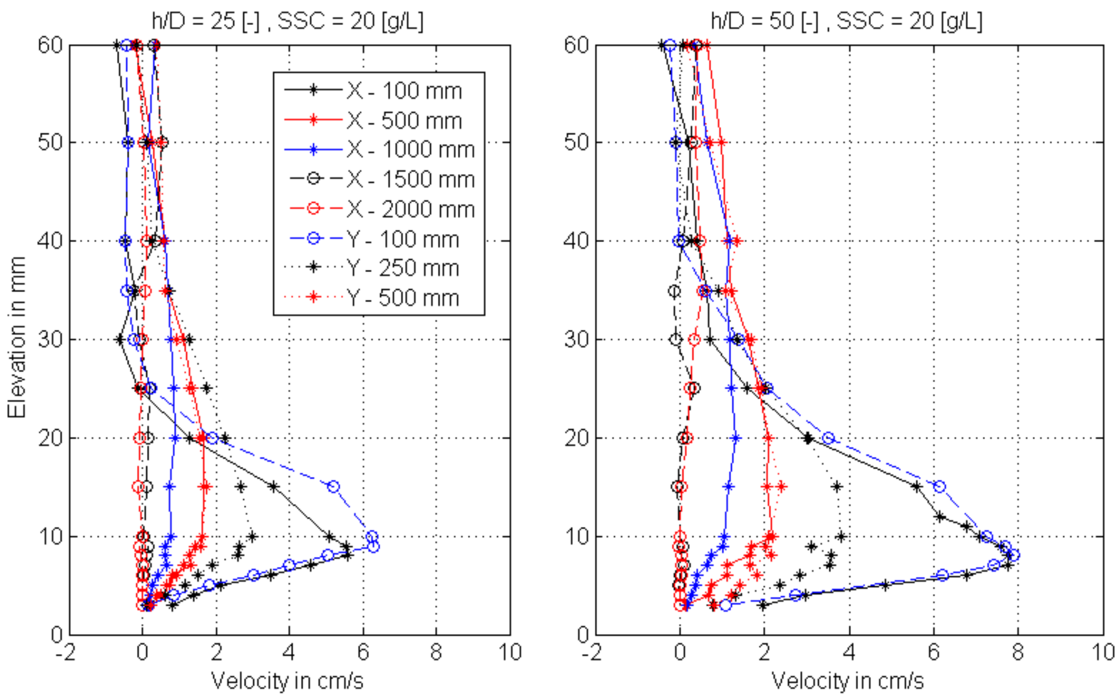


Figure 5. Turbidity current velocity profiles (Ux) taken for a relative height of 25 mm and 50 mm from the bed, both at an initial suspended sediment concentration of 20 g/l. In the legend, X represents the profile locations along the turbidity current length relative from the impingement point, and Y the width.

Figure 5 shows a relative good overlap between the velocity profiles on the x-axis and y-axis data at equal distances from the impingement point. These should be equal, as the plume spreads axisymmetric in radial direction after impingement, given a flat bed. This comparison can be used to estimate the measurement accuracy, which looks good.

The velocity profiles show a maximum peak roughly 10 mm above the bed, at a velocity which is in the order of 10% of the initial discharge velocity (71 cm/s). Initial results show that the plume discharged at 500 mm the height from the bed, has a turbidity current with higher maximum velocities compared to the plume released at 250 mm. This difference is maintained until the end of the near-field, roughly 1.5 – 2.0 meters (150 – 200 times the discharge pipe diameter).

This difference could indicate that the plume accelerates before hitting the bed, causing the plume released at a higher point to achieve higher current velocities after impact. Higher velocities of the current increase the capability of suspending particles on the bed and also carry the particles over a longer distance. This would mean that, based on these two experiments, it would be advisable to discharge closer to the bed rather than farther away with respect to the environmental impact.

Further analysis of the created dataset in the near-future should indicate whether these findings are consistent. It should also be noted that field conditions which are not considered in these experiments, such as the presence of a sedimentary bed or ambient currents, could render different results. There is also a scaling factor of 1:50 involved which creates inaccuracy when scaling all parameters to field scale. This can however be done more accurately with a numerical model, which can be validated based on the gathered measurement data.

Acknowledgements

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B.V. The Authors are grateful for their support. The effort and enthusiasm of MSc students P. Byshimo, S. Warringa and laboratory technicians F. Brakel and E. Stok was also considered essential to the success of the experiments.

References

Byishimo P (2018) Experiments and 3D CFD simulations of deep-sea mining plume dispersion and seabed interactions. MSc Thesis. Technical University of Delft, The Netherlands. In print.

Decrop B (2015) Numerical and experimental modelling of near-field overflow dredging plumes. PhD Thesis, Ghent University, Belgium.

Lee J H W and Cheung V (1990) Generalized lagrangian model for buoyant jets in current, Journal of Environmental Engineering 116: 1085-1106.

Jirka G H (2004) Integral model for turbulent buoyant jets in unbounded stratified flows. part I: single round jet, Environmental Fluid Mechanics 4 : 1-56

Spearman (2016) Insights and future research into the impacts of deep sea mining, WODCON XXI Proceedings, Miami, USA. pp. 1174-85

Warringa S (2017) Plume impact on the sea floor, MSc research exercise report, Technical University of Delft, The Netherlands.

Wit L de (2015) 3D CFD Modelling of overflow dredging plumes. PhD Thesis, Technical University of Delft, The Netherlands.

Keywords: Turbidity plumes, dispersion and deposition, laboratory experiments.

Ir. Frans van Grunsven

Ir. Frans van Grunsven is currently finalizing his PhD research at the Technical University of Delft in the section Offshore and Dredging Engineering. He holds a Master's degree in offshore and dredging with a background in Mechanical Engineering. He specializes in the field of fluid dynamics concerning the flow of sediment-water mixtures for dredging and marine mining applications. During his master thesis, he designed and built a laboratory test-setup to investigate the hydraulic transport of highly concentrated slurries within long vertical pipes for the application in deep sea mining. During his experiments, he found experimental proof for a theoretical blocking mechanism within the vertical transport system. Within his current research, he studies the initial development of turbidity plumes and their interaction with the seabed.

Design considerations for deep sea mining umbilicals

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ABSTRACT

Outline:

· De Regt Marine Cables.

· The link between system requirements and umbilical requirements (which system requirements have the largest impact on the umbilical design).

· Design options for deep sea mining umbilicals (showing the various options for strength member constructions, power conductors and data-transmission).

· Technical challenges and risks (outline on the most important technical challenges and risks involved in the construction, production and usage of deep sea umbilicals).

· Umbilicals for the SWORD and Blue Nodules project.

Deep-Sea Mining R&D Activities in the NMRI

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ABSTRACT

The NMRI is the major research center of maritime technology in Japan with world-class research facilities. During the last decade, the NMRI's Deep Sea Technology Research Group has allocated a significant R&D effort on subsea technology applied to Deep-Sea Mining (DSM). The main focus is on the hydrothermal deposits located within the Japanese EEZ. In this article, we will introduce two experimental facilities, the Deep-Sea Basin and the High-Pressure Tank, that have been used for the DSM reduced-scale experimental research. Then we will present some R&D projects regarding the dynamic behavior of riser pipes, multiphase flow inside the pipe for ore-lift, and seafloor mineral processing.

Introduction

Japan's territorial sea combined with its Economic Exclusive Zone (EEZ) has about 4,470,000 km^2 of the sea surface, which is about 12 times larger than the Japanese land area. Further, there are the tectonic convergent boundaries of three main plates, namely, Pacific plate, Philippine Plate, and Eurasian Plate. Along two of these convergent boundaries, namely, Okinawa Trough and Izu-Ogasawara Arc, there are several submarine hydrothermal fields where the precipitation of sulfide minerals from hydrothermal fluids generated the Seafloor Massive Sulfides (Figure 1). Such hydrothermal fields are located in water depths between 700~1600m.

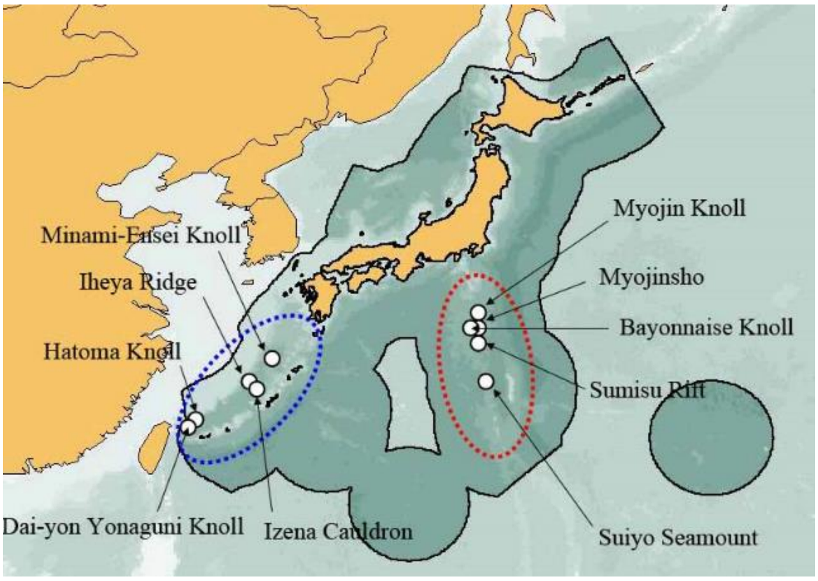

Figure 1. Major hydrothermal fields in the Japanese EEZ. The Izu-Ogasawara Arc is located inside the red-dashed circle, and the Okinawa Trough is inside the blue-dashed circle. The area within the solid lines is Japanese EEZ (Nakajima et al., 2018).

During the last decade, the NMRI has been developed several R&D projects with different partners regarding riser pipe, multiphase flow in a pipe, seafloor mineral processing system, environmental impact, etc. However, in this article, we will present only experimental research projects funded by the NMRI's own budget and the competitive research funds (Kakenhi) granted by the Japanese Society for the Promotion of Science (JSPS).

Research Facilities

Deep-Sea Basin

The Deep-Sea Basin is Japan's deepest experimental basin with 35 m of water depth (Figure 2). It is composed by a circular basin (diameter of 16 m and depth of 5 m) and a deep pit (diameter of 5 m and depth of 30 m). This basin is equipped with a visual measurement system that is composed of sets of cameras installed along the basin. This system can measure the 3D motion of several targets that are attached to the reduced scale model. The basin also has a wave generation system composed of 128 sets of flap-type absorbing wave generators capable to provide multidirectional regular and irregular waves. We can also generate water current in a specific location inside the basin.

In the Deep-Sea Basin, we have carried out experiments regarding riser pipes and internal multiphase flow (e.g. air-lift) that we will give some examples later in this article.

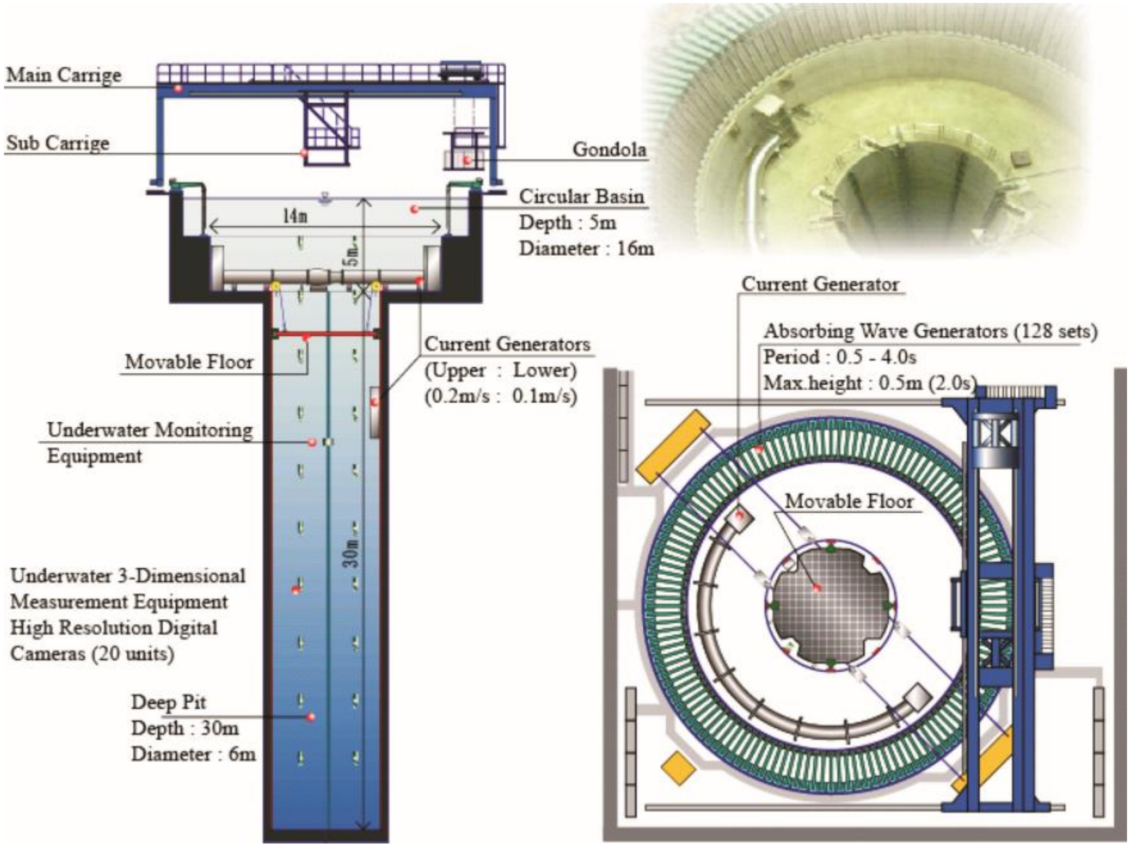

Figure 2. The NMRI'S Deep Sea Basin.

High-Pressure Tank

The High-Pressure Tank has a volumetric capacity of 2.8 m^3 (diameter of 1.1 m and depth of 3 m). Inside the tank, there are (i) the Circulation Equipment to generate a water current on the bottom, (ii) six monitoring cameras installed along the tank, and (iii) a pipe for injection of fluid (Figure 3).

The tank maximum internal pressure is 60 MPa and the internal temperature can be reduced down to 3° C. These pressure and temperature combined corresponds to an ocean environmental condition of 6000 m of water depth.

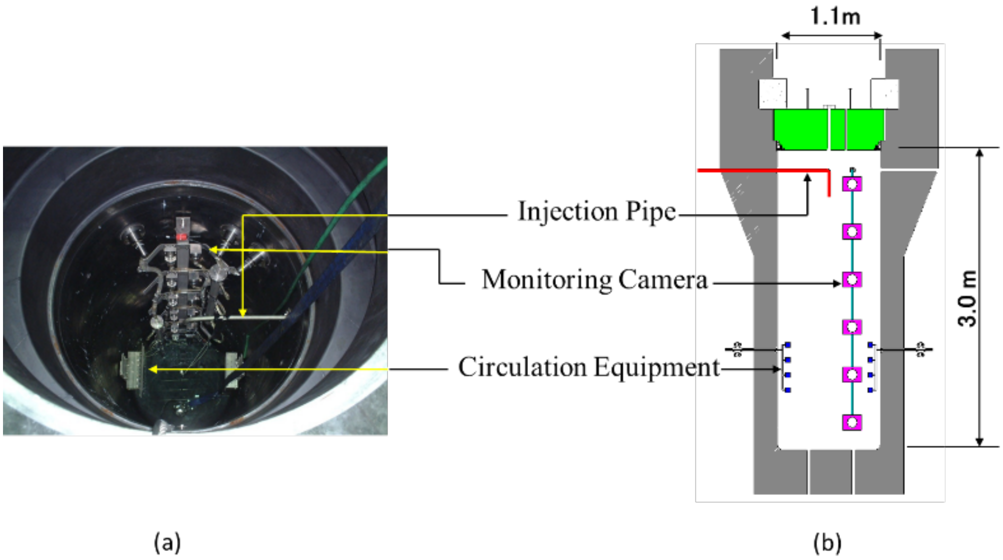

Figure 3. The NMRI's High-Pressure Tank. (a) Top view of the tank showing internal devices and (b) schematic of the side view of the tank.

R&D Activities

Figure 4 shows a schematic of SMS production system. A Seafloor Mining Tool collects the SMS crude ore located on the seafloor. Then this ore is pumped to a subsea lift pump to be conveyed throughout an ore-lift riser up to the production vessel. Because the sea water from seafloor may have different chemical and physical characteristics than the sea surface water, the seafloor sea water shall be conveyed back to the bottom throughout a separate water-return riser. Following, we will present some experimental projects that we have been developed in the NMRI.

Riser System

We carried out several experiments using reduced scale model of riser and flowlines including multiphase internal Flow. Figure 5 shows details about the first experiment that we compared single-phase (only water) and multiphase flows (water and solids) riser dynamic response of the top oscillation. In this experiment, the fluid was injected from the top. Figure 6 compares the results in the frequency domain. We can see that the main response occurred at the same frequency of the top oscillation. When we compare the amplitudes response, the modal shape is different due to the internal flow.

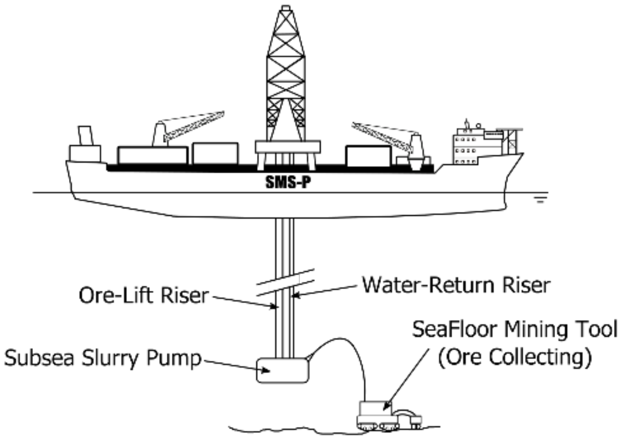

Figure 4. Schematic of a SMS production system.

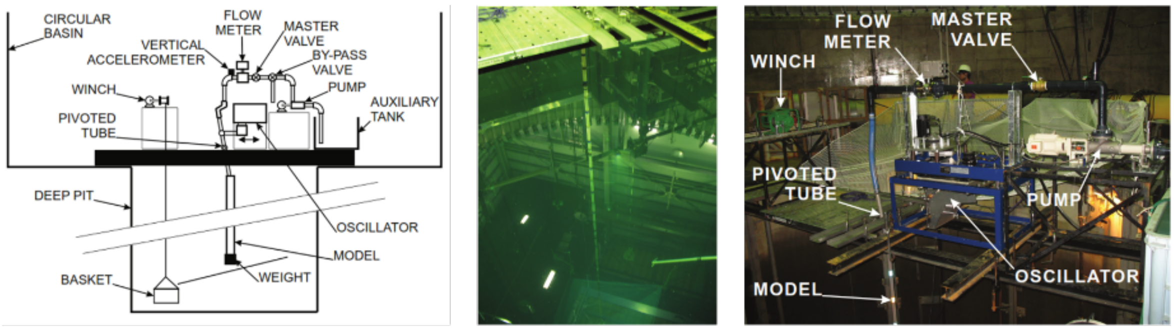

Figure 5. (a) Schematic of the riser experiment; (b) picture of riser model in the basin; and (c) picture experimental apparatus (Yamamoto et al., 2010).

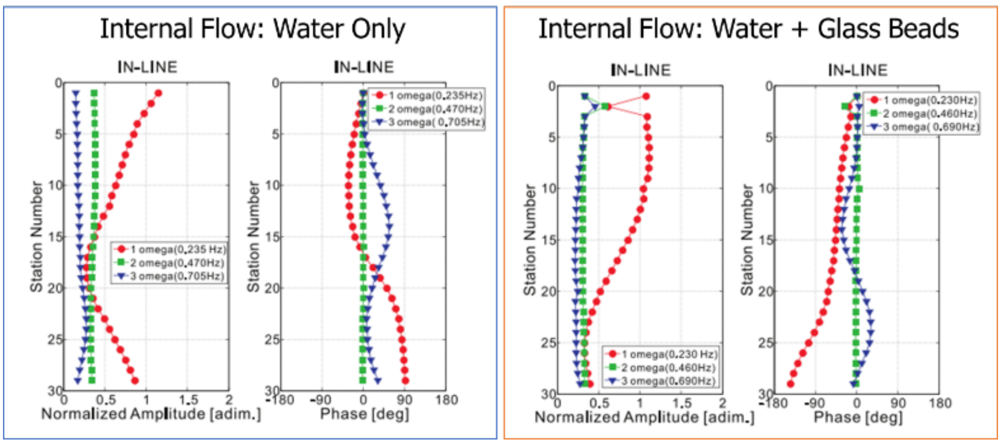

Figure 6. Comparison of response for a riser model with the internal flow with only water and water with glass beads (Yamamoto, 2011).

Multiphase Flow in Pipes

We also carried out several experiments regarding multiphase flow conveyed in pipes. In Masanobu *et al.* (2017), we validated a proposed calculation model of multiphase flow pressure drop using several types of solids (Figure 7).

In another experiment, the air-lift was used to lift glass beads (diameter of 4 mm). Figure 8a shows the experimental apparatus. Figure 8b has the experimental results, we can observe that there are optimum liquid-gas ratios to maximize the solids lift.

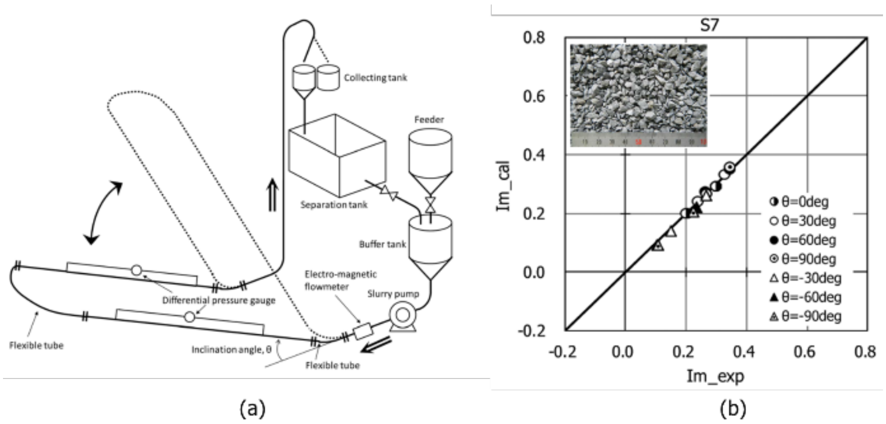

Figure 7. (a) experimental apparatus to measure pressure drop with different pipe inclination; (b) comparison of the experimental and calculated pressure drop of multiphase flow gravel-water (Masanobu et al., 2017).

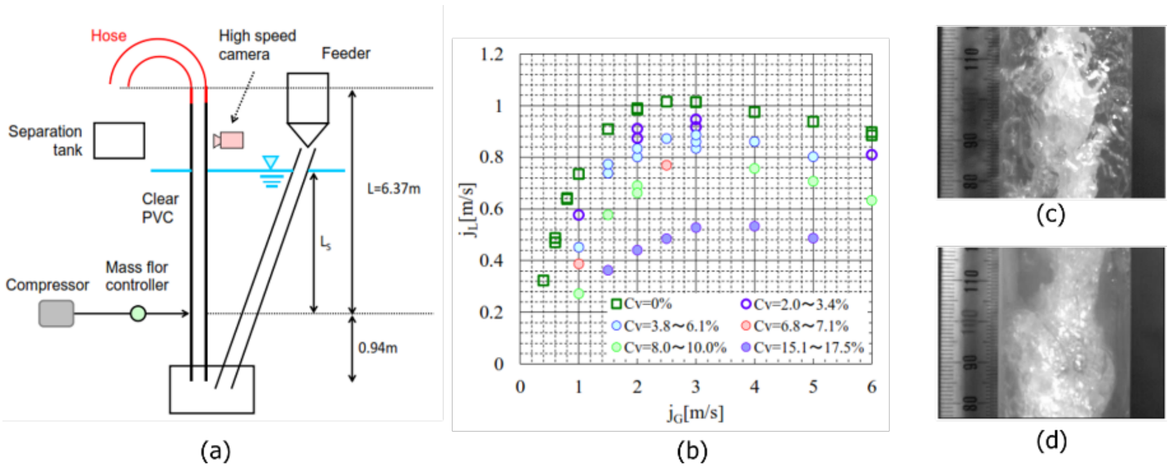

Figure 8. (a) Schematic of the apparatus used in the air-lift experiment; (b) relation of delivered solid concentration and water flow; (c) picture of churn pattern; (d) picture of plug pattern (Takano et al., 2017).

Seafloor Mineral Processing

In the conventional production system, the crude ore is pumped straight to the production vessel (Figure 4). Then the mineral is processed on land and the tailings must be properly disposed. However, the concept of the seafloor mineral processing (Figure 9a) intends to separate the tailings using a floatation column (Figure 9b) on the seafloor and only the high-grade ore is pumped to the surface. In this case, the tailings are left on the seafloor.

To process the mineral, it is necessary to grind the crude ore. Figure 10 shows the details about the ball mill grinder that was tested in the High-Pressure Tank. After the crude ore is reduced into fine particles, the high-grade ore can be separate from the tailings using a flotation column. The seafloor mineral processing includes also the development of Laser-Induced Breakdown Spectroscopy to measure the metal grade of the processed ore (Nakajima *et al.,* 2018).

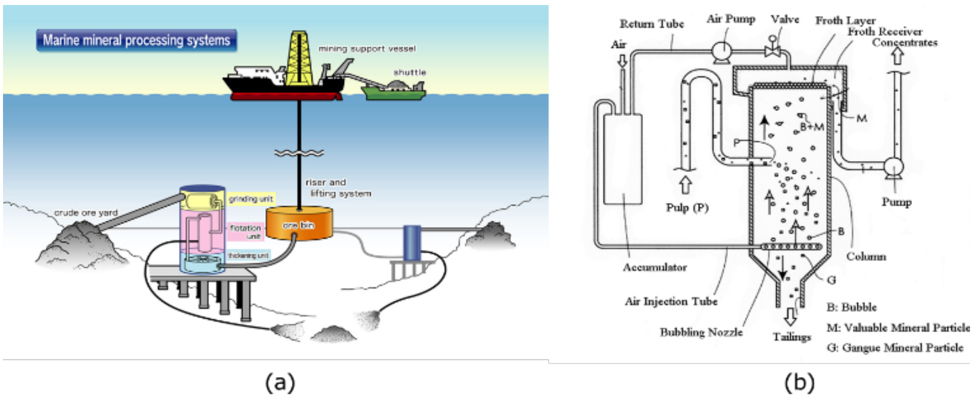

Figure 9. (a) The concept of the seafloor mineral processing for SMS. (b) The concept of the separation unit of the seafloor mineral processing system (Nakajima et al., 2018).

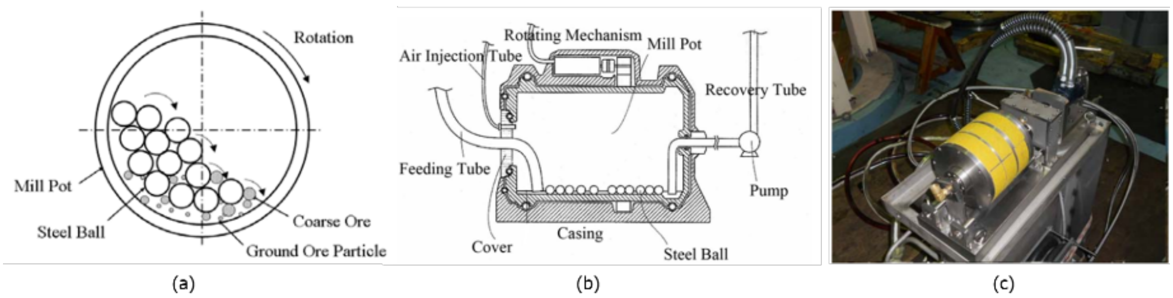

Figure 10. (a) Mechanism of ball mill grinder; (b) concept of grinding unit for the seafloor mineral processing; (c) reduced scale ball mill grinder tested in the High-Pressure Tank (Nakajima et al., 2013).

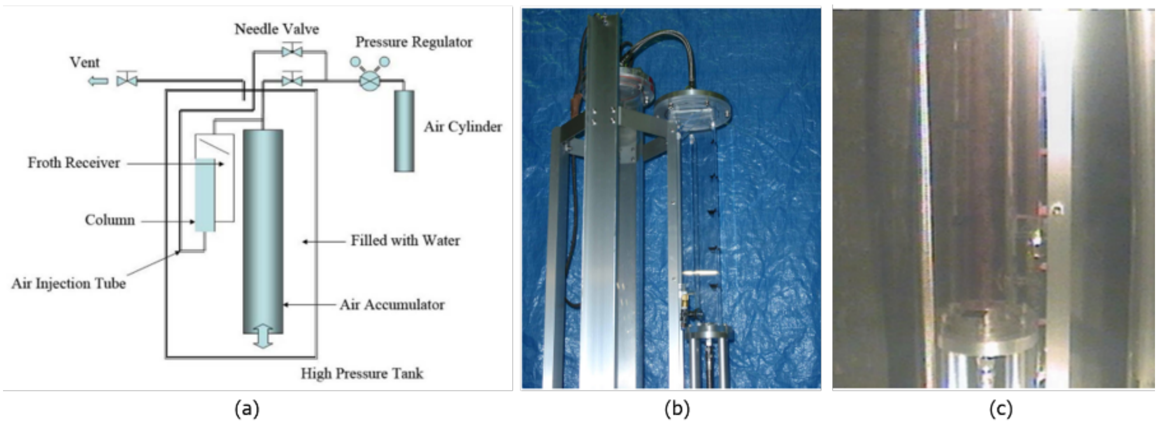

Figure 11. (a) Schematic of the reduced scale flotation column; (b) picture of the flotation column before the experiment; (c) picture of the flotation column during 5 MPa experiment in the High-Pressure Tank (Nakajima et al., 2011).

Conclusions

The NMRI's Deep Sea Technology Research Group has been developed several R&D projects regarding several subsea technologies applied to deep-sea mining. Several of these projects were carried out in cooperation with several Japanese companies and other governmental agencies.

During the last decade, we could expand our knowledge in this new technological field by the numerical simulation, experiments using reduced scale model and other analyses. However, only a fraction of these R&D projects has been published because the confidentiality contracts signed with our partners. Our efforts have been focused only on SMS located in the Japanese EEZ, but we are looking forward to expand our scope for different types of seafloor mineral accumulation.

References

Masanobu, S., *et al.* "Study on Hydraulic Transport of Large Solid Particles in Inclined Pipes for Subsea Mining," Journal of Offshore Mechanics and Arctic Engineering, Vol. 139, October 2017.

Nakajima, Y. *et al.* "Concept of Seafloor Mineral Processing for Development of Seafloor Massive Sulfides," in Proc. OMAE 2011, Rotterdam, OMAE2011-49981, 2011.

Nakajima, Y. *et al.* "Study on Grinding Technology for Seafloor Mineral Processing," in Proc. OMAE 2013, Nantes, OMAE2013-10756, 2013.

Nakajima, Y., *et al.* "Measurement of Metal Grade of Ore Particles in Slurry Using Laser-Induced Breakdown Spectroscopy," in Proc. Oceans'18, Kobe, 2018.

Takano, S., *et al.* "Experimental Study on Air-Lift Pumping for Subsea Mining," in Proc. 25^{th} JASNAOE Conference (in Japanese), 2017.

Yamamoto, M.*, et al.* "An Experimental Analysis of the Interaction between Hanged Pipe and Internal Flow," in Proc. OMAE 2010. Shanghai, OMAE2010-20312, 2010.

Yamamoto, M. "A Study about the Dynamic Behavior of Flexible Tubes Including Internal," Yokohama National University, Dr.Eng. dissertation, 2011

Keywords: Deep-Sea Mining, Research & Development, Riser Systems, Multiphase Flow in Pipes, Seafloor Mineral Processing.

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Some members of the NMRI's Deep-Sea Technology Research Group (the speaker wears the orange raincoat).

I have two academic backgrounds: Petroleum Engineering & Ocean Engineering. I earned my BS degree in Control & Automation Engineering and MSc degree in Petroleum Engineering from the University of Campinas, Brazil. My doctor degree in Ocean Engineering was issued by the Yokohama National University, Japan.

My career has a few academic positions: project researcher at the University of Tokyo (Japan) and assistant professor in Well Construction at the University of Sao Paulo (Brazil). Since April 2018, I am a researcher in the NMRI's Deep Sea Technology Research Group. Currently, my R&D interest includes Subsea Production Systems, Subsea Well Construction, Methane Hydrate Development and Deep-Sea Mining.

Tectono-magmatic controls for seafloor massive sulfide deposit (SMS) formation in a back-arc setting; a clue to exploration

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ABSTRACT

A concept of plate-tectonic controls for the formation of seafloor massive sulfide (SMS) deposits in back-arc settings was established by Franklin et al. (2005). According to Franklin et al. (2005), a consequence of extension and rifting is subsidence, thinning of the crust, and the rise of hot, athenospheric mantle into the base of the crust. Underplating of the crust by mafic magmas results in low-pressure partial melting of the hydrated crust at a <15-km depth, and the generation of felsic anhydrous melts. The rapid ascent of hot felsic melts, along with mantle-derived mafic melts, results in bimodal volcanism that characterizes rift and volcanogenic massive sulfide deposits (VMS) environments. The rapid and focused advection of the magmatic heat within the rift to the near-surface environment which are required to sustain vigorous long-lived VMS hydrothermal systems. Faults within rift environments may also allow seawater to penetrate into subvolcanic intrusions and mix with magmatically generated metalliferous fluid or allow a direct magmatic contribution from shallow crustal level (3–12 km) magma chambers (Franklin et al., 2005, and references therein). In addition, the caldera-forming processes are favorable for the formation of VMS deposits and the focused high heat flow and cross-stratal structural permeability that is restricted in time and space to caldera development provides an explanation for the clustering of VMS deposits and their restriction to specific time-stratigraphic intervals and structures in the evolution of submarine central volcanic complexes (Franklin et al., 2005, and references therein). The concept is persuasive,

although it is based on a series of logically constructed reviews mainly focused on ancient on-land deposits.

To investigate the genesis of SMS deposits and to establish an effective method for their exploration, scientific oceanic drilling was conducted from 2014 to 2016 in three distinct morphological areas of the actively rifting middle Okinawa Trough in Japan, namely, the Iheya North Knoll, Iheya Minor Ridge, and Izena Hole (e.g., Takai et al., 2015; Kumagai et al., 2017a, b). The Okinawa Trough is a seafloor depression extending for 1,200 km behind the Ryukyu arc-trench system and is regarded to be either in its initial rifting stage, which began 6–9 Ma and precedes normal/stable seafloor spreading as the main stage of back-arc basin formation (Letouzey and Kimura 1985), or in its second stage of its rifting, which began 2 Ma (Sibuet et al. 1998). A Kuroko-type SMS deposit and active hydrothermal vents have been reported in this area (e.g., Halbach et al. 1989; Takai et al. 2011, 2015). Therefore, the Okinawa Trough is one of the foremost areas to understand in-situ and juvenile SMS formation. From a tectono-magmatic point of view, Yamasaki (2018a) further develops Franklin's concept based on coherent geological, petrological, and geochemical data from this area. A sequence of intrusion and solidification of basaltic magma, hydration of basaltic materials, and partial melting of those rocks can reasonably and coherently explain the origin of hydrothermal circulation and mineralization of three distinct morphological areas in the middle Okinawa Trough through alteration and SMS mineralization. Specifically, felsic magma is essentially formed by water-fluxed melting of basaltic materials formed by the previous mafic magmatism. This mechanism reasonably explains the similar isotopic signatures between mafic and felsic rocks by contemporaneous magmatism of bimodal composition, which has been suggested by previous studies. Introduction of seawater into the deep crust and water-fluxed melting in these areas inevitably involves high-temperature hydrothermal alteration and leaching of metal elements from mafic materials and produces Cu-rich, bimodal-mafic mineralization. Since the magmatism produces voluminous felsic rocks in the upper crust, the Cu-poor but Zn- and Pb-rich, bimodal-felsic mineralization is an expected result of felsic magmatism.

Confirmation of the concept of tectono-magmatic controls for formation of SMS deposits in the back-arc setting provides us with an important clue for their exploration as by-products. In general, electromagnetic surveys provide one of the most effective exploration methods of SMS deposits, corresponding to remote-sensing and/or airborne surveys for on-land deposits (e.g., Kawada and Kasaya, 2017). In addition, geochemical surveys offer one of the most powerful and direct tools employed in the exploration of on-land ore deposits. During on-land surveys, identification of alteration zones is commonly used to delineate mineralized areas. However, it is very difficult to perform oceanic SMS surveys without using benthic multi-coring systems (BMSs). As a result, there is a lack of information regarding the relationship between mineralization and alteration. Thus, it is challenging to determine the threshold constraint associated with the potential for ore deposits. The well-characterized sub-seafloor hydrothermal systems in the middle Okinawa Trough, which contain delineated recharge-discharge zones, provide an opportunity to both verify and develop geochemical exploration methods. In Yamasaki (2018b), whole-rock geochemical data were obtained from samples taken from recharge and discharge zones, and from migration zones between these two regions. The resulting geochemical signatures are difficult to interpret due to variations in mineralization as well as magmatic effects. Normalization of the compositions of samples obtained from the discharge and migration zones relative to the composition of the recharge zone reveals the relationship between the average normalized values of rare-earth and ore-related elements (Yamasaki, 2018b). This method successfully distinguishes enrichment due to magmatic differentiation and mineralization. The approach described herein also allows the location of the discharge zone to be inferred, even in the case of a thin covering of sediment above the seafloor. This technique could allow surveying via systematic or grid sampling using dredging and/or piston-coring methods, both of which are simpler and less expensive than conventional methods.

References

Franklin JM, Gibson HL, Jonasson IR, Galley AG (2005) Volcanogenic massive sulfide deposits. In: Hedenquist JW, Thompson JFH, Goldfarb RJ, Richards JP (eds) Econ Geol 100th Anniv Vol, 523–560

Halbach P, Nakamura K-I, Wahsner M, Lange J, Sakai H, Käselitz L, Hansen R-D, Yamano M, Post J, Prause B, Seifert R, Michaelis W, Teichmann F, Kinoshita M, Märten A, Ishibashi J, Czerwinski S, Blum N (1989) Probable modern analogue of Kuroko-type massive sulphide deposits in the Okinawa Trough back-arc basin. Nature 338:496–499

Kawada Y, Kasaya T (2017) Marine self-potential survey for exploring seafloor hydrothermal ore deposits. Sci Rep:7, doi: 10.1038/s41598-017-13920-0

Kumagai H, Nozaki T, Ishibashi J-i, Maeda L, CK16-01 on-board member (2017a) Cruise Report SIP-HOT II "Explorer" (SIP-Hydrothermal deposit in Okinawa Trough) CK16-01 (Exp. 908), JAMSTEC, Yokosuka (443 pp) (http://www.godac.jamstec.go.jp/catalog/data/doc_catalog/media/CK16-01-908_all.pdf)

Kumagai H, Ishibashi J-i, Nozaki T, Maeda L, Yamada Y, Saruhashi T, Kyo M, CK16-05 On-board Member (2017) Preliminary results of the CK16-05 Cruise: Scientific drilling in Okinawa Trough of coring, logging using geothermal tool and refit of Long-term monitoring apparatus. JpGU–AGU Joint Meeting 2017, Chiba, SCG71-13

Letouzey J, Kimura M (1985) Okinawa Trough genesis: structure and evolution of a backarc basin developed in a continent. Mar Petrol Geol 2:111–130

Sibuet J-C, Deffontaines B, Hsu S-K, Thareau N, Le Formal J-P, Liu C-S, ACT party (1998) Okinawa trough backarc basin: Early tectonic and magmatic evolution. J Geophys Res 103:30245–30267

Takai K, Mottl MJ, Nielsen SH, the Expedition 331 Scientists (2011) Proceedings of IODP, 331: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.331.2011

Takai K, Kumagai H, Kubo Y, CK1404 on-board member (2015) Cruise Report SIP-HOT I "Pathfinder" (SIP-Hydrothermal deposit in Okinawa Trough) CK14-04 (Exp. 907), JAMSTEC, Yokosuka (116 pp.) (http://www.godac.jamstec.go.jp/catalog/data/doc_catalog/media/CK14-04-907_all.pdf)

Yamasaki, T., 2018a. The role of bimodal magmatism in seafloor massive sulfide (SMS) ore-forming systems at the middle Okinawa Trough, Japan. Ocean Sci J, in press.

Yamasaki, T. 2018b. Identification of geochemical signatures associated with seafloor massive sulfide mineralization at the Iheya North Knoll, middle Okinawa Trough. J Geochem Explor 188:55–72.

Keywords: Okinawa Trough, Iheya North Knoll, Iheya Minor RIdge, Cross-ministerial Strategic Innovation Promotion Program (SIP), DS/DV Chikyu

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Updated Economic Feasibility Analysis of Cobalt-rich Manganese Crust Mining Including the Substrate Rock Usage for Phosphates

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ABSTRACT

The importance of cobalt-rich manganese crusts on the Pacific seamounts for possible future rare metal sources has been recognized these 30 years. The thin layer-type coverage and the micro-topographic undulation of basement affect not only the excavation efficiency but also the economy of mining venture. Because of these distribution characteristics, no economic feasibility has been recognized through the past economic analyses. On the basis of a recent geological study about seamount rocks, a possibility of byproduct substrate recovery for phosphorous supply with cobalt-rich manganese crust mining has been highlighted. In the mining model, the substrate rocks are utilized as phosphates for agricultural and chemical usages. Under some preliminary technical and economic assumptions, the possibility of cobalt-rich manganese crust mining venture is examined. The results show a better economy of the venture including the substrate rock usage for phosphorous supply.

Introduction

Cobalt-rich Manganese Crusts and the Economic Feasibility

Cobalt-rich manganese crusts on the Pacific seamounts received attention as potential sources for strategic metals such as Co, Ni, Cu, and Mn, due to their vast distribution and higher cobalt concentration than manganese nodules (Cronan, 1980; Halbach, 1982; Manheim, 1986). In the earlier stage, the geological distribution characteristics were reported (Cronan, 1984; Clark et al., 1984; Misawa et al., 1987; Pichocki and Hoffert, 1987) and a systematic feasibility of the mining was studied (Hawaii DPED, 1987).

From the end of 1980s, Japan did many survey cruises for cobalt-rich manganese crusts in and around the Mid-Pacific Mountains (Yamazaki et al., 1994; Usui and Someya, 1997; Yamazaki and Sharma, 1998; MMAJ, 2001). Some key technological studies for the mining and the processing also were conducted (Aso et.al, 1992; DOMA, 1995; Yamazaki et al., 1995; Rokukawa, 1995; Yamazaki et al., 1996; DOMA, 1998). On the basis of these studies and referring some economic evaluation results for manganese nodule mining ventures (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990; Soreide et al., 2001), the economic potential of mining cobalt-rich manganese crusts for Co, Ni, and Cu was evaluated by Yamazaki et al. (2002). Some options and updated economies were considered in the series of the studies (Yamazaki and Park, 2005; Yamazaki, 2007; Goto et al., 2009; Goto et al., 2010). No economic feasibility of the crust mining venture, however, has been recognized, though the important role for future rare metal sources has been recognized (Hein, 2006).

Phosphorus Demand and Supply

Phosphorus is one of the three elements of fertilizer together with nitrogen and potassium, and it is essential elements for organisms. Many countries depend the phosphorous supply on on-land phosphates from US, Morocco, China, etc. Supporting the world population increase by food supply in developing countries, we need more phosphates. In developed countries including Japan, therefore, the recycle of phosphorus in population concentrated areas from food waste, sewage, and incineration ash, has been studied, but it is not costly and it has not been put to practical use (http://phosphorusfutures.net/).

These years, Japan imports the phosphates, about 300,000 tons per year, mainly from China and Morocco (http://www.waterforum.jp/twj/wscj/mtg/doc/1015-12.pdf). Marine phosphates near shore areas have received much attention as future Cd-free phosphate fertilizer resources in developed countries such as New Zealand and US these years (http://www.rockphosphate.co.nz; http://www.dondiego.mx). Japan, however, has no chance of such supply sources near shore areas.

Phosphorus Contents in Seamount Basement Rocks

Most of substrate rocks of cobalt-rich manganese crusts has recently been clarified as phosphatized limestone and hyaloclastite (Hein et al., 2016). About 12-15 % in their weights are phosphorous they are as shown in Fig. 1. This is an interesting topic for Japan, because we have huge areas of cobalt-rich manganese crusts in the Japan's exclusive economic zones (EEZ) and the adjacent ocean areas (MMAJ, 2001). The basement rocks unavoidably recovered with cobalt-rich manganese crusts during the mining operation (Goto et al., 2009) are equivalent to imported phosphates supplied from on-land resources.

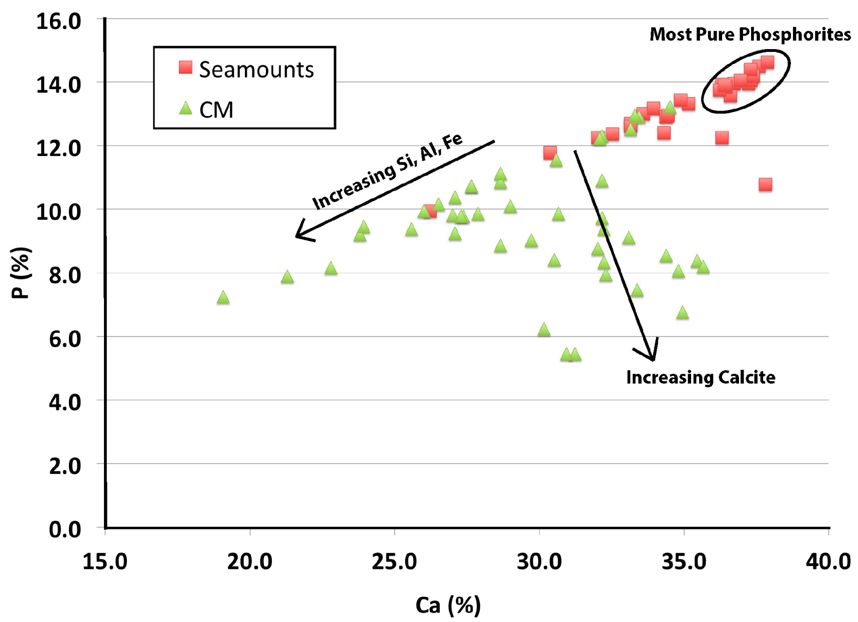

Fig. 1 Phosphorous contents in seamount rocks (Hein et al., 2016)

Mining Scenario of Cobalt-rich Manganese Crusts

Excavation Simulation by Seafloor Miner Model

Evaluating the excavation efficiency of cobalt-rich manganese crust mining, a simulation study by a miner model under idealized distribution conditions was conducted by the authors (Goto et al., 2009). The miner and the excavation models are introduced in Figs. 2 and 3, respectively.

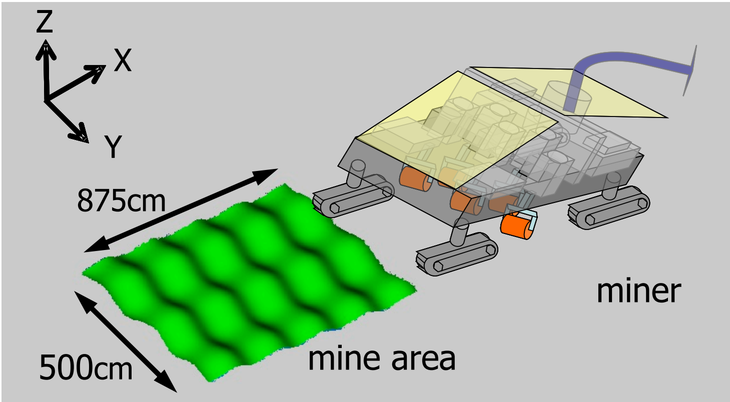

Fig. 2 Miner model for simulation (Goto et al., 2009)

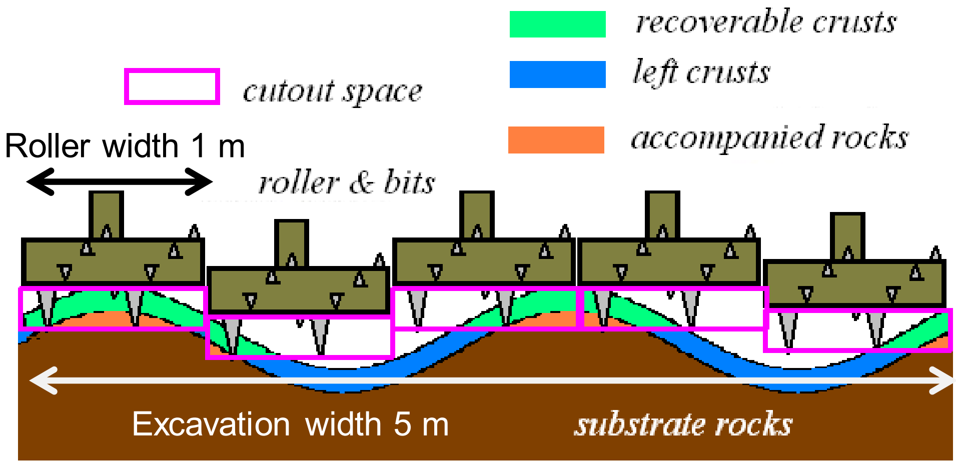

Fig. 3 Excavation model for simulation (Goto et al., 2009)

A result of the simulation is introduced in Fig. 4. The thickness of crust layer was assumed as 10 cm. Cross directional sigh wave patterns in micro-topographic undulations and a 10-degree inclination of mine area were given as idealized distribution conditions of Type 4 in Fig. 4. The amount of accompanied substrate rocks obviously increases by the cutout depth and the increase of recoverable crusts. The ratios of crusts and rocks in cases of 25 cm and 30 cm in cutout depth are certainly not good, because they look like a substrate rock mining.

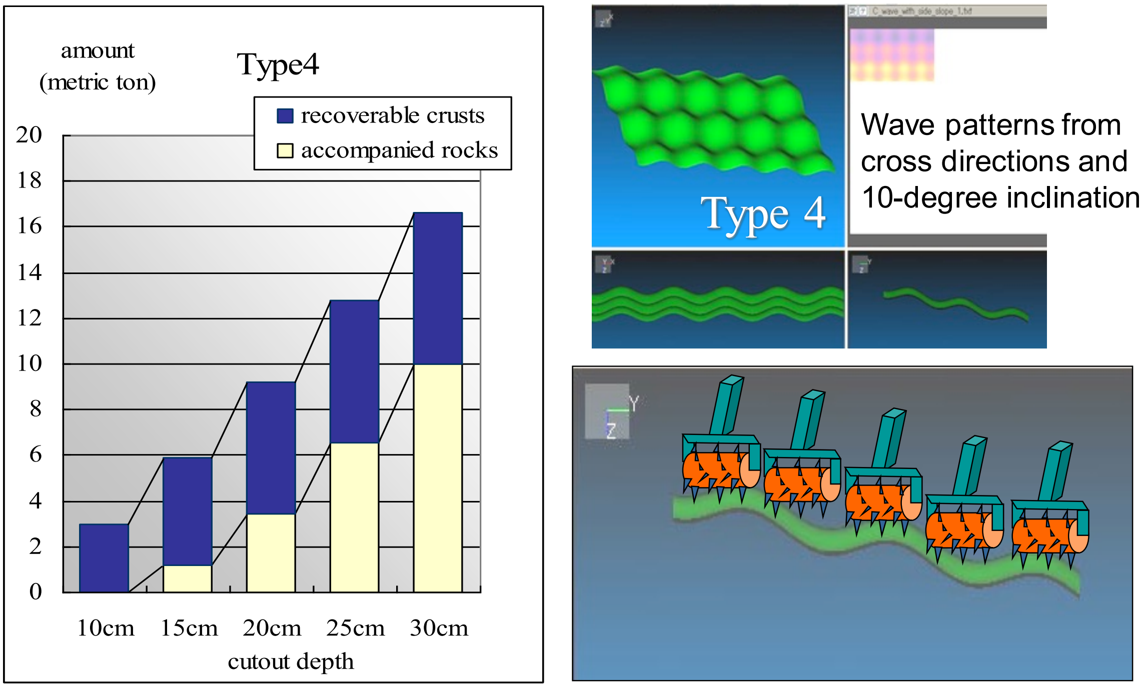

Fig. 4 A result of excavation simulation (Goto et al., 2009)

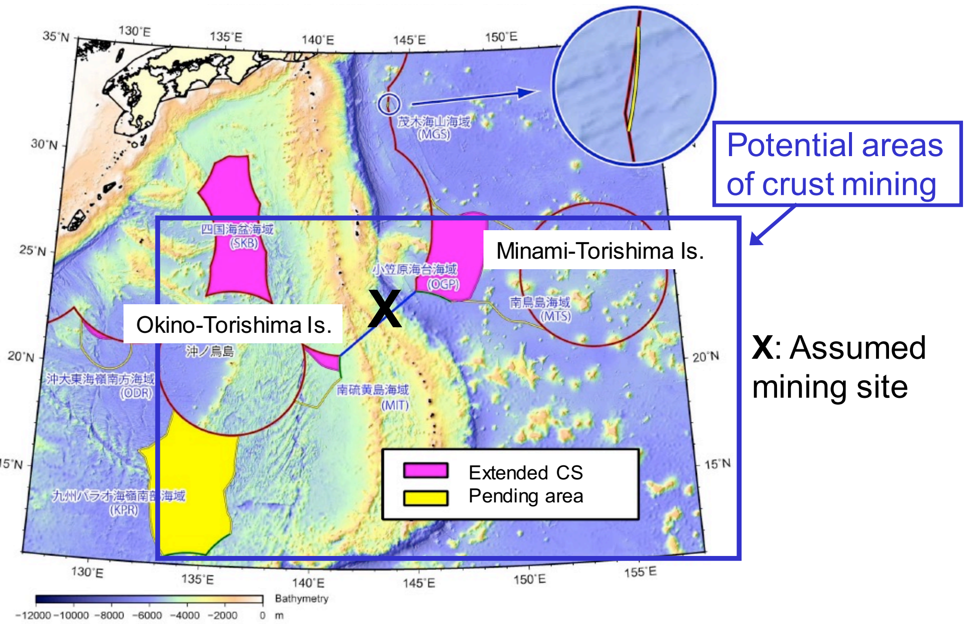

Fig. 5 Potential area of crust mining and assumed mining site

Mining Venture Model of Cobalt-rich Manganese Crusts for Japan

On the basis of the reported phosphorous contents of seamount basement rocks (Hein et al., 2016) and the authors' previous studies for economy of cobalt-rich manganese crust mining (Yamazaki et al., 2002; Yamazaki and Park, 2005; Yamazaki, 2007; Goto et al., 2009; Goto et al., 2010), a new mining venture model of cobalt-rich manganese crusts including the substrate rock usage for phosphates has been created. In the model, the assumed mining site is given in the potential area of crust mining in Japan's EEZ as shown in Fig. 5. The outline is of the model is introduced in Fig. 6. In the previous studies, after the ore dressing the substrate rocks were necessary to direct to dispose. The cost of dispose is very expensive in Japan because of the small land area and the much rain. In the new model, however, after the ore dressing, the substrate rocks are sold as phosphates.

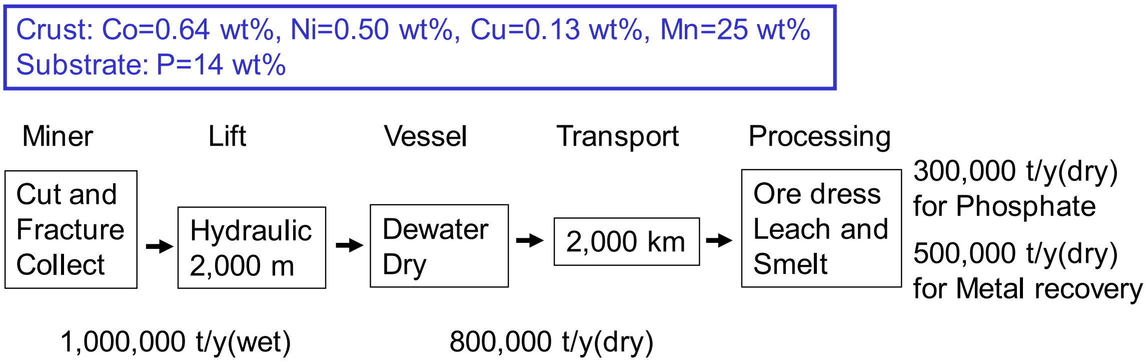

Fig. 6 Mining venture model for Japan

Economic Feasibility Analysis of the Mining Venture

Additional Conditions for Economic Analysis

Some additional parameters are necessary for the economic feasibility analysis of the mining venture. The parameters assumed in the analysis are summarized in Table 1. Because of the outer ocean condition of the mining site, the operation days per year is selected as 250. Referring two economic feasibility analyses for manganese nodule and seafloor massive sulfide mining (ISA, 2008; Okuhara, 2017), CAPEX and OPEX of the mining venture are calculated. They are introduced in Table 2. The CAPEX and OPEX of the mining, transportation, and ore dressing are introduced from Okuhara (2017), and the ones of the metallurgical processing is from ISA (2008).

Table 1 Parameters of operation of mining venture

Annual gathered	1 Mt
Daily gathered	4,000 t/day
Number of days worked	250 days/year
Transportation distance	2,000 km
Metal price	10 years average price except phosphate
Development terms	20 years (5 for construction and 15 for operation)

Table 2 CAPEX and OPEX of mining venture

Subsystem	Ore flow (t/y)	CAPEX(US$M)	OPEX(US$M)
Mining	1,000,000	730	133
Transportation	800,000	216	65
Ore dressing	800,000	39	15
Metallurgical processing	500,000 (Phosphate 300,000)	283	75
Total		1268	288

One more important parameter is metal price. The average ones last 10 years in Table 3 are given. The term last 5 years is selected for phosphate, because an influence of the phosphate price rise occurred in 2008 and 2009 is wanted to exclude.

Table 3 Metal prices used in analysis

Element	Average price from 2008 to 2017 except phosphate (US$/t)
Copper	6678
Nickel	16121
Cobalt	34698
Manganese	2463
Phosphate	120 (Ave. of last 5 years)

Table 4 Result of economic analysis

Net Present Value (US$M)	Internal Rate of Return (%)	Payback period (year)
-387	-6	22.9

Table 5 Result of sensitivity analysis by latest cobalt price

Net Present Value (US$M)	Internal Rate of Return (%)	Payback period (year)
390	5	12.1

Results of Economic Analysis and Sensitivity Analysis by Latest Cobalt Price

The result of analysis is shown in Table 4. Though the money inflow and outflow is improved about US$ 100 million per year with the phosphate sales, the economy is still negative. Therefore, a sensitivity analysis by cobalt price is conducted. The cobalt price at the end of 2017 has become about 3 times higher than the one in 2016 (cobalt.sekai-market.com). The back ground is a market forecast for electric and plug-in-highbred vehicles (https://sgforum.impress.co.jp/sites/default/files/image/sgnl201512_04zu3.png). Because cobalt is used as electrode for lithium-ion battery onboard of the vehicles, the demand is expected to increase with the market trend. The result of sensitivity analysis is introduced in Table 5. A better and positive result it is.

Concluding Remarks

The result of economic analysis of cobalt-rich manganese crust mining venture including the substrate rock usage for phosphorous supply is negative. However, the result of sensitivity analysis by cobalt price is positive. Further quantification of the mining venture model and understanding of future metal market are necessary.

References

Andrews, BV et al. (1983). Economic Viability of a Four-Metal Pioneer Deep Ocean Mining Venture, US Dept of Commerce, PB84-122563, 201p.

Aso, K et al. (1992). "Effect of Vibration Absorbers on the Longitudinal Vibration of a Pipe String in the Deep Sea - Part 1: In Case of Mining Cobalt Crusts," Int J Offshore and Polar Eng, Vol 2, pp 309-317.

Charles, C et al. (1990). "Views on Future Nodule Technologies Based on IFREMER-GEMONOD Studies," Materials and Society, Vol 14, pp 299-326.

Clark, A et al. (1984). "Assessment of Cobalt-rich Manganese Crusts in the Hawaiian, Johnston and Palmyra Islands' Exclusive Economic Zones," Natural Resources Forum, New York, UN, Vol 8, No 2, pp 163-174.

Cronan, DS (1980). Underwater Minerals, Academic Press, London, 362pp.

Cronan, DS (1984). "Criteria for the Recognition of Areas of Potentially Economic Manganese Nodules and Encrustations in the CCOP/SOPAC Region of the Central and Southwestern Tropical Pacific," South Pacific Marine Geol Notes, Vol 3, No 1, pp 1-17.

DOMA (1995). Research Report on Mining System for Cobalt-Rich Manganese Crusts, Deep Ocean Minerals Association, Tokyo, 92p (in Japanese, unpublished).

DOMA (1998). Research Report on Ore Dressing Technology for Cobalt-Rich Manganese Crusts, Deep Ocean Minerals Association, Tokyo, 158p (in Japanese, unpublished).

Goto, K et al. (2009). "Effects of Microtopography on Mining Possibility of Cobalt-rich Manganese Crusts," Proc 8th ISOPE Ocean Mining Symp, Chennnai, pp 239-245.

Goto, K et al. (2010). "Preliminary Economic Feasibility Analysis of Cobalt-rich Manganese Crust Mining for Rare Metal Recovery," Proc. 29th Int. Conf. on Ocean, Offshore and Arctic Eng., Shanghai, Paper No. OMAE2010-20243.

Halbach, P (1982). "Co-rich Ferromanganese Seamount Deposits of the Central Pacific Basin," in Halbach, P, and Winter, P, eds, Marine Mineral Deposits--New Research Results and Economic Prospects, Marine Rohstoffe und Meerestechnik, Bd 6, Verlag Gluckkauf, Essen, pp 60-85.

Hawaii Department of Planning and Economic Development (1987). Mining Development Scenario for Cobalt-Rich Manganese Crusts in the EEZ of the Hawaiian Archipelago and Johnston Island, State of Hawaii, 326p.

Hein, J (2006). "Seamounts and Cobalt-rich Ferromanganese Crusts," Presentation in ISA Workshop on Mining Cobalt-rich Ferromanganese Crusts & Polymetallic Sulphides in the Area, July 31- Aug. 4, 2006, Kingston, Jamaica.

Hein, JR. et al. (2016). "Marine Phosphorites as Potential Resources for Heavy Rare Earth Elements and Yttrium," Minerals, 6, 88.

Hillman, CT, and Gosling, BB (1985). Mining Deep Ocean Manganese Nodules: Description and Economic Analysis of a Potential Venture, US Bureau of Mines, IC 9015, 19p.

ISA (2008). Polymetallic Nodule Mining Technology: Current Status and Challenges Ahead, Workshop Report held in Chennai, ISBA/LTC/CRP.4 (limited circulation to workshop attendees).

Manheim, FT (1986). "Marine Cobalt Resources," Science, Vol 232, pp 600-608.

Misawa, Y et al. (1987). "Cobalt Rich Manganese Crusts around Marcus Island," Marine Sciences Monthly, Vol 19, No 4, pp 209-214 (in Japanese).

MMAJ (2001). Survey Report for Deep-sea Mineral Resources (Cobalt-Rich Manganese Crust) in FY 2000, Metal Mining Agency of Japan, Tokyo, p 98 (in Japanese, unpublished).

Okuhara, K (2017). "Updated Economic Feasibility Analysis of SMS Mining Venture," Pre-print for Summer Seminar in Marine System Eng. Dept., Osaka Prefectue Univ. (in Japanese).

Pichocki, C, and Hoffert, M (1987). "Characteristics of Co-Rich Ferromanganese Nodules and Crusts Sampled in French Polynesia," Marine Geol, Vol 77, pp 109-119.

Rokukawa, N (1995). "Development for Hydrometallurgical Process of Cobalt Rich Crusts," Proc 1st ISOPE Ocean Mining Symp, Tsukuba, pp 217-221.

Soreide, F et al. (2001). "Deep Ocean Mining Reconsidered a Study of the Manganese Nodule Deposits in Cook Island," Proc 4th ISOPE Ocean Mining Symp, Szczecin, pp 88-93.

Usui, A, and Someya, M (1997). "Distribution and Composition of Marine Hydrogenetic and Hydrothermal Manganese Deposits in the Northwest Pacific," in Nicholson, K et al. eds, Manganese Mineralization: Geochemistry and Mineralogy of Terrestrial and Marine Deposits, Geol Soc London Spec Publ, pp 177-198.

Yamazaki, T et al. (1994). "Microtopographic Analysis of Cobalt-Rich Manganese Deposits on a Mid-Pacific Seamount," Marine Georesources and Geotech, Vol 12, pp 33-52.

Yamazaki, T, and Sharma, R (1998). "Distribution Characteristics of Co-Rich Manganese Deposits on a Seamount in the Central Pacific Ocean," Marine Georesources and Geotech, Vol 16, pp 283-305.

Yamazaki, T et al., (2002). "Development of Technical and Economical Examination Method for Cobalt-Rich Manganese Crusts," Proc 12th Int Offshore and Polar Eng Conf, Kita-Kyushu, pp 454-461.

Yamazaki, T, and Park, S-H (2005). "Economic Validation Analyses of Japan's Nodule, Crust, and Kuroko-type SMS Mining in 2004," Proc 6th ISOPE Ocean Mining Symp, Changsha, pp 65-70.

Yamazaki, T (2007). "Economic Validation Analyses of Japan's Proposed Nodule, Crust, and Kuroko-type SMS Mining in 2006," Proc Oceans 2007, Vancouver.

Keywords: Cobalt-rich Manganese Crust, Economy, Phosphate, Seamount, Substrate

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1981-1985	Manganese nodule lifting technology
1986-1989	Nodule and sediment geotechnology
1990-1994	Distribution characteristics of cobalt-rich manganese crusts
1995-2000	Nodule collector test on a seamount
1995-2000	Environmental assessment technique for deep-sea mining
2001-Present	Technical and economic evaluation of deep-sea mining
2002-Present	Mass balance ecosystem modeling for chemosynthesis
2006-Present	Strategic R&D planning of economical deep-sea mining

Preference for an oral presentation

Permit to archive the abstract (PDF) with OneMine.org (digital library for minerals and mining) at the conclusion of the UMC.

A study on processing of seafloor massive sulphides from the Loki's Castle area at the Arctic Mid-Ocean Ridge

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ABSTRACT

Seafloor massive sulphides (SMS) can serve as a potential resource of metals such as Cu, Zn, Au and Ag. SMS rock samples from the Loki's Castle area at the Arctic Mid-Ocean Ridge are comprised of sulphide bearing minerals such as pyrite, chalcopyrite, isocubanite, galena, sphalerite, whereas the gangue consists mainly of barite and silica. Sphalerite, chalcopyrite and isocubanite show complex intergrowth textures on the nano- to microscale. Various mineral processing tests were conducted in order to recover copper, zinc and silver. It was shown that sensor-based sorting can be efficiently used for preconcentration of SMS rock samples. A significant amount of waste (i.e. barite and silica) was removed in the preconcentration stage with very low losses of copper and zinc to the waste fraction. The upgraded samples were sent to the next processing stages. The results showed that the complex mineralogy of the SMS material provided challenges to conventional mineral processing methods. Hydrometallurgical processing was applied as an alternative method for extraction of metals from SMS. Leaching experiments were conducted using solutions of different lixiviants, and it was shown that leaching of SMS together with manganese nodules would facilitate efficient recovery of metals from these resources.

Keywords: mineral processing; sensor-based sorting; flotation; leaching; seafloor massive sulphide; deep-sea minerals.

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Aasly holds a PhD in process mineralogy. He is currently an associate professor at the Norwegian University of Science and Technology (NTNU) and has a special interest in the relationship between the mineralogy and mineral processing properties of minerals and ores. Aasly´s interest in Deep Sea Mining is within mineral characterization and especially to the process mineralogical challenges related to this type of mineralizations. Since 2015 he has been project manager for the MarMine project at NTNU.

Impact of High-Resolution Bathymetric Mapping on Resource Estimation in the French Exploration Contract for Polymetallic Nodules

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ABSTRACT

Ifremer, on behalf of the French government, holds an Exploration Contract with the ISA for polymetallic nodules in the CCFZ. As part of its exploration activities, the NODULE (2015) cruise was conducted to acquire a 50 m resolution bathymetric coverage of the eastern sectors of the Contract. In 2017, Ifremer initiated an update of the Contract's mineral resource estimate. Metal grades and nodule abundance were modelled using ordinary kriging. The inferred mineral resource is 436 Mt (wet) of polymetallic nodules at an average abundance of 10.7 kg/m² with a cut-off grade of 7 kg/m². Based on the geological data, seamounts, sedimentary basins and steep slopes contain no nodules. Technical studies of most of the contractors have determined that nodule collectors could not maneuver on slopes above 5 to 10°. Thus, Ifremer has selected a quite conservative slope threshold of 7 % (about 4°) and a backscatter threshold of -29.5 dB to delineate nodule-free areas. This has a significant impact on the resource estimate, as about 54 % of the eastern Contract areas are excluded. Near-seafloor high-resolution mapping and photographic transects, associated with finer-spaced box-core sampling could constitute a next step to better constrain the mineable areas and to get a higher level of confidence in the resource estimation.

Keywords: Polymetallic Nodules, CCFZ, Mineral Resource Estimate, High-Resolution Bathymetry

Florian Besson

Florian Besson is a scientist in the Marine Geosciences department at Ifremer, Brest and is one of the marine geologists responsible for the Marine Mineral Resources Program. In 2012 he received his MSc degree in Geology and Environment with a specialization in Mineral Resources Management from the Institut Polytechnique LaSalle Beauvais, France. His experience includes more than 6 years in exploration of land-based and marine mineral deposits with the industry and research institutes. He has participated in six research expeditions in the southwestern Pacific, the CCFZ and the Mid-Atlantic Ridge, studying polymetallic nodules and polymetallic sulphides deposits.

Development of A Vertical Transport System: An Experimental Approach

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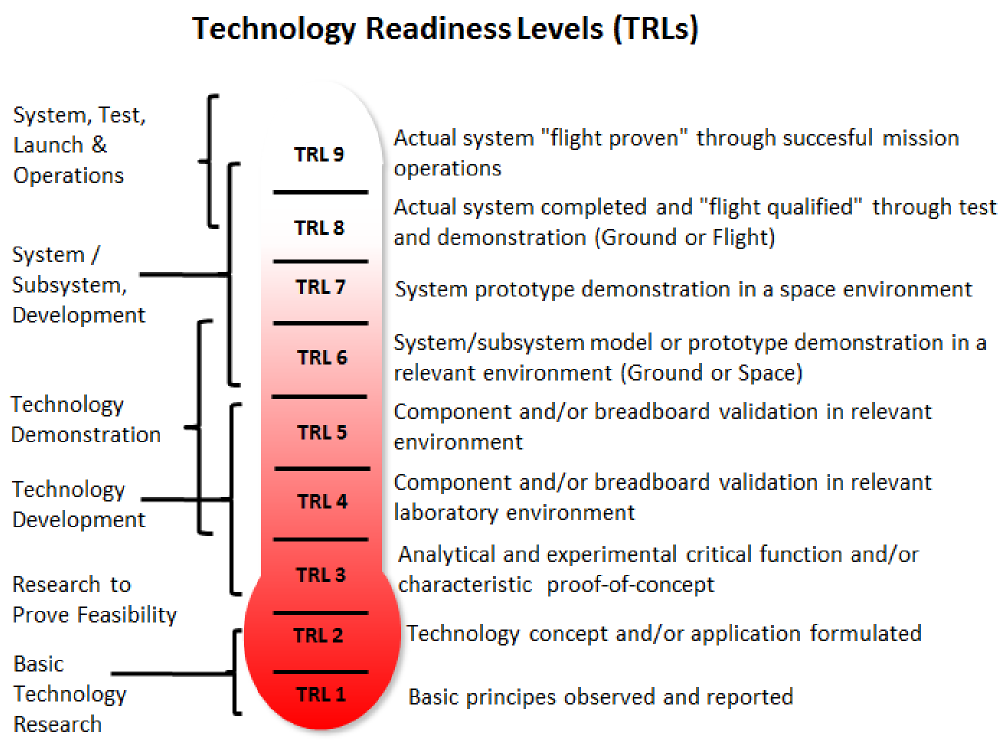
INTRODUCTION

Starting in February 2014, 19 partners from EU industry, research institutions and academia joined forces and formed the Blue Mining consortium. In the following four years, they have set out to work on the development of deep sea mining technology, looking into exploration, identification, economic assessment and vertical transport systems for the mining of seafloor massive sulphides and polymetallic nodules. In the beginning 2018 this research & development project has come to an end.

The Blue Mining project was one of the first EU subsidised projects embracing the TRL system. This system describes a method of de-risking technology using a simple 9-step approach. This method requires experimental testing in laboratory and relevant environments to be able to reach the higher levels (TRL>5)

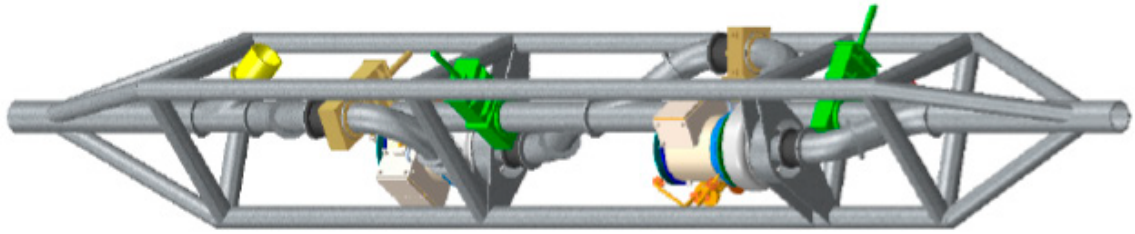


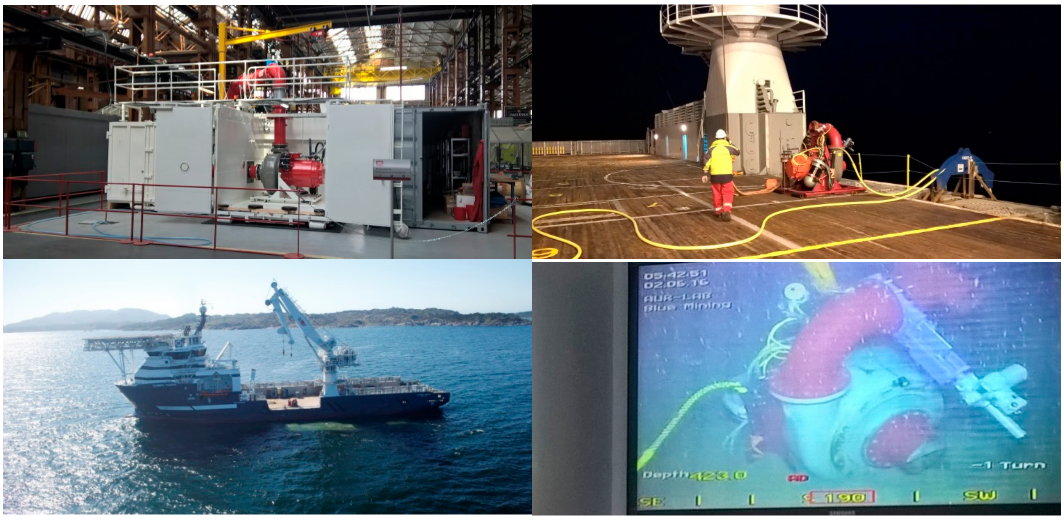
This paper will discuss the progress in development of the vertical transport system, with a focus on the performed experimental work. This paper will discuss three topics:

- Booster station technology
- Riser dynamics
- Vertical hydraulic transport process.

BOOSTER STATION TECHNOLOGY

Deep knowledge of transport processes is a prerequisite for a clog free vertical transport One of the key technologies in the VTS is the booster station. The centrifugal pump booster station concept is developed in Blue Mining, it consists of two centrifugal pumps and multiple valves, assembled in member-type frame. Deep sea conditions pose special requirements on all components due to the extreme pressures at large water depths. In the Blue Mining project a Deep Sea Special Motor has been developed and tested in laboratory and in the field. The motor is completely filled, lubricated and cooled using seawater due to its unique open structure, furthermore it does not require any lubricants minimizing the environmental pressure of the motor. The motor is first extensively tested in a laboratory, after these tests have been concluded successfully, the motor is shipped to Norway where it has been successfully tested for more than 100 hours at 425 meter water depth.





VALIDATION OF RISER DYNAMICS

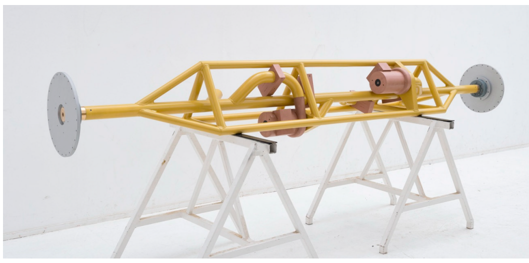
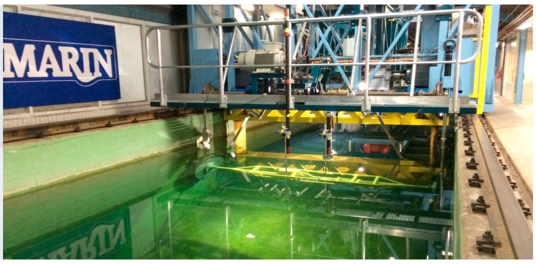
The vertical transport system will be subjected to a variety of external loads. In the aNySIM simulation package a wake-oscillator model is implemented with which time-domain simulations can be conducted for deep-sea mining riser systems. This model requires hydrodynamic coefficients as input, which can be determined with model tests or CFD calculations. In Blue Mining the booster station has been tested in the MARIN Concept Basin on a 1 to 6 scale in order to find the appropriate hydrodynamic coefficients.

A full length deep sea mining VTS could not be properly scaled for a model basin test. Therefore, a shorter dedicated validation model was constructed. Hereafter, the full depth system can be numerically modeled with the validated software functionality (model-to-model approach).

The wake-oscillator model, simulating Vortex Induced Vibrations were validated by towing and oscillating an instrumented flexible riser model through the depressurized wave basin. During this test campaign tests with forward velocity were carried out with four pretension settings. Furthermore, the tests were repeated a scaled booster station clamped on the flexible riser.

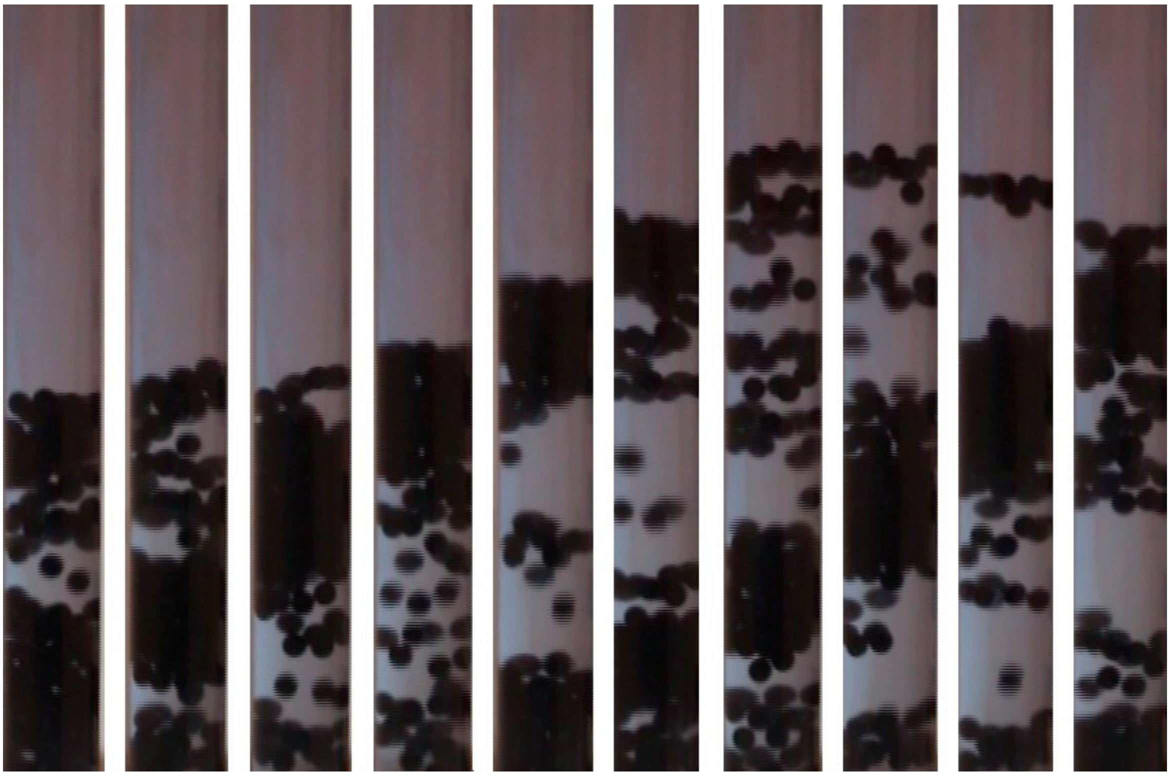
Based on the test results from the first test campaign, additional tests were conducted with a hexapod (Steward platform). The hexapod can play motion files in 6DoF. In this second test series surge and sway oscillations with/without forward speed of the carriage were conducted.

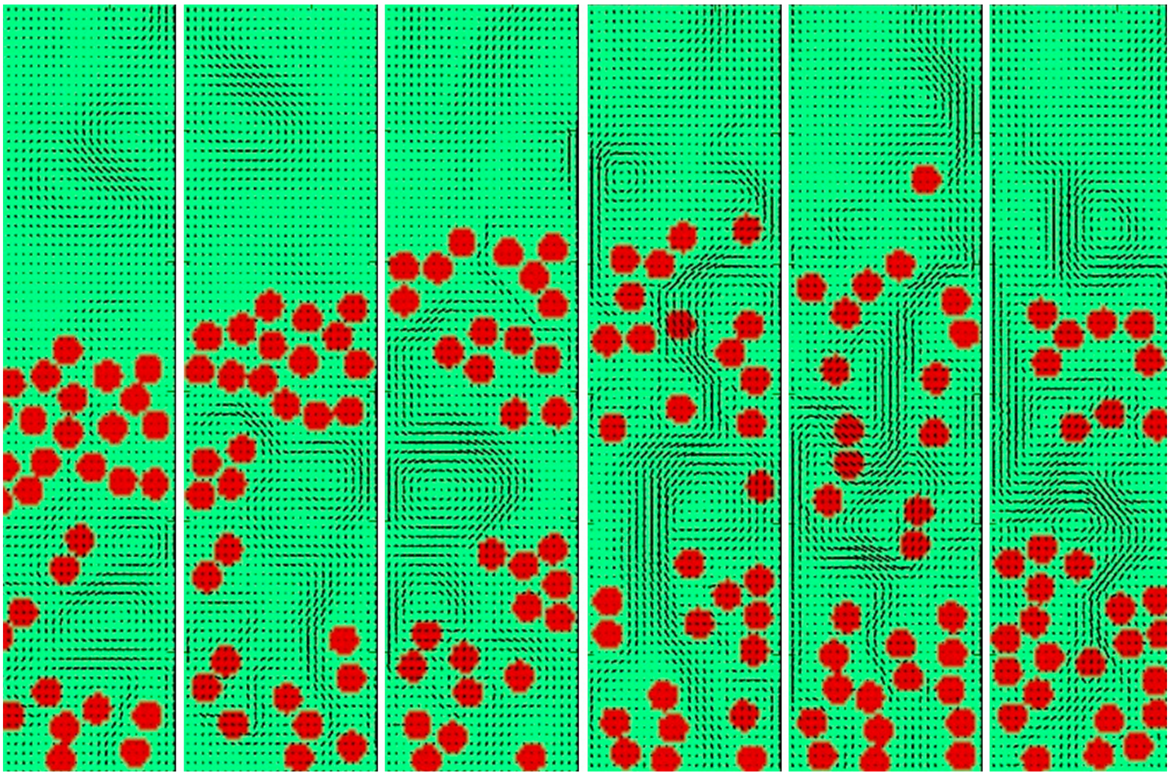
A large data set of fluid-structure interaction validation is available to validate numerical models. These numerical models can consist of CFD models with an interface with a FE-model of the structural model of the riser. Furthermore, lumped mass time domain models with a wake oscillator functionality can be validated with this data set.

VERTICAL HYDRAULIC TRANSPORT PROCESS

Deep knowledge of transport processes is a prerequisite for a clog free vertical transport system. Research efforts thus far have focused on computational modelling of the long distance vertical transport, backed by laboratory scale experiments of specific phenomena. After finishing the laboratory experiments there was a need to take a next step in the scale of experiments to increase confidence and understanding. Besides that, one of the unresolved issues at the start of Blue Mining was the occurrence of density waves, a topic that needed to be revisited. Density waves are regions of increased material concentration that travel through the riser, comparable to sound being a pressure wave through air and comparable to traffic jams occurring in dense traffic when someone suddenly hits the brakes. These waves are a potential source of instability, i.e. they might diminish after creation or they could grow into massive plugs. An example is given below. These plugs could be a showstopper for the mining operation, so methods for prediction would be a valuable competence in flow assurance analysis. The prediction of density waves however is not trivial. In Van Wijk et al. (2016) analytical methods for density wave prediction were explored. Although for the case of fluidization the method seemed promising, the application to actual transport conditions weren't conclusive.





In order to get more clarity on these density waves, two directions were chosen in Blue Mining. The first direction aimed for numerical modelling of the phenomenon with CFD (a 2D Immersed Boundary Method). In 2017 this method proved successful in qualitatively mimicking the occurrence of density waves as shown below, making it a promising technique for actual prediction of waves during operational conditions. The second direction was an investigation into vertical transport of sand, gravel and real (crushed and sized) manganese nodules in a 136 meter long riser in a mineshaft in Freiberg, Germany. This test setup is unique in its size: it is the largest vertical test section ever built in Europe dedicated to the vertical transport of solids. A team of IHC and TUBAF engineers and scientists investigated the validity of the models used in the transport simulations with a focus on the occurrence of density waves, the frictional losses in the vertical riser and control techniques for the pump system.

Keywords: Deep Sea Mining, Vertical Transport, Hydraulic, Booster Station, Pump, Electromotor.

Wiebe Boomsma

Wiebe Boomsma is the manager Product Development at Royal IHC, a supplier of equipment, vessels and services for the offshore, dredging and wet mining markets based in the Netherlands. Wiebe received his master's degree in Mechanical Engineering from the Eindhoven University of Technology in 2006. After holding several positions in academia and the semiconductor industry, he started at Royal IHC in 2009. Since then his work has focused upon developing new technologies and products for the deep sea mining market. In 2013 Wiebe is appointed Manager Product Development and responsible for product development for the Deep Sea Mining and Mineral processing market.

An innovative solution to a common problem: SAGRES decision support for deep-sea mining and maritime spatial planning activities

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INTRODUCTION

For the last decades, deep-sea marine resources such as seabed massive sulfides (SMS), polymetallic nodules and ferromanganese crusts (Fe-Mn crusts) have received an ever-increasing amount of attention worldwide for their abundance in critical metals and potential commercial value. This interest has mostly been driven by the growing world demand for raw materials, in particular for high- and green-technology applications (*e.g.*, hybrid and electric cars, batteries, photovoltaic solar cells, cell phones, super magnets), as well as by industrialized countries governments other than BRICS states need to secure a more diversified supply of metals, resulting in a new deep ocean exploration boom. Since the oceans and its resources are increasingly seen as indispensable for humans needs and their challenges in the decades to come, this boom increments pressure on marine areas, either in international or within countries economic exclusive zone (EEZ).

Since 2002, the International Seabed Authority (ISA) has signed up 29 contracts with several entities and national governments from multiple countries (*e.g.*, Japan, China, Germany, France, Russia, India, Rep. of Korea, UK, Canada, Brazil) for exploration for deep-sea mineral resources in international waters, either for scientific or commercial proposes, which together cover over 1.3 million km^2 [1]. In turn, over 300 exploration licenses, covering more than 650,000 km^2, have been granted within the EEZ of Pacific countries such as Papua New Guinea, Tonga, Fiji, Solomon Islands and Vanuatu [2, 3]. This number is expected to increase very rapidly, as 77 countries have proposed to the United Nations the extension of their continental shelf in order to extend their EEZ and jurisdiction over potential deep-sea mineral resources [4]. Its estimated that 42% of the potential areas for SMS occurrences, 54% for cobalt-rich Fe-Mn crusts, and 19% for polymetallic nodules lie within the EEZ of coastal countries [5]. In addition, a huge amount of seafloor is yet to be explored and evaluated. Combined, the size of the granted exploration areas represents less than 10% of the overall area thought as most favorable for the occurrence of the 3 types of deep-sea mineral resources above mentioned. This means that today's assessments on deep-sea mineral resources are only a rough approximation.

Current deep-sea mining (DSM) prospection and exploration (P&E) is usually performed by conducting surveys at progressive scales of definition (from regional to local). Typically, it requires long months of planning by P&E experts and the methodical use and combination of several technologies and techniques to generate first-order maps for targets definition, testing and location of an economic deposit. Although specifically developed for deep-sea exploration, this conventional approach is highly expensive, time-consuming, complex, risky, and only allows covering limited areas of the seafloor, not always in a cost-effective way. Also, according to ISA exploration regulations [6], contractors have to relinquish 50% of their exploration concessions after 8 years, presumably the least favorable area, hopefully already interpreted as such, and therefore devoid of large and economically interesting mineral deposits. Moreover, few countries and maritime governance and policy-making authority (MGPA) bodies have the capacity needed and expertise to pursue deep ocean exploration and/or develop the policy and regulation framework to produce and manage reliable information on deep-sea mineral resources to ensure that their maritime territory and marine resources are managed in a responsible and sustainable manner. Together, these constraints pose major limitations, given the huge effort on time and investment by commercial companies in the exploration phase to define target areas to test and locate economic deposits, and the lack of information by MGPA on potential deep-sea mineral resources to strength its capacity of governance, management and promotion of investments. In this overall framework, it has become increasingly recognized the need to adopt new solutions towards a more technological achievable, successful and economically viable DSM sector.

In the follow up of an ESA Small Arts funded project "SAGRES", ISQ is designing and developing an innovative and interactive decision-making solution to support stakeholders closely related with DSM P&E and maritime spatial planning activities. Immediate visualization on a map of known and predicted P&E target areas and inferred mineral resources together with the distribution of economic potentials, location and favorability at a multiscale level is an added value to improve multi-objective planning capabilities and reduce the time and costs needed for prior data gathering and analysis.

Concept, results and future developments

SAGRES decision-making support solution combines and exploits the added-value of free, open access multisource Earth Observation data (EO; satellite, ground base, web information platforms) with cutting edge machine learning techniques to deliver integrated, affordable and easy-to-use key information on the distribution, location and favorability of exploration target areas at several scales. Quick access to this added-value information can greatly improve the decision-making and management capabilities of DSM companies and of MGPA bodies, by directly contributing to operations time-consuming planning, costs, uncertainty and risks reduction, as well as for the development of an inclusive and sustainable regulatory framework and maritime spatial planning.

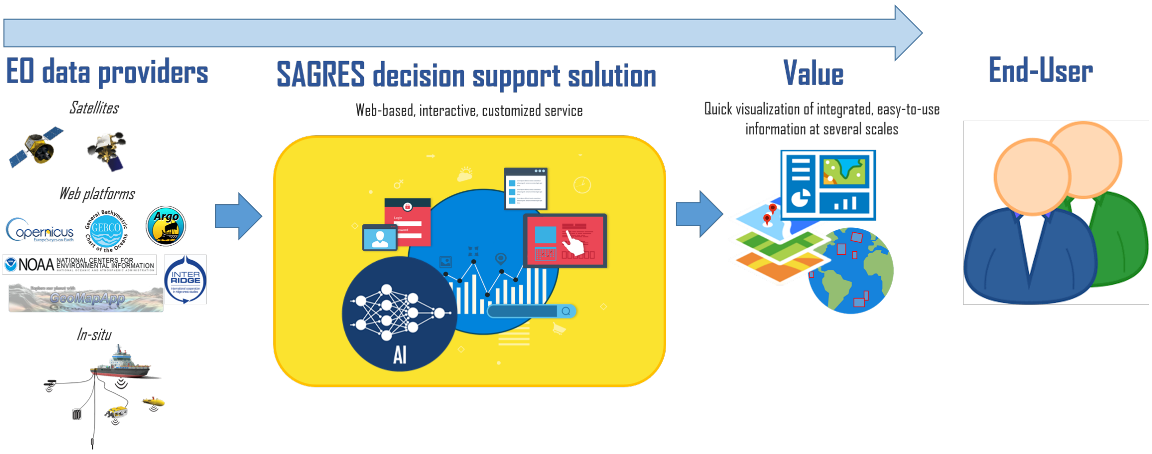

Figure 1 – SAGRES innovative concept and added-value key points.

SAGRES project focused on forecasting favorable P&E target areas for occurrence of Fe-Mn crusts at the North Atlantic Ocean. Although the model development and calibration was mainly based on satellite data and available observed site reports, the first modelling results determined by the artificial neural network prototype model enable to achieve an accuracy up to 80%. By taking into account some of the key morphological (depth range, slope) and geological (tectonic setting) dependable factors typically considered for the occurrence of economically viable Fe-Mn crusts, the forecasted P&E target areas within several testing areas defined have shown a favorability up to 77%, and a very good match with known Fe-Mn crusts occurrences in the North Atlantic (*e.g.*, Madeira-Tore Rise; Fig. 2).

The results achieved during SAGRES proof of concept demonstrate the feasibility of the approach developed, and allows to conclude that this approach can enable statements to be made about the spatial distribution, location and favorability of potential target areas for deep-sea mineral P&E on untapped regions/areas by use of free, open access and available EO data. The SAGRES approach can thus be extended to other types of deep-sea mineral resources, and contribute to improve DSM P&E and maritime spatial planning activities efficiency, decision making, competitiveness and sustainability.

On the basis of these first results, ISQ is currently embracing different approaches to improve the prediction and mapping of potential P&E target areas and lower the predictive errors by integrating more key dependable factors, by exploring, testing and comparing the capabilities of different machine learning algorithms, and by integrating more features into the solution that best fulfils the end-users needs and requirements.

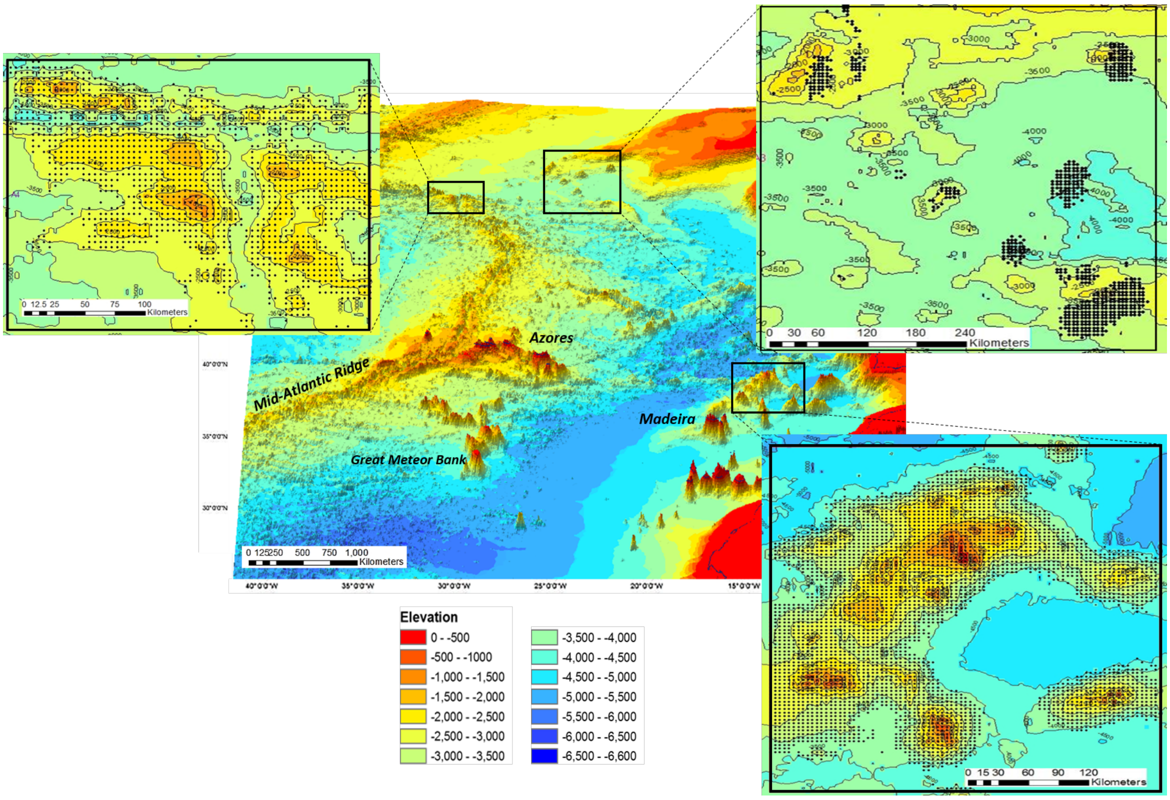

Figure 2 – SAGRES proof of concept results for several test areas for forecasting and mapping potential Fe-Mn crusts P&E target areas.

Keywords: Innovative; decision support; deep-sea mining; forecasting and mapping; time and costs reduction

References:

[1] https://www.isa.org.jm/deep-seabed-minerals-contractors

[2] SPC-EI Deep Sea Minerals Project: Deep sea minerals frameworks to inform decision-making, http://dsm.gsd.spc.int/index.php/news

[3] Nautilus Minerals Overview, www.nautilusminerals.com/irm/content/overview.aspx?RID=252&RedirectCount=1

[4] UN Oceans & Law of the Sea, Submissions, http://www.un.org/depts/los/clcs_new/commission_submissions.htm

[5] Petersen, S., Krätschell, A., Augustin, N., Lamieson, J., Hein, J., Hannington, M.D. (2016) News from the seabed – Geological characteristics and resource potential of the deep-sea mineral resources. *Marine Policy*, Vol 70, p. 175-187.

[6] Consolidated Regulations and Recommendations on Prospecting and Exploration, International Seabed Authority 2015 Revised Edition, pp. 264, https://www.isa.org.jm/sites/default/files/files/documents/en-rev-2015.pdf

João R.S. Carvalho

João R.S. Carvalho received his PhD from Lisbon University in 2016, specialty in metallogenesis and economic geology. From 2006 to 2016 his work has been focused in mineral resources assessment, geochemistry and metallogenesis, in particular in polymetallic VMS deposits at the Iberian Pyrite Belt and on their related bi-products (Au, Ag, In, Se, Ge). Since late 2016 he is working at the Sustainable Innovation Centre, ISQ, under the SAGRES project, which aims to develop smart solutions to support decision-making for the exploration of deep-sea mining resources. This new research area focus has enable to expand his knowledge on deep-sea mineral resources, and to adapt technology from the space industry to prospect and explore offshore mineral deposits.

Simulation of two-phase flow in airlift pump using 1D two-fluid model

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INTRODUCTION

Airlift pumping, utilize compressed air that is injected at the bottom of a vertical pipe submerged in the water, reduces the mixture density inside the pipe and lifts the liquid or mixture of liquid and solids. This type of pumping technology, which is simple and without moving parts submerged in water, which provides several advantages compared to the mechanical pumping. Airlift is used in various difficult pumping applications such as transport of fluids corrosive to metals, explosives, nuclear and toxic materials in chemical industries, diamond mining and coal transport. Application of airlift to deep sea mining conditions was investigated by extensive laboratory experiments [1], theoretical analysis [2], and limited proof of concept field studies [3] starting in 1970's with the discovery of huge amounts of manganese nodules discovered on the seabed at a depth of ranging from 4000 to 6000 m . Even after extensive investigations over the last five decades, there exists no commercial application of airlift technology for lifting of minerals. The major problems with the application airlift for deep ocean mining was (a) lack of control over the expansion of the injected gas, which increases the velocity in upper part of the riser pipe (b) lower efficiency compared to mechanical pumping [3]. Different flow regimes are encountered in airlift pumping: bubble, slug, churn and annular flow. Annular flow regime is the least efficient in lifting of particles and churn flow has better efficiency [3].

Several studies have been reported to investigate the performance of airlift pump operating in two-phase flow conditions focusing on the effect of submergence ratio, location of the gas injection point, and liquid properties such as surface tension and viscosity. Theoretical investigations were reported based on the one-dimensional steady state momentum balance method by assuming the particular flow pattern inside the pipe [4]. These models were later improved by including the compressibility of the gas phase and including the improved correlations for the interphase and wall friction terms. Very few studies were focused on the development of dynamic models based on multi-fluid modeling approach [2]. Recently, the dynamics of slug flow behavior in vertical pipe using one-dimensional two-fluid model is investigated using 1D two-fluid mechanistic modeling approach [5]. They controlled the superficial velocities of two fluids independently, which is different in case of airlift pump where the compressed air was injected to lift the water. In the present work, a 1D two-fluid model utilizing both slug capturing and slug tracking is used to predict the performance of airlift pump operating in two-phase flow conditions. The obtained results were validated with the experimental results reported in literature [6]. The model is used to analyze the different flow patterns observed for various air mass flow rates.

Methodology

The model presented in this study is based on finite volume Lagrangian slug tracking model concept first tested [7] and later extended and modified in several PhD studies [8]. The simulation code is written in C^{++} programming in Qt frame work. Control volumes are represented by objects bubble and slug sections. Similarly, the borders/cell-faces between objects are represented by different types of border objects. When the liquid holdup in a bubble section approaches a user defined limit (= 0.98 in the current study), the bubble section is converted to a slug section object. Similarly, slug to bubble section conversion is applied when the void fraction in slug reaches a maximum value, or when the slug becomes too short.

The mass, pressure and momentum conservation equations shown below are all integrated over the gas and liquid control volumes,

$$\frac{\partial M_f}{\partial t} + \int_{A_{bf}} \rho_f \left(\boldsymbol{u}_f - \boldsymbol{u}_b \right) \cdot \boldsymbol{n}_f dA_{bf} = M_f^{src}$$

$$\frac{\partial M_f}{\partial t} = \frac{\partial \left(\rho V \right)_f}{\partial t} = \left[\left(\frac{\partial \rho_f}{\partial p} \right)_{T_f} \frac{\partial p_f}{\partial t} + \left(\frac{\partial \rho_f}{\partial T} \right)_p \frac{\partial T_f}{\partial t} \right] V_f + \rho_f \frac{\partial V_f}{\partial t} = M_f^{src} - \int_{A_{bf}} \rho_f \left(\boldsymbol{u}_f - \boldsymbol{u}_b \right) \cdot \boldsymbol{n}_f dA_{bf}$$

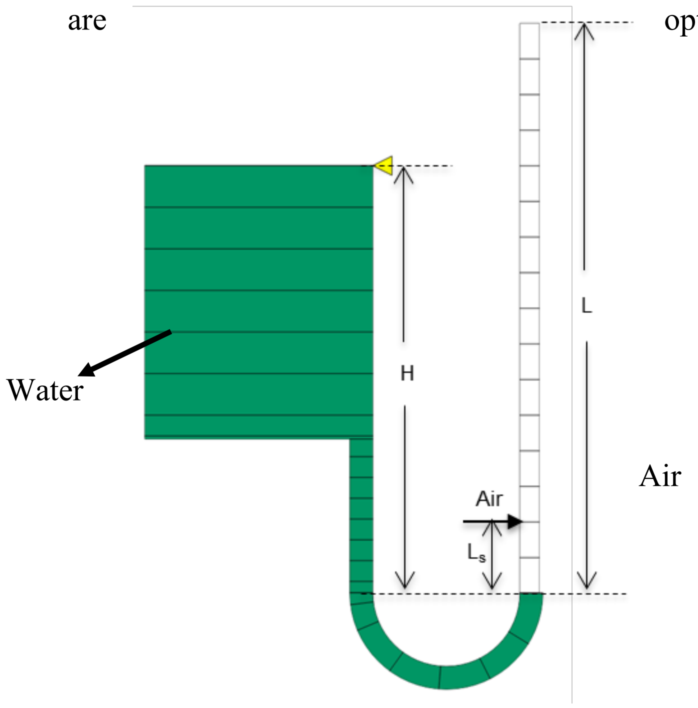
$$\frac{\partial}{\partial t} \int_{V_{k,j}} \rho_{k,j} u_{k,j} dV + \int_{A_{k,j}} \rho_{k,j} \left(u_{k,j} - u_{b,j} \right) u_{k,j} dS = - \int_{V_{k,j}} \frac{\partial p_j}{\partial x} dV$$
$$- \int_{V_{k,j}} \rho_{k,j} g \frac{\partial \left(h_{k,j} \cos\theta \right)}{\partial x} dV - \int_{V_{k,j}} \frac{\tau_{i,j} S_{i,j}}{A_{k,j}} dV - \int_{V_{k,j}} \frac{\tau_{k,j,wall} S_{k,j}}{A_{k,j}} dV - \int_{V_{k,j}} \rho_{k,j} g \sin\theta dV + \frac{\partial}{\partial t} \int_{V_{k,j}} \rho_{k,j}^{src} u_{k,j}^{src} dV$$

The mass equation is solved for all of the section objects regardless of type, while the momentum equation is solved for the border objects. The momentum equation is solved for the mixture liquid and mixture gas velocity, while the mass equation is solved for all sub-fields. The system of equations were discretized on a staggerd grid. Since, we solve for the momentum of the mixture fields and not for each sub-field, the velocity of each sub-field is related to the corresponding mixture field by a linear slip relation. In the present study, no-slip condition is used, meaning that all sub-fields travel with the same velocity as the mixture field. The time step is controlled by the Courant–Friedrichs–Lewy (CFL) criterion.

Since, some of the control volumes are moving, sections can both grow and decrease in length. Because of this, certain grid management operations are needed: short sections are merged together with neighboring sections of similar type, and long sections might be split into two shorter sections. Sections might also be converted from one type to another, for instance from bubble to slug, or slug to bubble. The grid management is controlled by grid coefficients for the bubble and slug sections. A bubble section is merged with a neighboring bubble section if the length is smaller than the grid coefficient, and split in two if the section length is larger than twice the grid coefficient. Similar methodology is applied for slug sections. The complete details of the model can be found in work by Smith (2017).

The geometry used in the present study is shown in Fig. 1, which is adopted from the experimental investigation [6]. The length (L) of the vertical riser pipe is 3.75 m, the inner pipe diameter (D) is 25.4 mm, and down-comer pipe inner diameter is 30 mm and tank with large diameter (10D) is used to maintain constant level of water at height H. Air is injected at height L_s = 0.2m from pipe bottom. Submergence ratio is defined as Sr = H/L.

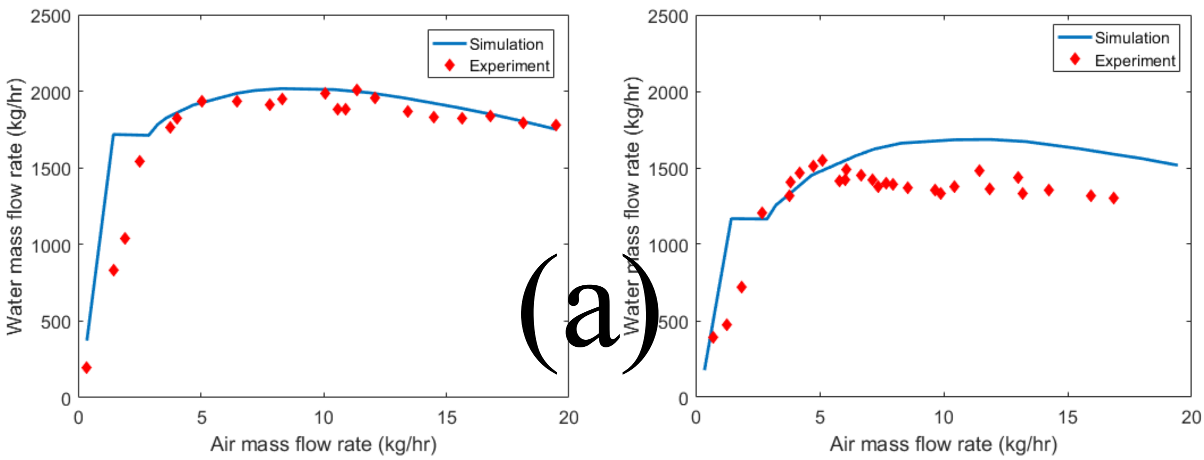
Constant atmospheric pressure boundary condition is applied at the outlet boundary, and mass flow source is used for the air injection at location L_s. Continuous inflow of water is maintained at the inlet boundary to maintain the hydrostatic head at the pipe bottom for a given submergence ratio. Initially the pipe is filled with water until the bottom of the vertical pipe. After careful investigation, grid size controlling parameters for bubble, slug coefficients, void in slug and holdup parameters are optimized.



Figur 1: Schematic diagram of the geometry used in simulations. Pipe is filled with the water until the bottom of the vertical pipe at time t = 0

Results and discussion

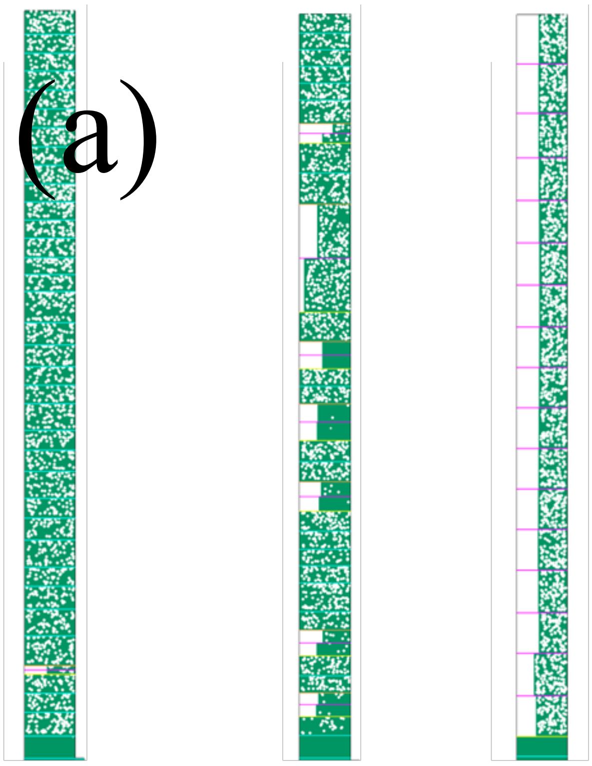
Simulations were conducted for two different submergence ratio Sr=0.75 and 0.67. For each submergence ratio case, the air flow rate was varied and the corresponding water flow rate water was computed. The results for the amount of lifted water in the riser pipe, at different values of injected air mass flow rates are shown in Figure 2 and compared with the experimental results [6]. There is a good agreement between the results obtained from the model and the experimental results over a wide range of air mass flow rates with discrepancy less than 20%. From Fig. 2, we can observe that the amount of lifted water increases with the air flow rate until it reaches a maximum value beyond which the liquid flow rate drops slightly and becomes stable despite the increased air flow rate. The observed results can be correlated to the change in flow patterns from bubble-slug-churn-annular with the gradual increase of air mass flow rate as reported from experimental visual observations [6]. The region of the slug-churn flow is the main region where the pump should be operated in order to achieve maximum efficiency. The maximum lifting of water flow rate is reached when the frictional pressure drop caused by further increase



Figur 2: Variation of water mass flow rate with the airmass flow rate: comparision of simulation results with the experimental results reported by Kassab et al. (2009) for submergence ratio(a) Sr = 0.75 and (b) Sr = 0.67

in the airflow rate exceeds the buoyancy effect of the additional air [9].

Figure 3 shows the visualization of the holdup of the liquid phase in the pipe at three different airflow rates from low to high. Dispersed bubbly flow can be observed at low airflow rates as shown in Figure 3a and transition to slug flow happens at intermediate flow rate as shown in Figure 3b. At higher flow rates, annular flow regime is observed as shown in Figure 3c. The flow patterns observed fin the simulations are similar to the visual observations reported in experiments [6].



Figur 3: Visualization of the flow pattern along the vertical pipe for submergence ratio Sr = 0.75 case at air mass flow rate (a) 1.4 kg/hr (b) 3.75 kg/hr (c) 18 kg/hr. Green color: water phase, white color: air, white circles: air bubbles entrained in water

This work is currently in progress to extend it to deep-sea mining conditions where the pipe diameter and length are larger compared to the parameters considered in the present study. Dynamic flow conditions such as varying air mass flow rate and the effect of air injection at multiple locations along the riser pipe will be investigated.

References

[1] M. Weber, Y. Dedegil, Transport of solids according to the air-lift principle, Proc. 4th Int. Conf. Hydraul. Transp. Solids Pipes. Alberta, Canada, H1, 1–23 and (n.d.) 93–94.
[2] N. Hatta, H. Fujimoto, M. Isobe, J.-S. Kang, Theoretical analysis of flow characteristics of multiphase mixtures in a vertical pipe, Int. J. Multiph. Flow. 24 (1998) 539–561. doi:10.1016/S0301-9322(97)00074-8.
[3] R.L. Doyle, J.E. Halkyard, Large Scale Airlift Experiments for Application to Deep Ocean Mining, in: ASME 2007 26th Int. Conf. Offshore Mech. Arct. Eng., American Society of Mechanical Engineers, 2007: pp. 27–36.
[4] T. Yoshinaga, Y. Sato, Performance of an air-lift pump for conveying coarse particles, Int. J. Multiph. Flow. 22 (1996) 223–238. doi:10.1016/0301-9322(95)00067-4.
[5] R.I. Issa, F. Galleni, Mechanistic simulation of slug flow in vertical pipes using the one-dimensional two-fluid model, Multiph. Sci. Technol. 27 (2015) 229–245. doi:10.1615/MultScienTechn.v27.i2-4.90.
[6] S.Z. Kassab, H.A. Kandil, H.A. Warda, W.H. Ahmed, Air-lift pumps characteristics under two-phase flow conditions, Int. J. Heat Fluid Flow. 30 (2009) 88–98. doi:10.1016/j.ijheatfluidflow.2008.09.002.
[7] O.J. Nydal, S. Banerjee, Dynamic Slug Tracking Simulations for Gas-Liquid Flow in Pipelines, Chem. Eng. Commun. 141–142 (1996) 13–39. doi:10.1080/00986449608936408.
[8] I.E. Smith, A 7-field Lagrangian slug capturing and slug tracking model with higher order methods, NTNU, 2017. https://brage.bibsys.no/xmlui/handle/11250/2455762.
[9] D.J. Reinemann, J.Y. Parlange, M.B. Timmons, Theory of small-diameter airlift pumps, Int. J. Multiph. Flow. 16 (1990) 113–122. doi:10.1016/0301-9322(90)90042-H.

Keywords: Airlift pump, two-phase flow, 1D two-fluid model.

Niranjan Reddy Challabotla

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Effects of sedimentation from deep-sea mining: a benthic disturbance experiment off New Zealand.

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There are a number of likely impacts from mining operations, but a key issue is uncertainty about the environmental effects of sediment plumes created by disturbance to the seafloor and discharge of processed waters. The New Zealand National Institute of Water and Atmospheric Research (NIWA) is undertaking a research project to improve understanding of such impacts (relevant to both mining and trawl fisheries), by examining the extent and persistence of sediment plumes, the immediate impact and subsequent recovery of seafloor exposed to these plumes, and the effect on functioning of ecologically significant species. The project will use a combination of field survey experimentation with *in situ* observations and controlled laboratory-based experiments.

The field work begins in May 2018 when an area of up to 1km^2 at depths of 400-500 m on the Chatham Rise, 450 km east the New Zealand South Island will be subjected to disturbance by an upgraded former NOAA Benthic Disturber. The suspended sediment load created by the disturbance will be tracked and monitored, with the effects on seafloor animals examined by pre-and post-disturbance sampling. A wide range of seafloor sampling, benthic landers, towed cameras, oceanographic moorings and water column monitoring will be carried out over a three week period. Monitoring surveys will be repeated in 2019 and 2020 to determine the longer-term resilience and recovery of disturbed communities.

The laboratory-based side of the programme, also starting in 2018, involves holding live deep-sea corals and sponges in tanks at NIWA, and exposing them to various levels and duration of particle loads in the water in order to reveal lethal thresholds as well as sub-lethal effects of settled and suspended sediment.

The presentation will present preliminary results of the May-June field program.

Keywords: plumes, environmental impact, benthic disturber, New Zealand

Design of Power Distribution System for Deep-Sea Mining: What are the Criteria and Challenges?

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ABSTRACT

Deep-sea mining is in the future perspective of mining industry and it is currently in the technological development phase. The focus of this study is on the electrical power system that provides sufficient energy for the mining equipment at the seafloor, excavating Seafloor Massive Sulfide (SMS) deposits. SMS deposits usually exist at water depths between 1500 m and 4000 m. Despite the similarities of SMS deposits excavation to the open-pit terrestrial mines, more energy is required to drill and crush the ores in the hyperbaric conditions [1], which can be done whether by static trench cutters [1] or by mobile mining crawlers [2]. In addition, the ores vertical transportation by subsea pumps requires several MW electrical power that can be supplied by all-electric subsea motors or hydraulically from water injection motors located on the surface.

The power requirements can be fulfilled by an offshore or subsea power network. As the SMS mines are usually in remote locations, the straightforward solution will be an isolated offshore grid mounted on a vessel or platform similar to the most of offshore Oil & Gas projects. These power systems resemble the onshore microgrids for industrial purposes operating in island mode. However, in contrast with the onshore power networks, there are space and weight limitations in offshore infrastructures, which impose the design compactness to be a priority. In addition, having a very high reliability is necessary in the design approach of the offshore projects due to the extraordinary high expenses corresponding to repair and maintenance. The other design criterion is to improve the power system efficiency in order to reduce the size of the power equipment cooling

apparatus, operational costs and CO_2 emissions produced by diesel/LNG onboard generators. There are a few studies considering power system distribution for seafloor mining industry. Among them, [3] has investigated the AC and DC alternatives for SMS mining in 2400 m water depth by considering Solwara 1 project scenario introduced by Nautilus Minerals Inc. [2]. In this study, a power system design tool will be presented taking into account various water depth, power consumption levels, different distribution configurations (AC and DC) and the aforementioned design criteria.

Keywords: AC microgrid, DC microgrid, Deep-sea mining, Seafloor Massive Sulfide, Subsea power distribution.

Razieh Nejati Fard received her B.Sc. degree in electrical engineering from the University of Tehran, Iran in 2010. She received the M.Sc. degree in electrical power engineering from the Norwegian University of Science and Technology in June 2013. After graduation, she joined the Wärtsilä R&D center in Trondheim and worked on vessels electrifications until March 2015. She is currently a Ph.D. candidate working on the power system design for deep-sea mining applications. She is also research assistant for the courses "Marine and Offshore Power Systems" and "Power System Analysis" at NTNU. Her research interests include Power systems and microgrids, power electronic converters, electrical drive systems and control strategies, in addition to the challenges deriving from their implementation in the subsea and offshore environments.

REFERENCES

[1] G. Spagnoli, S. A. Miedema, C. Herrmann, J. Rongau, L. Weixler, and J. Denegre, "Preliminary Design of a Trench Cutter System for Deep-Sea Mining Applications Under Hyperbaric Conditions," *IEEE Journal of Oceanic Engineering,* vol. 41, no. 4, pp. 930-943, 2016.

[2] *NAUTILUS Minerals website. Available:* http://www.nautilusminerals.com/IRM/content/default.aspx.

[3] R. N. Fard and E. Tedeschi, "Investigation of AC and DC power distributions to seafloor mining equipment," in *OCEANS 2017 - Aberdeen*, 2017, pp. 1-7.

Tellurium-bearing minerals in sulfide chimneys from ultramafic-hosted Semyenov-2 hydrothermal field, Mid-Atlantic Ridge

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INTRODUCTION

High tellurium contents in the ancient volcanogenic massive sulfides (VMS) and modern seafloor massive sulfides (SMS) have been reported by V.Maslennikov (Maslennikov et al., 2013). However findings of tellurium minerals in SMS are rather rare. The only reported coloradoite and bi-melonite, have been found in massive sulfides from Rainbow hydrothermal field (Fouquet, 2010). Here we present data about Te - minerals in sulfide chimneys of different ages (up to 84.7 kyr - Cherkashov et al., 2010) from Semyenov-2 hydrothermal field.

The obtained results

The Semyenov hydrothermal cluster was discovered and studied in the course of cruises 30 and 32 of R/V Professor Logachev (2007 and 2009) at 13º31´ N, MAR. This area is associated with an oceanic core complex and associated with serpentinized gabbro-peridotites and basalts. Plagiogranites and tonalites have been dredged on seafloor in the Semyenov cluster area (Cherkashov et al., 2013; Pertsev et al., 2012).

In total, 25 sulfides samples have been studied. The major and minor mineralogical phases were identified using reflected light microscope. Major element compositions of ore-forming minerals were analyzed on a Hitachi S3400N scanning electron microscope at the Geomodel Center, St. Petersburg State University (St. Petersburg, Russia) with an AzTec Energy 350 (EDX) detector and an INCA 500 (WDX) detector.

Semeynov-2 deposits as a whole as compared to sulfides of MAR are enriched in Cu (average = 34.0%) and Zn (average = 8.5 %) as well as **Te** (average = 17 ppm), Au (average = 9 ppm), Bi (average = 25 ppm) Se (average = 400 ppm) and Ag (average = 92 ppm)

Based on the major mineral distribution, the chimneys are subdivided into chalcopyrite and sphalerite – chalcopyrite types.

Chalcopyrite type **(84.7 kyr):** The primary mineral is chalcopyrite and minor minerals are isocubanite, chalcocite. Accessory minerals are not observed.

Chalcopyrite type **(35.8 kyr):** The primary mineral is chalcopyrite and minor minerals are sphalerite, bornite, chalcocite, digenite. Accessory minerals include native gold, glaucodot, cobaltite, **Te-rich "sulfosalts".** Mineralization of tellurium are represented by **tellurobismuthite (Bi_2 Te_3), calaverite (Au Te_2), melonite (Ni Te_2).** Tellurobismuthite was reported in the central part of unaltered chalcopyrite aggregates (fig.1A). Occasional melonite was related to chalcopyrite grains. Calaverite occurs at the chalcocite - chalcopyrite replacement contact (fig.1B). Secondary sulfide (chalcocite, digenite) contain Te-rich "sulfosalts". The amount of Te-rich "sulfosalts" increasing with secondary sulfide content in chimneys.

Chalcopyrite-sphalerite type **(23.4 kyr):** The primary minerals are chalcopyrite, and sphalerite; minor minerals are bornite and covellite (fig.1C). Chimneys are represented by zonal texture including chalcopyrite with sphalerite overgrowths. Accessory minerals are native gold, electrum, glaucodot, galena, clausthalite, **Te-rich tetrahedrite**. Mineralization of tellurium are represented by **tellurobismuthite (Bi_2 Te_3), silvanite ($(Au,Ag)_2Te_4$), calaverite (Au Te_2).** Tellurobismuthite and silvanite are related with chalcopyrite grains from chp-sph aggregates. Native gold with Bi and Te contents are also found in association with Te-mineralization. Bornite-chalcosite aggregate replacing chalcopyrite contains abundant calaverite grains. There is Te-rich tetrahedrite (fig.1D) in digenite aggregates replacing sphalerite.

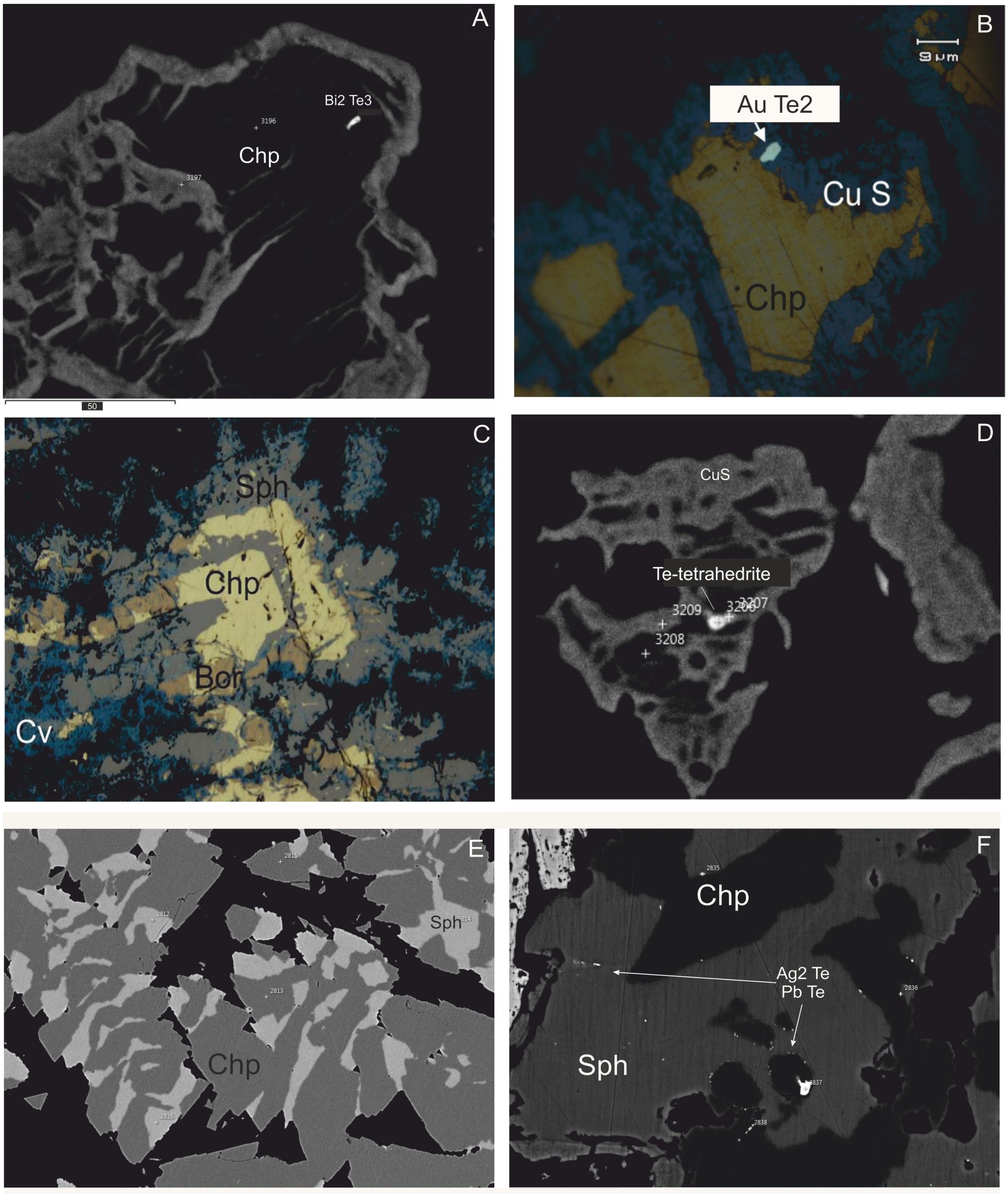

Figure 1. A – Tellurobismuthite **(Bi_2 Te_3)**,; B - Calaverite **(Au Te_2);** C – Chalcopyrite (chp)-sphalerite(sph) zonal texture; D - Te-rich tetrahedrite; E - The graphic growth of chp –sph; F - Hessite **(Ag_2Te)**, altaite **(Pb Te)**

Chalcopyrite-sphalerite type **(by present day/active):** The primary minerals are chalcopyrite and sphalerite and the minor mineral is covellite. The primary texture observed is the graphic growth of chalcopyrite and sphalerite around the chimney conduit (fig 1E). The wide diversity of accessory mineralization is related to this texture. **Hessite (Ag_2Te), altaite (Pb Te)**, electrum, klaustalite, tennantite form at the chp-sph boundary (fig1E). Altaite and hessite have Au and Bi content up to 2%. Occasional **tellurobismuthite (Bi_2 Te_3)** is observed in the center of chalcopyrite grains that are free of sphalerite.

Summarizing the mineralogical data of Te-minerals (table 1), the coincidence of Te minerals with Bi and Au to high-temperature chalcopyrite types and the entrainment of tellurium minerals with silver and lead in lower-temperature chimneys – sphalerite. Based on Te content versus age of chimneys, Te enrichment occurs at the first stage of hydrothermal vent and decreases with maturity of the system (Fig.2)

Table 1. Te-minerals in the sulfide chimneys

Chp-Shp (present day)	Chp-Shp (23.4 kyr)	Chp (35.8 kyr)	Chp (84.7 kyr)
Tellurium –bearing minerals in the primary sulfide minerals			
Tellurobismuthite + Hessite +++ Altaite +++	Tellurobismuthite ++ Silvanite +++	Tellurobismuthite +++ Melonite +	Non-observed
Tellurium –bearing minerals in the secondary sulfide minerals			
	Calaverite +++ Te-rich tetraidrite +	Calaverite ++ Te-rich “fahlore” +++	Non-observed

Figure 2. Tellurium concentration versus age of sulfide

We suppose that general tellurium enrichment in SMS from Semyenov-2 field compare with other MAR deposits is related to occurrence plagiogranites in the Semyenov cluster area. According to investigation provided to Te-minerals from (VMS) sulfide chimneys, the position and compositions of tellurides could reflect extreme gradients of temperature and oxygen and sulfur fugacities across the vent chimney. This process is controlled by the interplay between generally reduced, high-temperature, sulfide-rich hydrothermal fluids and oxygenated cool water (Maslennikov, 2013).

Distribution of tellurides in modern chimneys is connected to not only interaction between hydrothermal fluid and seawater along with host rock, but it is also linked to the age of sulfide and the degree of secondary alteration.

Acknowledgements

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References

Cherkashov, G et al. (2010): Seafloor massive sulfides from the northern equatorial Mid-Atlantic Ridge: New discoveries and perspectives. – In Marine Georesources and Geotechnology, v.28, p.222-239.

Cherkashov, G et al. (2013): Sulfide ores of the northern equatorial part of the Mid-Atlantic Ridge. – Oceanology, v.53, p.680-693.

Maslennikov ,V et al. (2013): Tellurium-bearing minerals in zoned sulfide chimneys from Cu-Zn massive sulfide deposits of the Ural, Russia. – Mineralogy and Petrology, v.107, p.67-99.

Pertsev, A et al. (2012a): Modern sulfide deposits of the Semenov ore region (Mid-Atlantic Ridge, 13º31´ N): Types of associated rocks of the oceanic core complex and their hydrothermal alteration. – Geology of Ore Deposits, v.54, p.334-346.

Keywords: seafloor massive sulfide, tellurium minerals, Mid – Atlantic Ridge

Anna Firstova

Anna Firstova graduated from St. Petersburg State University (bachelor and master levels) in 2010 and in 2012, respectively, and currently is a postgraduate of the same University. Since 2008 she has been working at VNIIOkeangeologia (Department of Geology and Mineral Resources of the Ocean). The primary focus of her research is study of mineral and chemical composition of seafloor massive sulfides.

Unlocking Critical Metals from Ferromanganese Nodules and Crusts – The Role of Iron during Dynamic Mineral Recrystallization

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ABSTRACT

The rapid advancement of *green* technologies in recent years is closely tied to an ever-increasing demand for raw materials. Innovative forms of zero-emission transportation and sustainable power generation will require a variety of traditional metals such as Ni and Co, but also many non-traditional metals (e.g., REY). Many of these elements are known to be highly enriched in deep-sea ferromanganese (Fe-Mn) nodules and crusts. However, unlocking these metals from their deposits through metal processing is – aside from deposit exploration and production – expected to be a critical component that will affect the overall economics of the marine mining value chain. Hence, research and development of tailored metal processing solutions which can target specific metals of interest in Fe-Mn nodules and crusts, is required. Dynamic mineral recrystallization (DMR) of Fe-Mn oxide phases is a geochemical process that may have notable potential for hydrometallurgical applications.

We have recently demonstrated that Ni can effectively be cycled between deep-sea Fe-Mn nodules and crusts and solutions through dynamic mineral recrystallization. DMR occurs in nature as abiotic background process during biogeochemical Mn cycling when dissolved Mn(II) is in direct contact with Mn oxides. Trace metals which are incorporated in the Mn host phases, are cycled between solid phase and solution via coupled dissolution (trace metal release) – reprecipitation (trace metal incorporation) mechanisms.

Our results previously showed that, although Ni experiences mineral-fluid repartitioning in $Mn(II)_{aq}$-free suspensions, increased $Mn(II)_{aq}$ concentrations (e.g., 1 mM $Mn(II)_{aq}$) significantly catalyze Ni exchange between solid phase and solution over time. Moreover, a trend was observed where hydrogenetic Fe-Mn crusts with low Mn/Fe ratios exhibit increased Ni exchange in comparison to hydrogenetic nodules (Fig. 1).

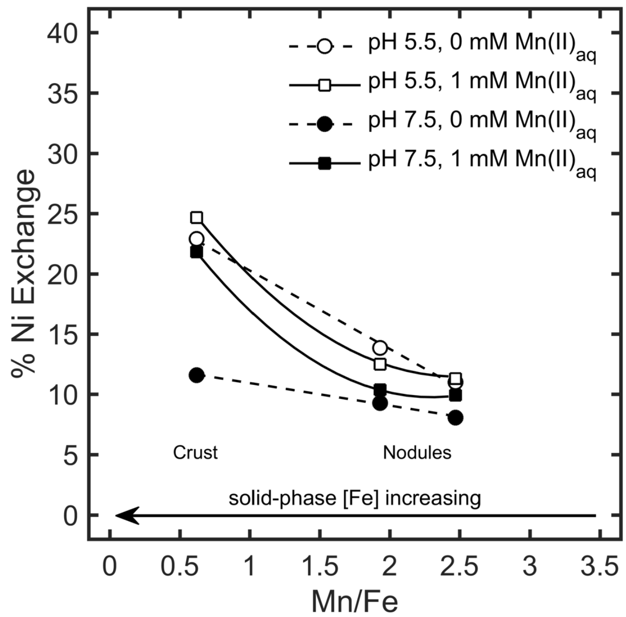

Fig. 1 Relationship between the percentage of Ni exchange and solid-phase Fe concentration. Ferromanganese nodules with low Fe content exhibit lower percentages of Ni exchange whereas for the Fe-Mn crust with high Fe concentration increased Ni exchange is observed.

In this study, we conducted subsequent metal exchange experiments with isotope tracers to explore the role of Fe, which is associated with the solid phase, during DMR. Moreover, the effects of aqueous Fe(II) addition to reactors with variable $Mn(II)_{aq}$ concentrations were investigated to shed a light on the $Fe(II)_{aq}$-$Mn(II)_{aq}$ interplay during dynamic mineral recrystallization. Based on our previous research and the preliminary findings of this study we hypothesize that DMR (a) has direct implications for the genesis, alteration, and trace metal enrichment of deep-sea ferromanganese nodules and crusts and (b) may represent a cornerstone for the development of tailored and eco-friendly hydrometallurgical metal extraction techniques.

Keywords: Ferromanganese Nodules, Polymetallic Crusts, Deep-sea Mining, Dynamic Mineral Recrystallization, Hydrometallurgy, Nickel Isotope Tracer

Statement:

I hereby grant permission to the event organizers to archive the abstract (PDF format) at OneMine.org at the conclusion of the Underwater Mining Conference 2018.

Tobias Hens

Tobias draws his expertise from diverse working experiences and a multidisciplinary background in geosciences which he acquired at Heidelberg University in Germany. At Monash University in Melbourne (AUS) he uses state-of-the-art analysis techniques, such as synchrotron light sources and isotope tracers, to investigate metal enrichment and mineral-fluid element cycling processes in ferromanganese nodules and crusts. The overall objective of Tobias' work is to apply aspects of fundamental research towards the advancement of sustainable and eco-friendly metal recovery solutions for deep-sea ferromanganese mineral deposits.

MARTEMIS – An Electromagnetic Coil System for the Detection of Buried Seafloor Massive Sulfides

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ABSTRACT

Past investigations of seafloor massive sulfides (SMS) focused on actively forming sites. New technologies are needed to explore for SMS deposits which have finished their active phase and are possibly covered by sediments or lava. For this purpose the new marine transient electromagnetic (TEM) induction system MARTEMIS was developed by GEOMAR.

The system was used for investigations in the Tyrrhenian Sea (Palinuro Seamount) and at the Mid-Atlantic Ridge (TAG area) and proved to be suitable for operations at shallow (~600m) and great water depths (~3600m) in steep and difficult terrain. Calibration measurements in the water column demonstrate that it is possible to acquire high quality data, which is fit to be evaluated in terms of inversions. However, these calibration measurements also demonstrated that great care has to be taken in the design of such an inductive coil system, because relatively small metal structures attached to the system may lead to significant static distortions in the measured transients.

The interpretation of TEM data acquired at the Palinuro Seamount show a conductive layer in the vicinity of a previously drilled, buried SMS occurrence and serve as proof of principle of the system. Results also indicate that the conductive SMS unit is indeed a confined layer with limited thickness between 3 – 5m, which was not known from previous drilling. In a similar manner, results also hint at an unknown mineralization at depth in a second area of the Palinuro Seamount. Investigations by TEM measurements were accompanied by measurements of the ambient electric field (→ self-potential) and seafloor temperatures with

a heatflow probe as well as direct sampling with a gravity corer. The areal coverage of measurements and sampling allow for a greatly enhanced view of the structure.

In a similar manner investigations in the vicinity of the TAG area at the Mid-Atlantic Ridge, which were carried out at much greater water depth, demonstrated that the MARTEMIS system is suitable to be used at great water depth in challenging terrain. Several anomalies were detected at inactive structures in the vicinity of the TAG area (MIR zone, Shinkai Mound, Double Mound) which are all interpreted as SMS mineralization.

The synopsis of results demonstrates that the MARTEMIS system is a flexible tool suitable to find and characterize buried SMS occurrences, which are no longer associated to any hydrothermal activity.

Introduction

At present, the investigation of seafloor massive sulfides (SMS) is strongly limited by the available technology to the detection of actively forming sites, since detection of SMS deposits mainly relies on plume detection of active hydrothermal venting in the water column and seafloor morphological observations. While these methods have proven to be valuable for active sites, they do not allow the detection of deposits which are no longer associated to any hydrothermal activity and are possibly covered by sediments or lava. Therefore, new technologies are necessary which allow for the detection of buried SMS, which are no longer connected to any hydrothermal activity.

In land-based exploration, it has been common practice for several decades to use electromagnetic methods to detect and characterize massive sulfide deposits. However, when turning to marine investigations only a few electromagnetic experiments have ever been conducted on SMS, e.g. by Cairns et al. (1997) on the TAG hydrothermal mound or by Kowalczyk (2008) on the Solwara SMS deposits. In Swidinsky et al. (2012) our workgroup has proposed to use the transient electromagnetic (TEM) method and demonstrated that the TEM method is in principle not only useful for the detection of a deposit under a sediment cover but can also yield valuable information about its depth and potentially also its thickness.

Here, we will present results obtained with GEOMAR's new marine transient electromagnetic induction system (MARTEMIS), which were acquired over known and assumed SMS sites with no active hydrothermal activity.

Methods

The MARTEMIS system (Figure 1) is a coincident loop TEM system for the detection and characterization of conductive seafloor features like SMS. It is characterized by:

- adjustable coil size depending on size of A-frame (e.g. 4x4m2 – 6x6m2),
- transmitter currents up to 60A into one or two windings,
- operation of coil close to seafloor (2-10m),
- continuous measurement,
- operation at speeds up to 0.7kn.

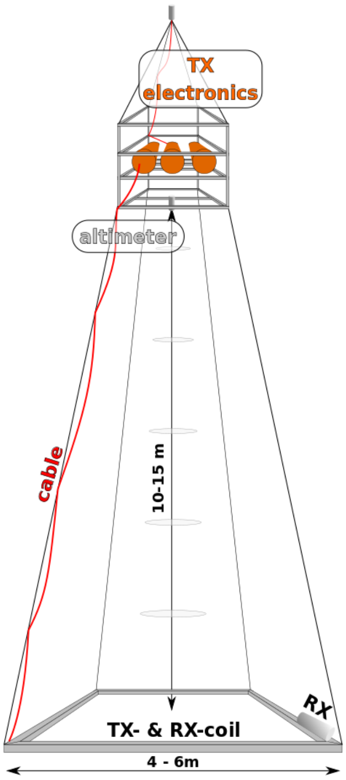

Figure 1: Sketch of MARTEMIS coil system.

The design of the system with a lower frame (holding the coincident transmitter and receiver coils) and an upper frame (holding the transmitter electronics and the altimeter) ensures that conductive metal parts (e.g. pressure housings) are at a sufficiently large distance to the sensor coils in order to minimize distortion effects.

The maximum operation depth of the system is mainly limited by the length of the ship's winch cable and the maximum depth rating of the pressure housings (currently 6000m). Additional sensors can be mounted to the system, e.g. two extra pairs of electrodes to the coil frame to measure the ambient electrical field.

Experiments & Results

Palinuro Seamount

The Palinuro Seamount (Fig. 2), which is located about 75km off the coast of Italy at a water depth of about 600m in the Tyrrhenian Sea, was the research target during two cruises (POS483, 2015; POS509, 2017; R/V Poseidon). Previous investigations had found up to 5m of massive sulfides in drilling cores, partially under several meters of sedimentary cover, in an area of about 45m x 27m (Petersen et al. 2014). Thus, the seamount was chosen as suitable target for testing the MARTEMIS system.

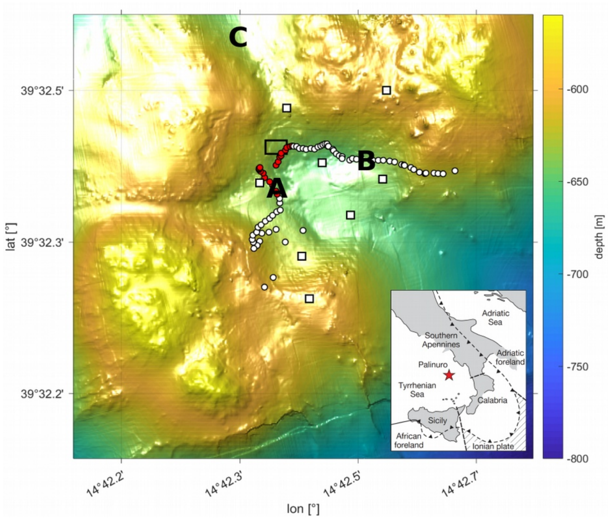

Figure 2: Bathymetric map of Palinuro Seamount with area outlining locations with SMS recovery from drilling (black rectangle), 700m long profile line of MARTEMIS system (circles), stationary OBEM receivers (squares) and marked areas A - C with anomalous EM responses.

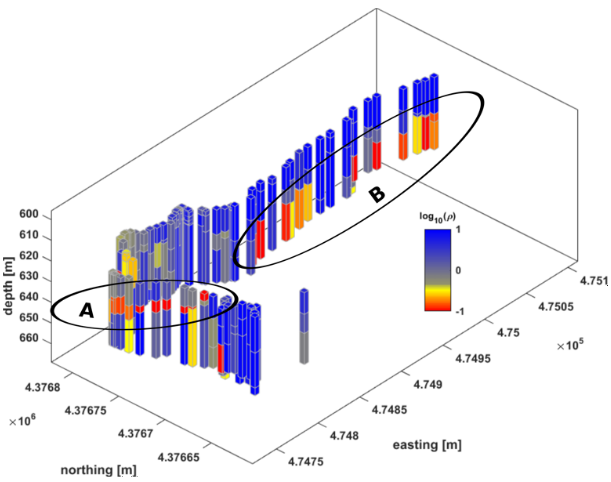

Figure 3: 1D inversion results of TEM measurements, conductive features (ρ~0.1Ωm, red) are indicative of SMS occurrences.

In 2015, TEM measurements with the MARTEMIS system showed anomalous responses (red circles in Figure 2, A) in the vicinity of the area where SMS had previously been recovered in drilling cores (black rectangle). Calibration measurements within the water column show that measured transients are only distorted at times earlier than ~1ms, but later times up to 20ms match the expected theoretical full space responses and are, thus, suitable for inversion (Hölz et al. 2015).

1D inversions of TEM data (Figure 3) were carried out and confirm the existence of a buried layer of conductive material (red, ~10S/m) in the vicinity of the previous drilling sites (A), which we interpret as SMS layer beneath sedimentary cover. Additionally, a conductive layer (B) was detected at greater depth (~15–20m), hinting at a so far unknown mineralization. At this depth the layer is at the detection limit of the system.

In 2017, follow-on investigations showed increased heatflow values and gravity cores containing sulfide rich sediments (sites B & C), which provided ground truthing and substantiate the interpretation of EM measurements (Hölz, 2017). An extended TEM data set with ~900 stations along ~9km of profile were also measured across the structure. Evaluation of this data set is still work in progress. First results of self-potential measurements and additional EM experiments were recently published and can be found in Safipour et al. (2017a, b; 2018). They also show a correlation between the known mineralization and the ambient electrical field.

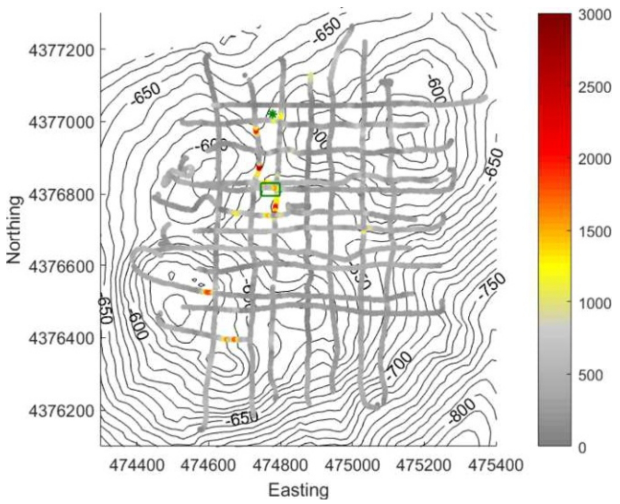

Figure 4: Ambient horizontal electrical field Eh. Anomalies are evident in the vicinity of the site of previous drilling (green rectangle). From Safipour et al., (2017a).

TAG Area

In 2016, regional scale experiments were carried out in the vicinity of the TAG (Trans-Atlantic Geotraverse) hydrothermal field during cruise JC138 (R/V James Cook). One of the experiments was carried out along an 8km long profile line in the working area 3-Mounds at a water depth of ~3600m (Figure 5). Calibration measurements in the water column revealed

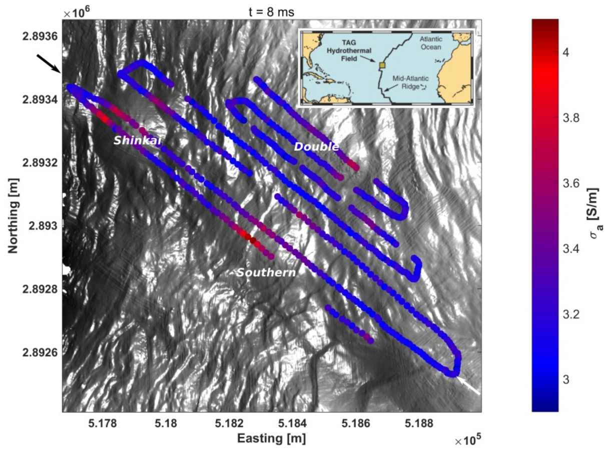

Figure 5: Bathymetric map of working area 3-Mounds. Colored dots show apparent conductivity (Swidinsky & Weiss, 2017) along the track of the MARTEMIS system. Anomalies are evident in the region of the known mounds.

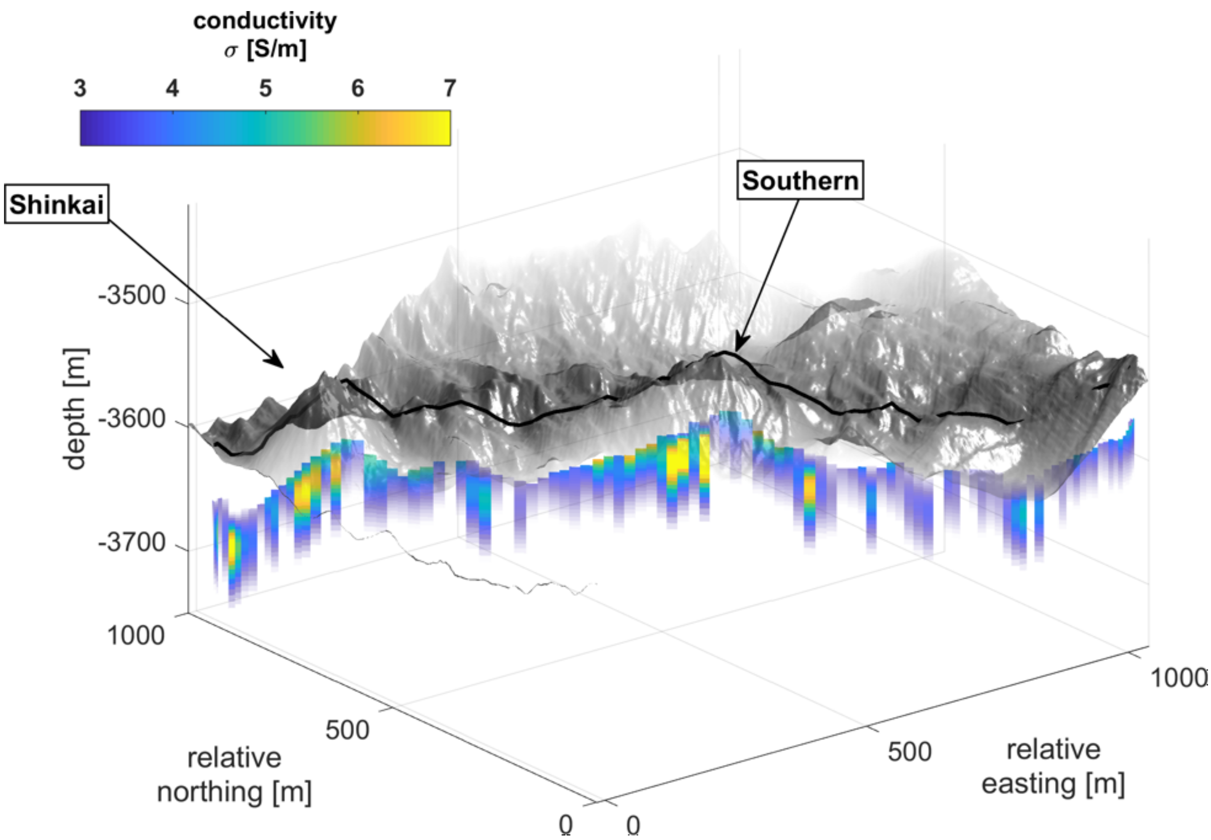

Figure 6: 3D view of bathymetry with the track line of the MARTEMIS system (black line) and stitched 1D inversion results of TEM measurements (shifted down for better visibility) along profile 6 (marked by arrows in Figure 4). Conductive features (yellow) are evident on the western flanks of Shinkai and Southern Mound. Low conductivities (<3S/m) are blanked out because the system has no sensitivity to resistive features.

significant distortions, which were only recognized after the experiment. In subsequent testing the problem was traced back to additional weights, which had been attached onto the coil frame during this experiment. Theoretical considerations and modeling show that these distortions can be considered to be static (similar in Schamper et al. 2014) and that calibration measurements within the water column may be used to correct for the distortions.

Apparent conductivities show anomalous values in the vicinity of the three mound structures (Figure 5). 1D inversion results (Figure 6) along a selected profile show conductive features at the western flanks of Shinkai and Southern Mound. Laboratory investigations confirm that such high conductivities require the presence of high grade SMS (Spagnoli et al. 2016).

Conclusion

The MARTEMIS coil system designed at GEOMAR has been built as a tool for the investigation of sediment covered SMS, which are no longer connected to any hydrothermal activity, thus, being impossible to find with conventional detection methods. A first test of the system at the Palinuro Seamount in 2015 served as proof of principle and also demonstrated, that the system may not only be used for the detection of conductive anomalies, but may also yield information about the geometrical characteristics (e.g. thickness and depth of conductor).

Subsequent experiments with the system showed that it may also be used in difficult environments like the Mid-Atlantic Ridge, where water depth of around 3600m and Alpine like bathymetry poses severe challenges for the experimental design.

The evaluation of data has shown that calibration measurements in the water column are a viable asset for the later evaluation of data, since they can help to verify the correct functionality of the system or may help to identify and remove static distortion effects in the data.

Acknowledgments

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Keywords: seafloor massive sulfides (SMS), transient electromagnetics (TEM), marine resources

References

Cairns, G, Evans, R & Edwards, RN (1996) A time domain electromagnetic survey of the TAG hydrothermal mound. Geophysical Research Letters, 23: 3455-3458.

Hölz S. (ed., 2017) RV POSEIDON Fahrtbericht / Cruise Report POS509 - ElectroPal 2: Geophysical investigations of sediment hosted massive sulfide deposits on the Palinuro Volcanic Complex in the Tyrrhenian Sea. GEOMAR Helmholtz-Zentrum für Ozeanforschung, Kiel, Germany, 63pp. DOI 10.3289/GEOMAR_REP_NS_39_2017

Hölz S, Jegen M, Petersen S & Hannington M (2015) How to Find Buried and Inactive Seafloor Massive Sulfides using TEM. Extended abstract to UMC Conference, Tampa Bay, Florida, USA.

Kowalczyk, P (2008) Geophysical prelude to first exploitation of submarine massive sulfides. First Break, 26: 99-106.

Petersen S, Monecke T, Westhues A., Hannington M, Gemmell JB, Sharpe R, Peters M, Strauss H, Lackschewitz K, Augustin N, Gibson H & Kleeberg R (2014) Drilling shallow-water massive sulfides at the Palinuro volcanic complex, Aeolian Island arc, Italy. Economic Geology: 109, 2129-2158.

Safipour R, Hölz S, Halbach J, Jegen M, Petersen S & Swidinsky A (2017a) A self-potential investigation of submarine massive sulfides: Palinuro volcanic complex, Tyrrhenian Sea. Geophysics, 82, A51-A56.

Safipour R, Hölz S, Jegen M & Swidinsky A (2017b) On electric fields produced by inductive sources on the seafloor. Geophysics, 82(6): E297-E313.

Safipour R, Hölz S, Jegen M & Swidinsky A (2018) A first application of a marine inductive source EM configuration with remote electric dipole receivers: Palinuro Seamount, Tyrrhenian Sea. Geophysical Prospecting, accepted.
DOI 10.1111/1365-2478.12646.

Schamper S, Auken E. & Sørensen K (2014) Coil response inversion for very early time modelling of helicopter-borne time-domain electromagnetic data and mapping of near-surface geological layers. Geophysical Prospecting, 62: 658-674.

Spagnoli G, Hannington M, Bairlein K, Hördt A, Jegen M, Petersen S & Laurila T (2016) Electrical properties of seafllor massive sulfides. GeoMarLett, 36: 235 - 245.

Swidinsky A, Hölz S & Jegen M (2012) On mapping seafloor mineral deposits with central loop transient electromagnetics. Geophysics, 77: E171-E184.

Swidinsky A & Weiss C (2017) On coincident loop transient electromagnetic induction logging. Geophysics, 82 (4): E211-E220.

Sebastian Hölz

Sebastian Hölz received his PhD from the Technical University of Berlin in 2007 for his work in land-based transient electromagnetics carried out in the Gobi desert in NW China. In the same year he joined the marine electromagnetic research group at the Helmholtz Centre for Ocean Research, GEOMAR, Kiel, Germany.

His work deals with all aspects of marine controlled source electromagnetics like experiment and instrument design, planing and implementation of experiments, data processing and data interpretation. In the past two years he was chief scientist for cruises to the Palinuro Seamount (Italy) and to the Grimsey Vent Field (Iceland) for the investigation of SMS occurrences and active hydrothermal systems with EM methods.

Site-banking of the Reserved Areas with the International Seabed Authority: for operation of the Enterprise or Joint Venture

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INTRODUCTION

The UN-General Assembly adopted an Agreement on 28 July 1994 entitled 'Agreement relating to the implementation of Part XI of the United Nations Convention on the Law of the Sea ((UNCLOS) of 10 December 1982'. The Agreement came into force on 16 November 1994, and consequently, the inauguration of the International Seabed Authority (ISA, or the Authority), located in Kingston, Jamaica.

The Authority is the organization through which States Parties to the Convention (168, as of 25 July 2017) shall, in accordance with the regime for the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction (the Area) established in Part XI and the Agreement, organize and control activities in the Area, particularly with a view to administering the mineral resources of the Area.

The legal regime for the administration and development of the mineral resources of the Area as it now exists are available in Part XI of the Convention1 which contains the legal framework governing "activities in the Area" and in Annex III to the Convention which contains the "Basic Conditions of Prospecting, Exploration and Exploitation" with respect to the resources of the Area2.

The 1994 Agreement relating to the Implementation of Part XI of the UNCLOS is the so-called 'parallel system'; as elaborated in article 153 of the Convention. The essential elements of the 'parallel system' include assured access for States parties and their nationals to seabed mineral resources along with a system of site-banking, whereby 'reserved areas' are set aside for the conduct of activities by the Authority through the 'Enterprise' itself or in association with developing States or in joint venture with the contractor who provided the particular reserved site2.

The right to apply for a plan of work for seabed activities (exploration and exploitation) in 'reserved areas' are accorded exclusively to developing States [or any natural or juridical person sponsored by them and effectively controlled by them or by other developing State, or any group of developing States) and the Enterprise by virtue of annex III, articles 4 and 9, of the Convention and regulation17 of the Regulations on Prospecting and

Exploration for Polymetallic Nodules in the Area3 (ISBA/19/C/17). The same provision applies to polymetallic sulphides (see ISBA/16/A/12/Rev.1, regulation 18) and to cobalt-rich ferromanganese crusts (see ISBA/18/A/11, regulation 18). However, because of the effect of the 1994 Agreement [Section 2 of the annex], the Enterprise is not in a position to avail itself of this right owing to a lack of capital and technology. The Enterprise is thus not set up and its right to reserved areas is now exercised exclusively by developing States.

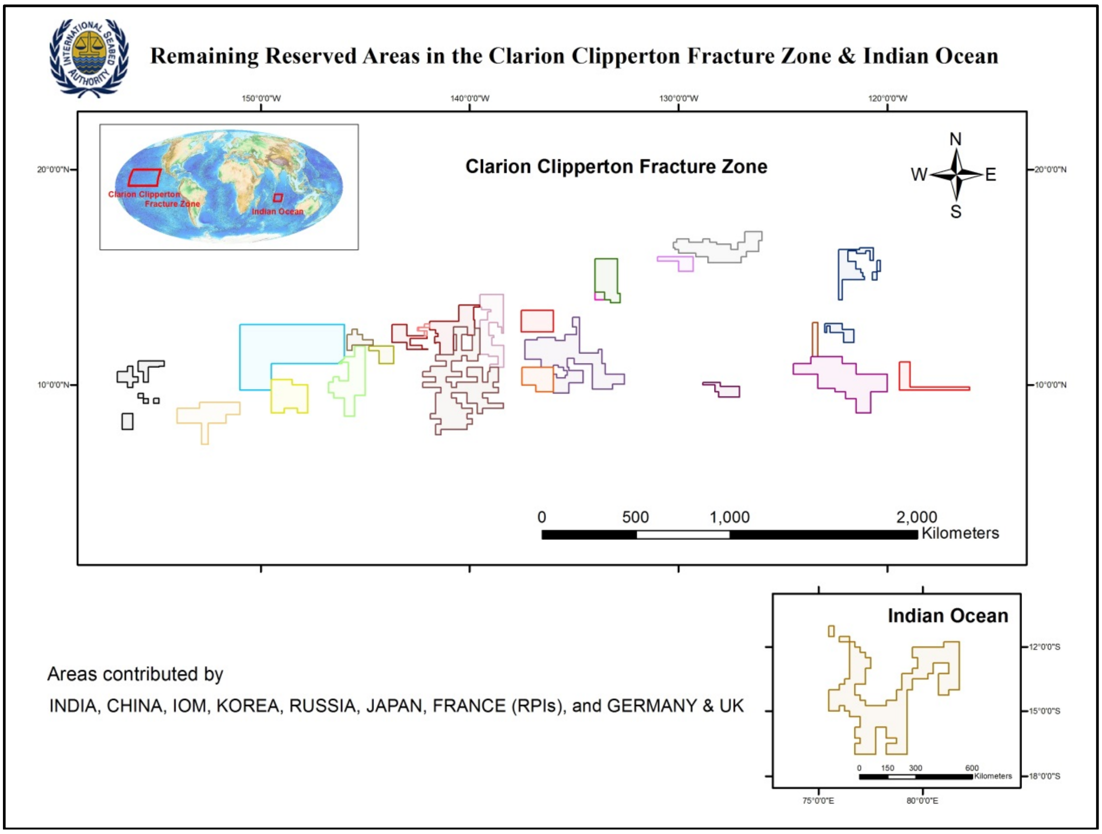
Since 2008, applications for plans of work for exploration relating to certain available reserved areas in the Clarian Clipperton Fracture Zone (CCFZ) have been submitted by entities sponsored by the following small island developing States: Cook Islands [Cook Islands Investment Corporation, (ISBA/20/LTC/3)], Kiribati [Marawa Research and Exploration Ltd. (ISBA/18/C/18)], Nauru [Nauru Ocean Resources Inc. (ISBA/17/C/9)], Singapore [Ocean Mineral Singapore Pte. Ltd.(ISBA/19/LTC/11)] and Tonga [Tonga Offshore Mining Limited (ISBA/17/C/10)].

The Tonga Offshore Mining Limited (TOML), application stated it as "a Tongan incorporated subsidiary of Nautilus Minerals Incorporated, which holds 100 per cent of the shares of TOML through another wholly owned subsidiary, United Nickel Ltd., incorporated in Canada" (ISBA/17/C/10, para. 15); whereas the Cook Islands Investment Corporation (CIIC) application was described as "the application by the CIIC supported by CI-GSR, an equal and equitable arrangement between the Cook Islands Government and another contractor G-TEC Sea Mineral Resources NV (GSR) of Belgium (ISBA/20/LTC/3, para. 12). In the case of Ocean Mineral Singapore Pty. Ltd., the contractor stated to collaborate with UK Seabed Resources Ltd., which holds two exploration licenses" (ISBA/19/LTC/11, para. 8).

The application area for a plan of work for exploration to obtain a contract, in the case of Nauru Ocean Resources Inc. (sponsored by Nauru), is area divided into four regions taken from four different reserved areas [ISBA/17/C/9]; Marawa Research and Exploration Ltd. (sponsored by the Republic of Kiribati) covered three regions in three blocks [ISBA/18/C/18]; whereas China Min metals Corporation (sponsored by China), application area was divided into eight blocks, selected from five different reserved areas [ISBA/21/C/2].

According to the decision papers by the Council, total 1,165,633 sq.km area has been contributed as Reserved Areas by the Contractors to the Authority in the CCFZ and 150,000 sq. km in the Central Indian Ocean Basin (CIOB). Of this 887,768 in the CCFZ is by the Contractors, who were earlier Registered Pioneer Investors (RPIs), and 150,000 sq. km. in the CIOB by India (the first registered Pioneer Investor with the Authority). By July 2017, total 888,203 sq.km area is available as reserved area with the ISA, and remaining has been allocated to the contractors for the exploration surveys in the CCFZ area [Figure].

Keywords: ISA, Reserved Areas, Polymetallic Nodules, Enterprise, Joint Venture



References

[1]Convention, Articles 133 to 191
[1]Consolidated text of the Convention and the 1994 Agreement see "The Law of the Sea –Compendium of Basic Documents" International Seabed Authority/The Caribbean Publishing Company, Kingston, Jamaica, 2001, pp. 48- 92 and Annex III pp.142-159
[2]www.biicl.org/files/1392_nandan_opening.doc
[3]Consolidated Regulations and Recommendations on Prospecting and Exploration, International Seabed Authority, 2015 [also see: https://www.isa.org.jm/mining-code]
[3]https://www.isa.org.jm/contractors/reserved-areas; and for ISBA/../…/ documents cited in the text.

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Pratima Jauhari (Ph.D.) is a Marine Geologist, with specialization in marine mineral exploration, sediment geochemistry, coastal and industrial surveys and swath bathymetry. She joined the National Institute of Oceanography (NIO) Goa, India, in 1982 and has worked there until 2013. One of her major contribution at the NIO was to the "Deep Sea Bed Exploration for Polymetallic Nodules" project. The team had surveyed over 4 million sq. km area in the Indian Ocean and identified potential 'mine-sites'containing nodules in an area of 75,000 sq. km in the Central Indian Basin. India became the first 'Registered Pioneer investor' with the International Seabed Authority for exploration of polymetallic nodules from the sea bed. She was leader of the project 'Mapping India's Exclusive Economic Zone, using multi beam-echo sounders'.

She has several publications in peer reviewed journals, technical reports and popular scientific articles including a book in Hindi language. She has sailed on 5 different ships for about 800 days for mineral exploration.

Since 2013, she is employed with the International Seabed Authority as Marine Geologist.

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An Information Theoretic Approach to Polymetallic Nodule Exploration using AUVs

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Abstract

Estimating the distribution of polymetallic nodules through conventional Autonomous Underwater Vehicle (AUV) based survey methods is tedious and exhaustive. In this work, we suggest an alternative, using an informative theoretic framework, referred to as adaptive informative path planning (IPP). This performs the task of data collection with a constraint on sampling time and energy to provide an approximation of the nodule density field across the survey area. We test our performance against conventional sampling paths and show that we are able to obtain a good approximation of the nodule density field within the stipulated time whilst optimizing on the AUV energy consumption.

I. INTRODUCTION

Polymetallic nodules (PMN) in the open oceans have received significant attention in the recent years due to presence of several economically significant elements such as nickel, copper, cobalt and molybdenum in them. Factors such as nodule grade, abundance, and their accessibility, have generated significant interest in the northeastern equatorial Pacific region known as the Clarion-Clipperton fracture zone (CCFZ) [1, 2]. The CCFZ is a large region spanning over approximately 9 million square kilometers stretching between Baja California and the Hawaiian Islands from east to west, and the Clarion and Clipperton fracture zones from north to south, as shown in Figure 1. The distribution of PMN within this region is by no means uniform. This is attributed to various environmental factors such as topographic undulations, surface biological activity, sediment type and thickness, and water depth [2, 3].

Many national institutes and consortia of international companies have explored PMN in CCFZ and data have been collected using various sampling (box coring, dredging), near-bottom photography and acoustic techniques to estimate nodule abundance [4, 5, 6]. However, given the vastness of the region it is not practically possible to survey the entire region to asses the PMN distribution. Hence efficient exploration strategies need to be devised to map these nodule resources.

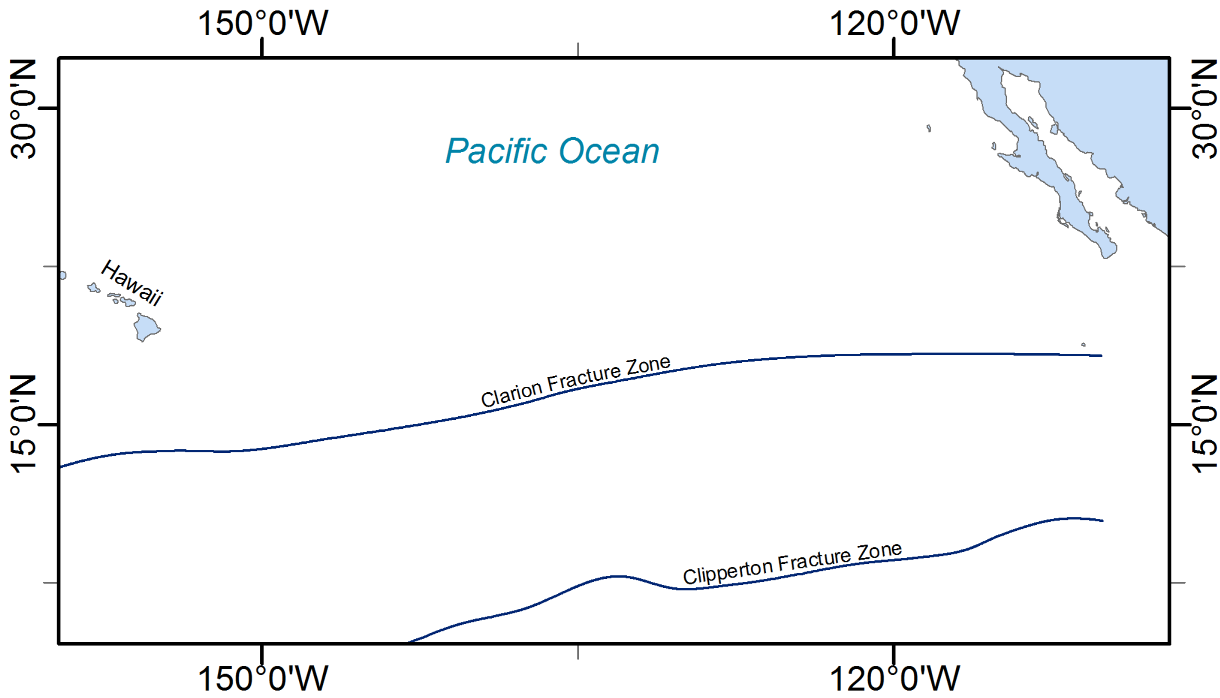


Figure 1: Region of Interest: Clarion Clipperton Fracture Zone

II. FORMULATION

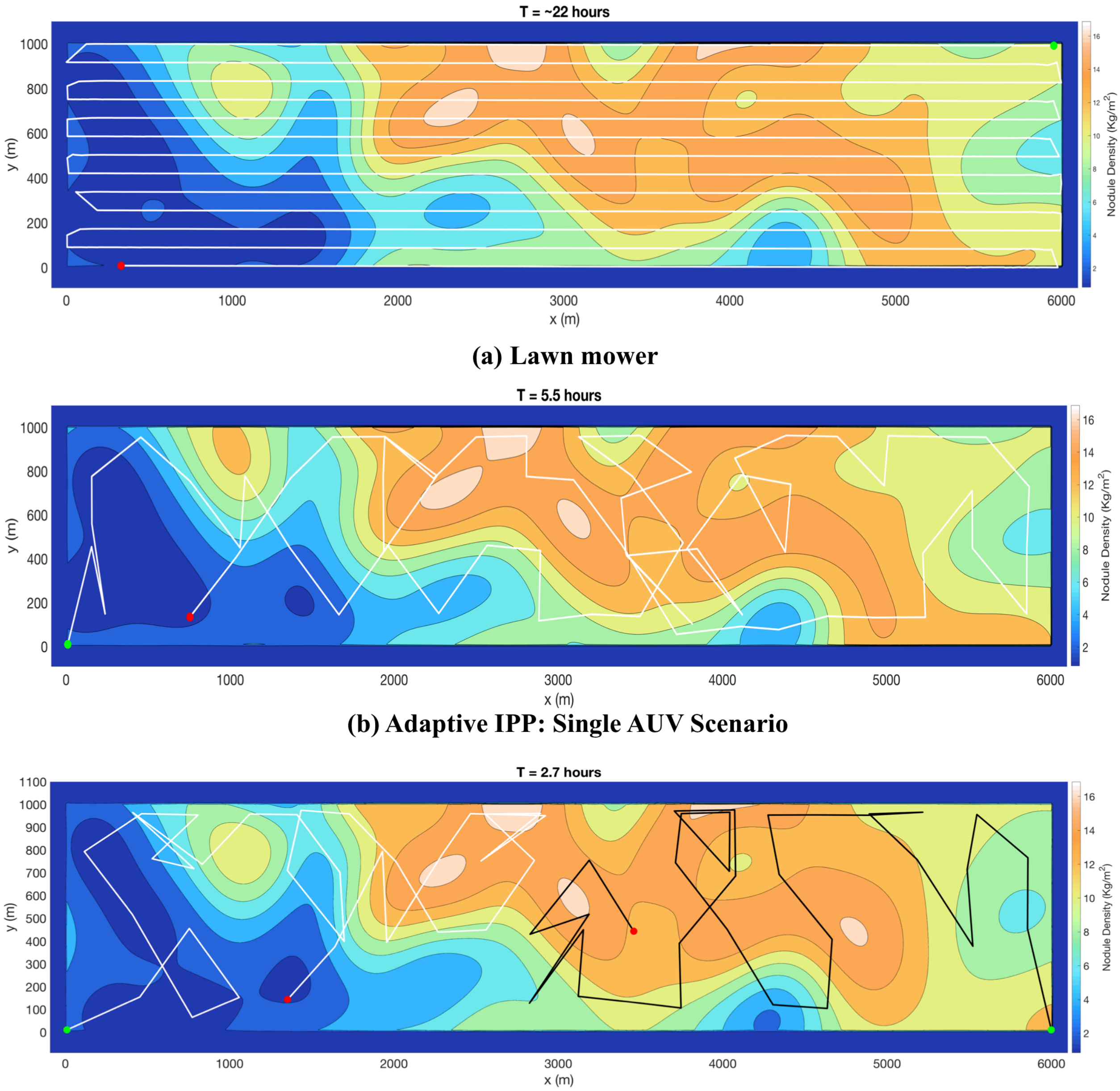
In conventional autonomous underwater vehicle (AUV) surveys, the vehicle traverses a predefined path, generally a lawn mower pattern, for collecting data (say geo-referenced optical and acoustical images). It is then analyzed to provide an estimate of the nodule density across the survey area. However, such an approach is time intensive as the AUV exhaustively surveys over a predefined path without exploiting the incoming information.

In this work, we present an adaptive informative path planning (IPP) framework for planning path to estimate nodule density variations across a survey area. The adaptive IPP framework effectively exploits the incoming information and hence is able to sample efficiently, leading to a significant reduction in survey time. This framework has three primary components, namely, field prediction, path planning using current information, and path traversal to collect more data [7]. It uses a sparse Gaussian process method (SPGP), to obtain an estimate of the nodule density field and the corresponding uncertainty in this estimate, represented as variance [8]. The informative paths are evaluated using an information measure for unobserved locations, generally for finite horizons. The AUV then traverses the path, which provides maximum information as per a predefined criterion and collects data to give a nodule density estimate across the survey area. We test our performance of adaptive IPP on a synthetically generated nodule density dataset and benchmark our results against that obtained from lawn mower approach.

III. RESULTS AND DISCUSSION

The dataset used as a ground truth is obtained by traversing in a lawn mower pattern over an area of 6 km x 1 km containing synthetically generated nodule density field, as shown in Figure 2. The AUV is assumed to be moving at a constant speed of 2 knots at an altitude of

5m from the seabed. It is assumed that the AUV gathers nodule density information once in every 10 seconds. The adaptive IPP generates the sampling path with constraints on both time and AUV's energy usage. The total AUV run length traversing in a lawn mower pattern is about 79 km with a total bottom time of ≈22 hours.



(a) Lawn mower

(b) Adaptive IPP: Single AUV Scenario

(c) Adaptive IPP: Two AUVs Scenario

Figure 2: Comparison of estimated PMN density maps and the AUV trajectory

In comparison, the bottom time required by the IPP framework to build a visibly similar nodule density field (refer Figure 2b) of the survey area at an average speed of 2.4 knots is about 5 hours and 30 minutes. This is approximately one-fourth of the total bottom time of a conventional lawn mower. Conversely, this also translates to the fact that for a given fixed amount of time T, the adaptive IPP framework can survey up to 4 times as much area as a conventional lawnmower approach can achieve with the same AUV energy constraints, without much loss in estimation accuracy.

Additionally, we also compare a multi-AUV IPP framework to perform adaptive sampling. Using this approach, if two AUVs are deployed, then the survey time is further reduced to 2 hours and 42 minutes as shown in Figure 2c. Furthermore, the evidence of IPP generating a good approximation of the ground truth is also seen through a low mean absolute error, in Figure 3 at the end of the mission.

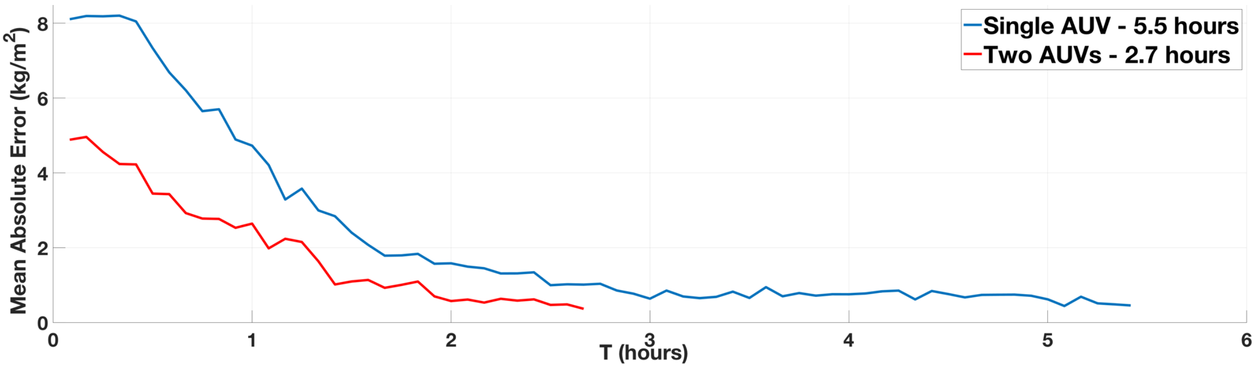


Figure 3: Performance comparison between one and two AUVs: Mean absolute error in the nodule density estimates across the entire survey area.

ACKNOWLEDGEMENT

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REFERENCES

[1] David Z. Piper, Kam Leong, and William F. Cannon. Manganese Nodule and Surface Sediment Compositions: DOMES Sites A, B, And C. In James L. Bischoff and David Z. Piper, editors, Marine Geology and Oceanography of the Pacific Manganese Nodule Province, number 9 in Marine Science, pages 437–473. Springer US, 1979.

[2] D. S. Cronan. Deep-sea nodules: distribution and geochemistry. Marine manganese deposits, 15:11, 1977.

[3] J. Z. Frazer and M. B. Fisk. Geological factors related to characteristics of sea-floor manganese nodule deposits. Deep Sea Research Part A. Oceanographic Research Papers, 28(12):1533–1551, December 1981.

[4] J. L. Mero. Economic aspects of nodule mining. Marine manganese deposits, pages 327–355, 1977.

[5] Rahul Sharma. Quantitative estimation of seafloor features from photographs and their appli- cation to nodule mining. Marine Georesources & Geotechnology, 11(4):311–331, 1993.

[6] Sang Hoon Lee and Ki-Hyune Kim. Side-Scan Sonar Characteristics and Manganese Nodule Abundance in the ClarionClipperton Fracture Zones, NE Equatorial Pacific. Marine Geore- sources & Geotechnology, 22(1-2):103–114, 2004.

[7] Rajat Mishra, Mandar Chitre, and Sanjay Swarup. Online informative path planning using sparse gaussian processes. Kobe, Japan, June 2018. Oceans'18, IEEE/MTS.

[8] Ma Kai Chieh, Liu Lantao, Heidarsson Hordur K., and Sukhatme Gaurav S. Data driven learning and planning for environmental sampling. Journal of Field Robotics, 2017.

Keywords: PMN exploration, informative path planning, AUV survey, deep sea mining

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DSM Concept Cube - A classification system for deep-sea mining concepts

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INTRODUCTION

The last decade has given rise to an increasing number of deep-sea mining concepts (DSMCs) outlining technical solutions for the production chain from seafloor mining to mineral or metal extraction. The vast technological and logistical challenges coupled with immature but rapidly evolving technology has spawned a great variety in proposed concepts, and the exact implications of the phrase 'best available technology' is very much an open question.

DSMCs differ significantly with respect to choice of technology, technological readiness level, degree of resource utilization, logistics, OPEX and CAPEX requirements, overall profitability, legal and political implications, not to mention environmental impact. Hence, a system for classifying concepts could provide a useful identification and structuring tool when performing economic, judicial or environmental assessments of DSMCs, as well as offering a general terminology to describe concepts sharing fundamental traits. This abstract proposes a DSMC classification system based on how a concept makes use of mineral separation at the different stages in the ore's journey from the deposit to the ocean surface and ultimately to onshore facilities.

Mineral separation, as a process step, is the key factor in determining both the state and mass flow of materials along the production chain and has, as such, a decisive effect on economy and environmental impact of any deep-sea mining project. A DSMC that is based on bringing the entire volume of broken ore to onshore facilities for processing will look very different from a concept based on pre-concentration (i.e. mineral separation) at the seafloor. Whereas the latter offers savings in the form of reduced energy cost for vertical transport, it also represents a substantial additional technological challenge. Furthermore, whether or not a concept relies on mineral processing at the seafloor or on a floating facility at the ocean surface above the deposit also determines the point at which mineral separation waste (i.e. tailings) must be managed. Different concepts offer different opportunities for tailings deposition, and are at the same time bound by different requirements.

The technology and logistics associated with handling of masses in general, and with tailings management in particular, represent the basic premise in the assessment of a concept's economic and environmental viability. As shown in the poster accompanying this abstract, the proposed classification system is simple, yet sufficiently comprehensive to facilitate subdivision and categorisation of DSMCs based on their most fundamental characteristics.

CLASSIFYING DSM CONCEPTS

The DSM Concept Cube

Most DSMCs will conform to a simple classification system based on whether or not the concept involves mineral separation: 1) at the seafloor (i.e. subsurface), 2) on the ocean surface above the deposit or 3) onshore. This results in eight possible combinations in a simple 2x2x2 classification cube. Each combination, or class, can be labelled by combining symbols in a three-symbol positional system (xyz), in which the positions represent the extent of mineral separation at the seafloor (x), on the surface (y) and onshore (z). Letting the respective symbols 'S' and 'N' denote 'separation' and 'no separation' yields the DSM Concept Cube [1] illustrated in figure 1.

The term 'mineral separation' requires a more precise definition. In the context of the proposed classification system 'mineral separation' refers to physical separation processes designed to separate the individual mineral components of the ore in order to achieve a concentration of valuable components. Typically, this would include froth flotation, gravity separation, sensor based sorting or magnetic separation, but all processes leading to a significant and intentional degree of concentration would fall within the definition. In contrast, processes primarily designed to alter the particle size distribution of the ore or to separate solids from water would not. Removal of fines prior to mineral separation or loss of fines during dewatering of mineral slurries could serve as examples of the latter, as would the rejection of problematic size fractions prior to vertical transport. Even though the concentration of valuable components in the material that is discarded during these processes could differ from that of the remaining ore, their effect on ore grade is of secondary importance.

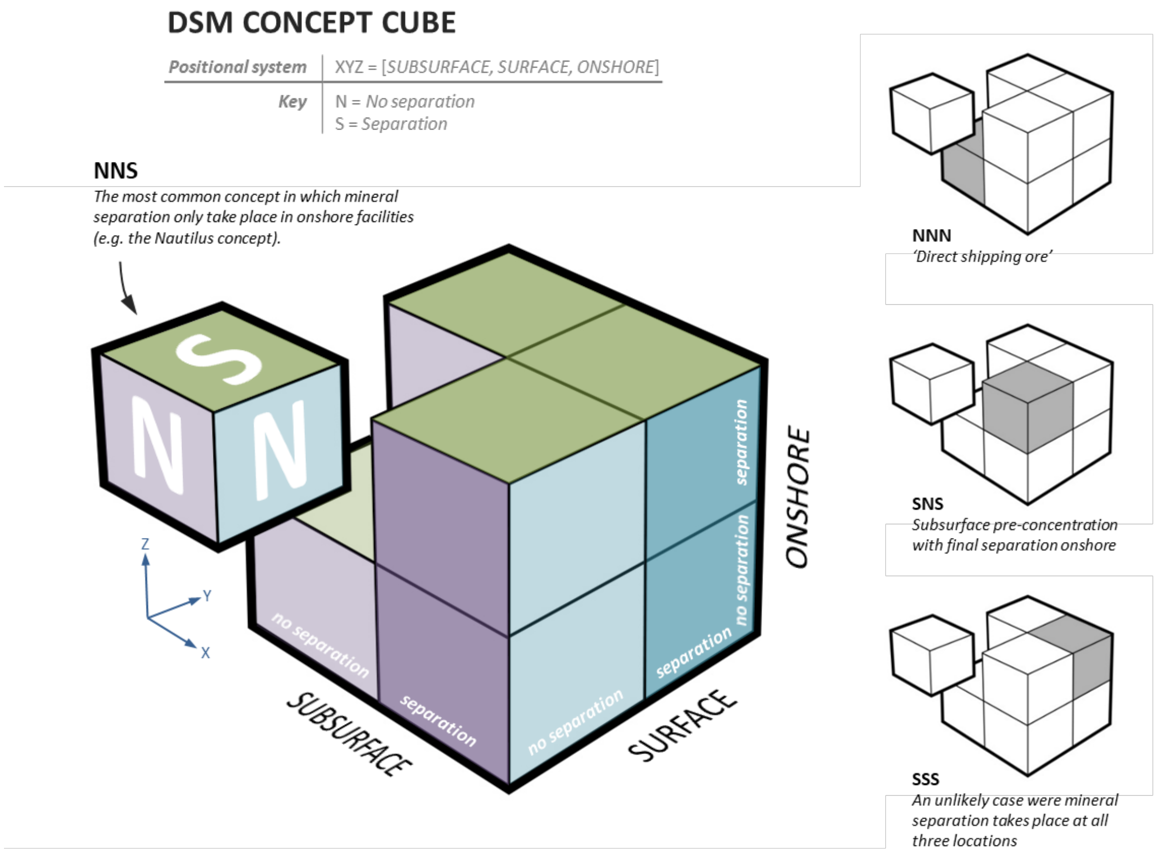

Figure 1. The Deep-Sea Mining Concept Cube

Class characteristics

From a technological point of view, the NNS concept highlighted in figure 1 represents the simplest of the DSMCs if not counting the NNN class (the DSM equivalent of 'direct shipping ores') that requires no mineral separation prior to metallurgical extraction. The remaining classes in the concept cube all rely on pre-concentration (mineral separation) on the seafloor and/or the ocean surface, and the main driving force for developing such concepts lies in the potential energy savings associated with transportation of the ore. Generating tailings on-site offer additional opportunities, but may pose restrictions on the separation process and create new environmental challenges. Pros and cons of the different concept classes in the DSM Concept Cube are presented and discussed in detail in the poster that will be exhibited at the 47th Underwater Mining Conference.

REFERENCES

[1] Kleiv, R.A, 2016: "A classification system for deep-sea mining concepts". Research Group Report M-RAK 2016:15. Mineral Production and HSE Research Group, Dept. of Geoscience and Petroleum, NTNU

Keywords: Deep-sea mining concepts, Mineral separation, Mineral processing, Tailings

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Characteristics of oceanic core complexes (OCCs) in Central Indian Ridge (8 °–12 °S) by high-resolution bathymetry and backscatter images

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Abstract

Over the past decade, sea-floor hydrothermal vent fields have been studied by many researchers because of their commercial potential of mineral resources and the origins of Earth's life. Approximately 300 of these are reported as massive sulfide deposits near the mid-ocean ridge, most of which are located in the Atlantic and Pacific ridges. However, only fourteen deposits have been identified in the Indian mid-ocean ridges. The Central Indian Ridge (CIR) between 8°S and 12°S is composed of three segments with a slow full-spreading rate of 33-37 mm/yr. The hydrothermal activity at the slow-spreading center can be generated along the ridge axis attended by volcanism or along the tectonic features, such as oceanic core complexes (OCCs). OCC is an exposed mantle rocks composed of peridotite and ultramafic rocks uplifted through long-lived detachment fault processes which can also lead to extensive hydrothermal circulation near the slow-spreading center. Therefore, the identification of OCC's properties will be an important indicator for finding the sea-floor hydrothermal vents. To study hydrothermal activity of the CIR, Korea Institute of Ocean Science and Technology (KIOST) have conducted expeditions using R/V Onnuri over four years (2009-2011, 2017). High-resolution bathymetry and backscatter data was obtained during expeditions using multibeam echo system of EM120 in 2009-2011 and deep-tow side-scan sonar system of IMI-30, which has more higher resolution than EM120, in 2017. In this study, we use these high-quality data for constraining location and size of OCC. We also analyze the geophysical and morphotectonic characteristics of OCC gathering high-resolution bathymetric map and backscatter image.

Keywords: oceanic core complex, bathymetric map, backscatter image, side-scan sonar

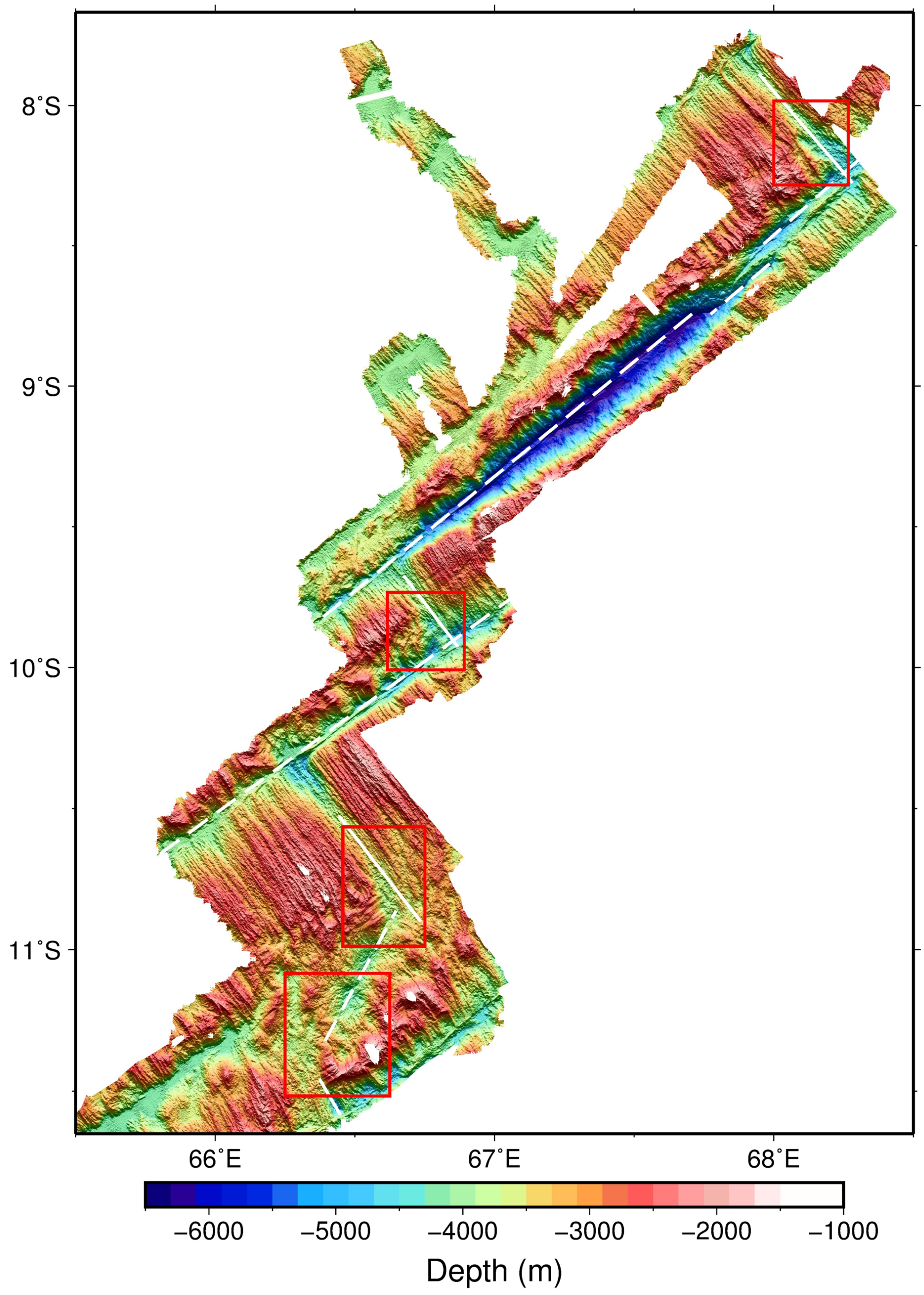

Figure 1. Sea-floor image generated from the multibeam bathymetry data (EM120) of the CIR. The red rectangles top to bottom refer to target areas of this study. The detailed map showed in Fig. 2a-d. The thick and dotted white lines are the ridge axis and transform fault, respectively.

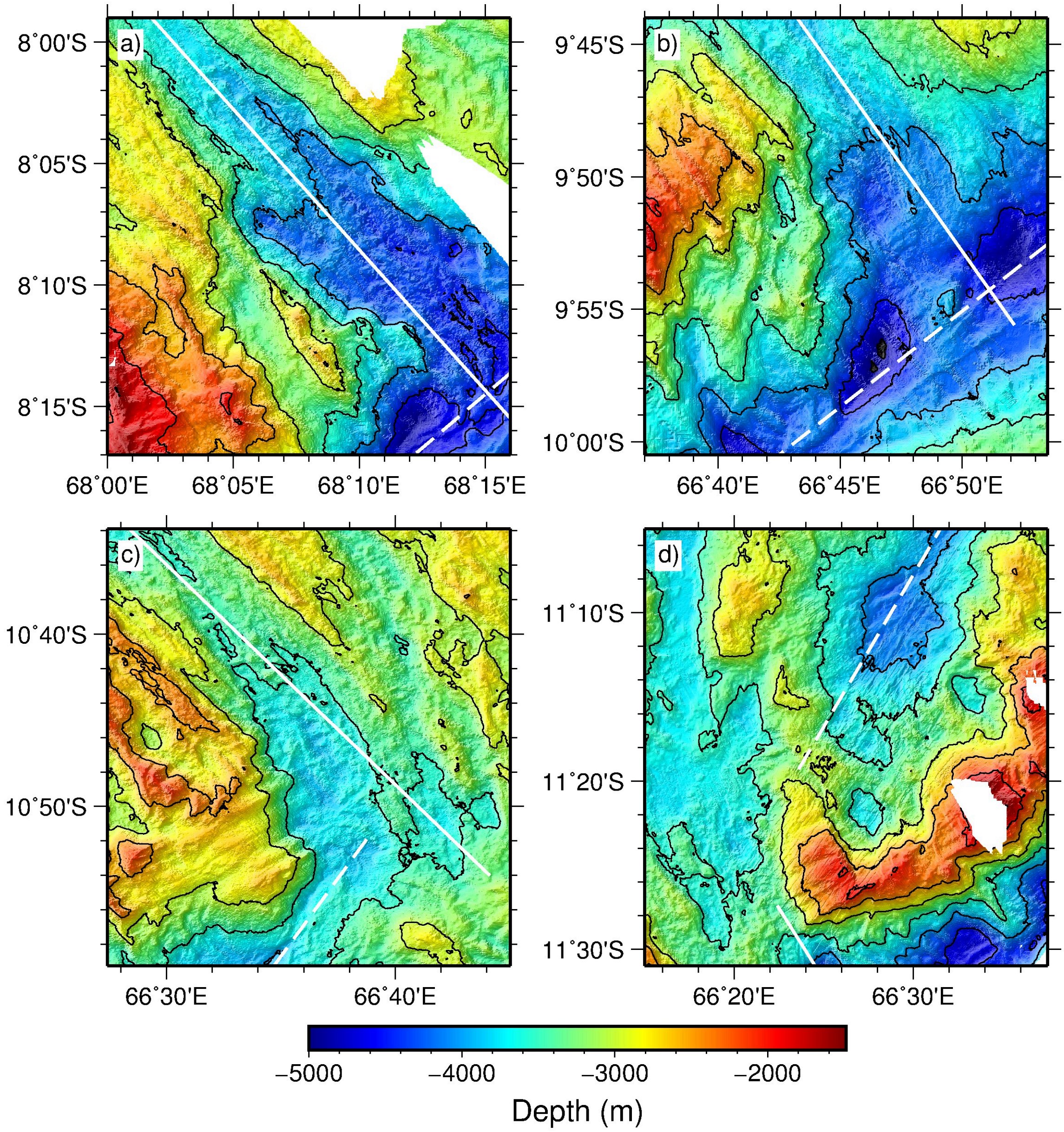

Figure 2. Detailed topographic maps blended bathymetry data from EM120 with IMI30. a) Segment 1. b) Segment 2. c) Segment 3-1. d) NTD 3-1 and Segment 3-2. The thick and dashed white lines are same as Fig. 1. Contour interval is 500 m.

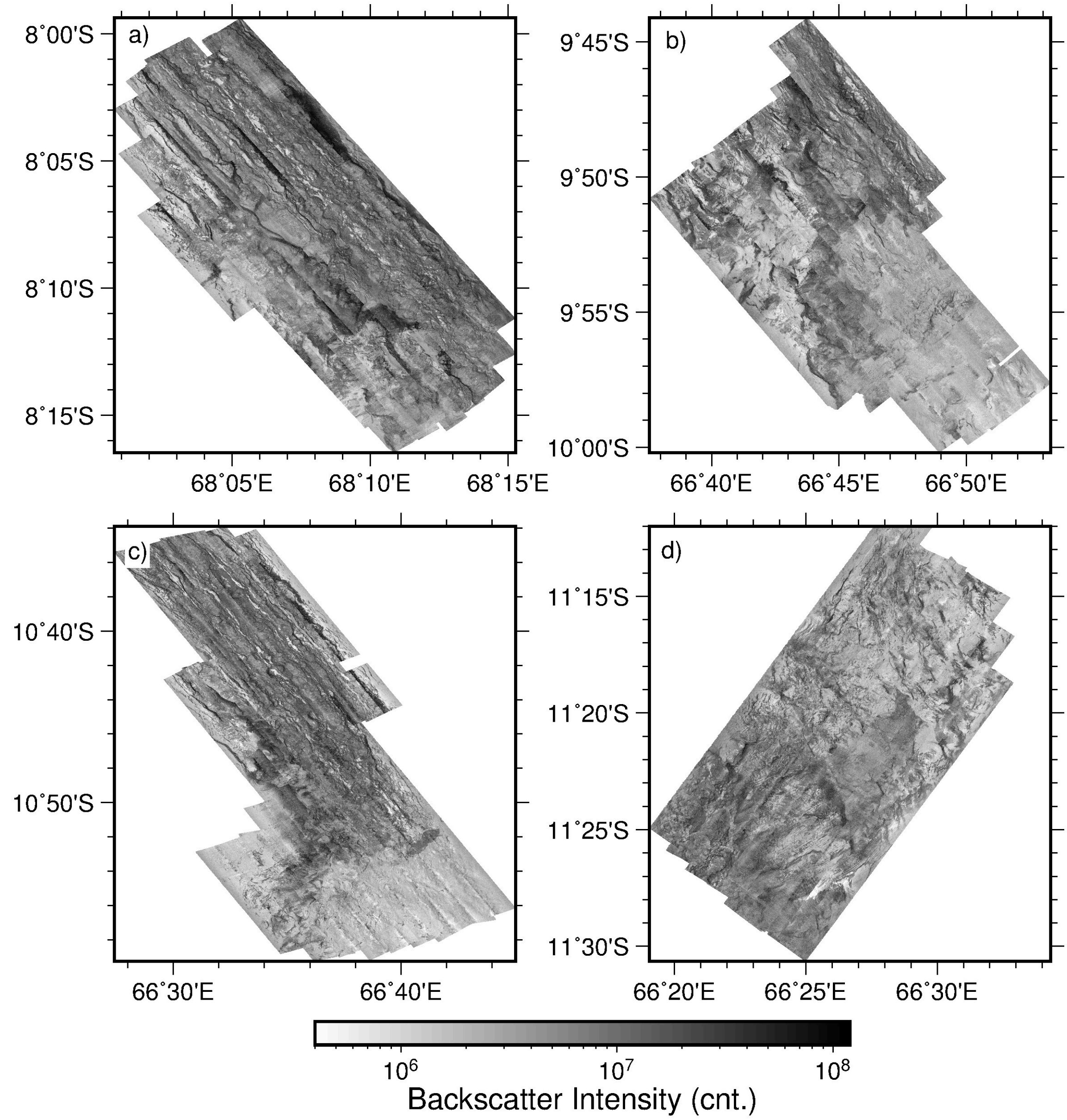

Figure 3. High-resolution backscattering images obtained by deep-tow side-scan sonar system IMI-30. a) Segment 1. b) Segment 2. c) Segment 3-1. d) NTD 3-1 and Segment 3-2.

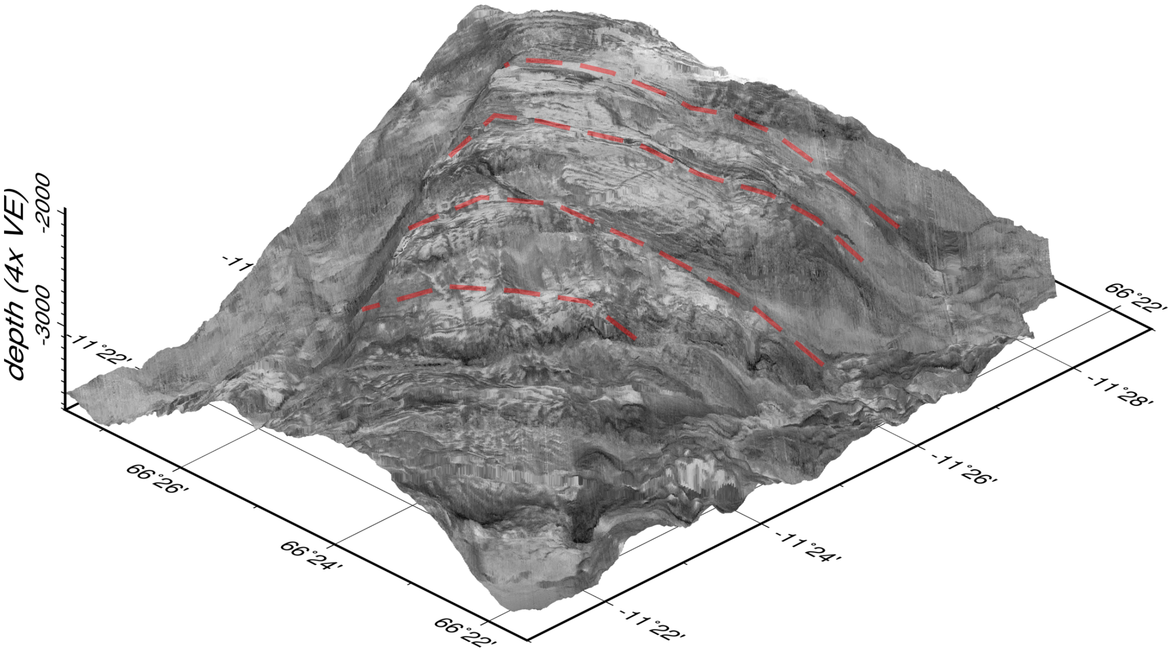

Figure 4. Three-dimension perspective view of OCC 3-2 (Pak et al., 2017) near NTD 3-1 zone showing IMI-30 sidescan data draped over blended bathymetry (IMI-30/EM-120). The dashed red lines denote the axis-perpendicular corrugation.

References

Pak et al., 2017. Tailings and their Disposal in Deep-Sea Mining, Proceedings of the Tenth (2013) ISOPE Ocean Mining and Gas Hydrates Symposium, Szczecin, Poland, September 22-26, 2013.

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Mineral phases and element associations of ferromanganese crusts, Amerasia Basin Arctic Ocean, based on sequential leaching

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INTRODUCTION

Ferromanganese (FeMn) crusts from Mendeleev Ridge, Chukchi Borderland, and Alpha Ridge, in the Amerasia Basin, Arctic Ocean, are similar based on morphology and chemical composition. The crusts are characterized by two- to four-layered stratigraphy. The chemical composition of the Arctic crusts differs significantly from hydrogenetic crusts from the North Pacific Prime Zone (PCZ; Hein et al., 2013), such as a high mean Fe/Mn ratio (2.6 versus 1.3) and low Si/Al ratio (1.8 versus 4.0), with lower Mn, Ca, Ti, P, Ba, Co, Cu, Ni, Pb, Sr, and Zn and higher Si, Al, Mg, As, Li, V, Sc, and Th. Based on Arctic FeMn crust mineralogy, chemical composition, and growth rates, crust formation was dominated by three processes: Precipitation of Fe-Mn (oxyhydr)oxides from ambient ocean water, sorption of metals by the Fe and Mn phases, and fluctuating but large inputs of terrigenous debris (Konstantinova et al., 2017; Hein et al., 2017). The Mn and Fe phases are hydrogenous and reflect bottom ocean-water chemistry and the aluminosilicate phase contains stable detrital minerals such as quartz, feldspars, zircon, monazite, and clay minerals.

A precise method of studying the distribution of elements in FeMn crust phases is sequential leaching that dissolves four mineral phases of different stability step-by-step, in the following order: easily leachable phase, mostly bio-calcite; manganese oxides; iron oxyhydroxides; and residual aluminosilicate minerals (Koschinsky and Halbach, 1995). Twelve bulk crusts and crust layer samples obtained from six hydrogenous FeMn crusts were studied. Those crusts were collected during Russian (Arktika 2012) and USA (HLY0805, HLY0905, and HLY1202) research cruises from different parts of the Amerasia Basin (Mendeleev and Alpha Ridges, Chukchi Borderland). Samples were chosen for the sequential leaching experiments based on their morphology, location, and water depth. Hydrogenetic crust (D07-33) from the Tuvalu EEZ, central-west Pacific Ocean, was included in the experiment for comparison. Recovery during the four-step sequential leaching, with respect to the bulk analyses, was between 80% and 120%.

Results

FeMn crusts from the Amerasia Basin are enriched of As, Li, V, Sc, and Th compared to Pacific crusts. One of the most significant features that controlled the layered structure of the Arctic crusts was the input of significant amounts of detritus (up to 36%), which originated from different sources and changed with time (Hein et al., 2017; Konstantinova et al., 2017). The residual phase, leach 4 (L4), of the Arctic crusts has higher amounts of most of the elements analyzed than do the Pacific crusts. The Chukchi crusts display the greatest amount of detritus among the Arctic crusts as determined in the L4 leach. Some elements (Li, Mg, Cs Zn, V) have higher concentrations associated with the Fe phase in Arctic crusts than in Pacific crusts, which results from higher FeOOH contents relative to MnO_2 (larger Fe/Mn ratio) in Arctic deposits. Most elements are similarly distributed between the hydrogenetic Mn and Fe phases for all the Arctic crusts.

Based on the sequential leaching experiments, elements that are enriched in the Arctic crusts (As, Th, V, and Li; no sequential leaching data for Sc) are characterized by higher contents in the residual L4 phase compared to Pacific crusts as mentioned; however, the main phases that host these enriched elements are the Mn and Fe (L2 and L3) phases. Thus, 18% of the As and 10 % of the Th are housed by the detritus with the remainder sorbed by the Fe hydroxides (L3). Vanadium occurs in three main phases: 30% in Mn-oxide phase (L2), 50% in Fe-hydroxide phase (L3), and 20% in residual aluminosilicate phase (L4). Lithium occurs 50% in the Mn phase and 30% in the residual detritus (L4). The maximum Li content occurs in a nodule from the northern part of Mendeleev Ridge, where Mn oxides host about 80% of the Li; this may relate to diagenetic input and Li is commonly enriched in diagenetic nodules. These data indicate that higher Li, As, Th, and V concentrations may have characterized the bottom waters during growth of the crusts. This was shown to be true for Sc, which is highly enriched in the Arctic crusts (Hein et al., 2017). The phase distributions of elements within the crust layers is similar among Arctic crusts, being somewhat different in the amount of the residual L4 phase based on measured total detrital content in the crusts.

Keywords: Ferromanganese crusts, Arctic Ocean, sequential leaching, element host phases

Reference

Hein J.R., Konstantinova N., Mikesell M., Mizell K., Fitzsimmons J., Lam P., Jensen L., Xiang Y., Gartman A., Cherkashov G., Hutchinson D. R., 2017. Arctic Deep-Water Ferromanganese-Oxide Deposits Reflect the Unique Characteristics of the Arctic Ocean. Geochemistry, Geophysics, Geosystems 18 (11), November 2017, https://doi.org/10.1002/2017GC007186.

Hein, J. R., Mizell, K., Koschinsky, A., & Conrad, T. A., 2013. Deep-ocean mineral deposits as a source of critical metals for high- and green- technology applications: Comparison with land-based resources. Ore Geology Reviews, 51, 1–14. https://doi.org/10.1016/j.oregeorev. 2012.12.001.

Konstantinova N., Cherkashov G., Hein J.R., Mirão J., Dias L., Madureira P., Kuznetsov V., Maksimov F., 2017. Composition and characteristics of the ferromanganese crusts from the western Arctic Ocean. Ore Geology Reviews 87, 88-99. DOI: 10.1016/j.oregeorev.2016.09.011.

Koschinsky A. and Hein J.R., 2003. Uptake of elements from seawater by ferromanganese crusts: solid-phase associations and seawater speciation. Marine Geology 198, 331-351.

Koschinsky, A., Halbach, P., 1995. Sequential leaching of marine ferromanganese precipitates: Genetic implications. Geochim. Cosmochim. Acta 59, 5113-5132.

Natalia Konstantinova

Natalia is currently a Ph.D. student at the Institute of Earth Sciences at Saint Petersburg State University in Russia, where she received a bachelor's degree in 2010 and a master's degree in 2012. Natalia's academic advisor is Georgy Cherkashov, professor at Saint Petersburg State University. After receiving her master's degree, Natalia was invited to work at the I.S. Gramberg Institute for Geology and Mineral Resources of the Ocean, where she gained further experience in geological and oceanographic research. Natalia is now able to work part-time at the I.S. Gramberg Institute while pursuing a Ph.D.

Natalia is currently studying ferromanganese crusts from the Arctic Ocean to better understand the nature and origin of these deposits. She worked at the USGS for nine months as a Fulbright Fellow with James R. Hein in 2016-2017, and again for 6 weeks in 2018.

Managing Deep-Sea Exploration Programs from Concept to Success

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ABSTRACT

Odyssey is a world leader in marine exploration and has undertaken expeditions in varying environments throughout the world addressing many commercial and regulatory demands. Odyssey works in a variety of settings such as shallow coastal territorial waters, abyssal plains in exclusive economic zones, and high seas in international waters on projects involving mineral exploration, environmental analysis, oceanographic survey, and recovery operations.

Odyssey Marine Exploration (Odyssey) excels in adaptively managing programs from initial concept through realization of commercial goals while successfully satisfying the regulatory and engineering demands of deep sea projects.

This poster presentation reveals best practices throughout a project life cycle and presents case studies in areas including but not limited to:

- Research practices to identify and define valuable subsea resources
- Project planning and licensing to achieve project goals and meet regulatory requirements
- Optimizing offshore operations to achieve desired results
- Designing projects to support processing and commercial programs

ABSTRACT FROM THE COOK ISLANDS SEABED MINERALS AUTHORITY

TITLE- Latest developments from the Cook Islands relating to the management of its large Seabed minerals resource of Cobalt rich Ferromanganese nodules.

- Technological, ecological, economical and legal aspects of Licencing in an EEZ for seabed minerals exploration and exploitation

ABSTRACT

The Cook Islands is a group of 15 islands, being a Polynesian nation in the heart of the South Pacific Ocean and now bears the name of famed English navigator Captain James Cook, who sailed here in the 1770's. In the 1800s, it was re-named "**the Cook Islands**" by illustrious Russian cartographers from the previous English name of "*The Hervey Islands*".

SEABED MINERALS

The Cook Islands has one of the world's most abundant deep seabed mineral (SBM) resources of Manganese nodules estimated at 10 billion tonnes, within its large Exclusive Economic Zone (EEZ) of almost 2 million square kilometres.

This knowledge has been gained through numerous scientific surveys conducted in the Cook Islands waters by many international scientific research entities, starting with a Russian deep seabed marine survey in the 1970's, from which many physical samples of these abundant Manganese nodules were first recovered. Some of the 1970's Russian samples are still retained in the Cook Islands more than 40 years later.

Then a comprehensive 21 year Pacific wide Seabed Minerals scientific study, between 1985-2005, undertaken by the Japanese and SOPAC[1] based in Fiji, confirmed that the Cook Islands has a vast, unique and valuable deep seabed minerals resource of Cobalt rich Manganese nodules. These Nodules contain many valuable minerals required by the global market including Nickel, Copper, Cobalt and Rare Earth Elements.

[1] SOPAC, now called the Pacific Community

In 2009, the Cook Islands Parliament passed the world's first national legislation, dedicated to the wise, sustainable management of the Cook Islands valuable national seabed minerals resource, ***the Seabed Minerals Act 2009***, and amended and updated this law again in 2015.

Under this law, any future seabed minerals activities must be conducted on sustainable principles, according to best international practice while adopting the precautionary principle and for the benefit of present and future generations.

The drafting of that specialised legislation was made possible through Government support and the invaluable technical assistance from the Commonwealth Secretariat, based in London.

In 2012, a ***Seabed Minerals Resource Assessment*** was contracted by the Seabed Minerals Authority and undertaken by the esteemed Professor David Cronan of the Imperial College of London. This Resource Assessment estimated the Manganese Nodule resource in the Cook Islands at more than 10 billion tonnes. The largest resource in any one EEZ.

In 2013, the Cook Islands Government then established the world's first government minerals office, related specifically to seabed minerals resource management, the ***Cook Islands Seabed Minerals Authority***.

From 2013 to 2018, the Cook Islands, by the Seabed Minerals Authority, has begun expertly building the required national capacity to properly administer this national seabed minerals resource.

This includes Seabed Minerals Authority legal staff working on Legal Internship attachments in international offices like DOALOS at the United Nations in New York and the International Seabed Authority in Jamaica. In 2016, two qualified Cook Islands technical personnel took part in separate "at sea" training opportunities, on deep sea exploration vessels, with Belgian GSR and German BGR.

This national Manganese nodule resource must be utilised for the benefit of present and future generations and according to best international practice, while fully complying with the 1982 United Nations Convention on Law of the Sea (UNCLOS) and all relevant international and regional treaties and agreements. Assistance to the Cook Islands from the ***SPC-EU Deep Sea Minerals Project*** (2011-16)[2] was instrumental in achieving this national goal and supporting the concerted effort towards wise seabed minerals management.

The Cook Islands has drafted **SBM Tax laws** and **Sovereign Wealth Fund Regulations** to wisely manage future national revenue generated from development of the seabed minerals resource, under our national jurisdiction.

In 2015, the Cook Islands passed its first ***Seabed Minerals Prospecting and Exploration Regulations***. These Regulations have established a robust and efficient Minerals Licencing system based on best international and industry practice.

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2 Pacific Community / Communauté du Pacifique

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In 2016, the Cook Islands Government signed a 15 year Exploration Contract with the **International Seabed Authority**, over a 75,000km2 area in the Clarion Clipperton Fracture Zone (CCZ).

In 2016 and 2017, the Cook Islands Government entered into 2 Seabed Minerals agreements with a United States-based company, Ocean Minerals LLC (OML), related to the future exploration and exploitation of its seabed minerals resources, in different mineral zones in our EEZ, known as **Sediments** containing **Rare Earth Elements** and another zone, containing an abundance of Manganese Nodules, rich in Cobalt.

In 2017, the Cook Islands Parliament passed the ***2017 Marae Moana Act***, being a national marine managed ocean space over our whole EEZ, based on conservation and zoned areas of resource utilisation, founded on a holistic, "whole of ocean" and precautionary approach. That unique Oceans law and framework was the culmination of years of development and support, and was based on wide, multi-stakeholder participation and community support.

In 2018/19, the Cook Islands are expecting to commence its Exploration Licencing process. This coincides with growing interest in Deep Sea Minerals sector driven by rising global prices for Cobalt and other important minerals.

The Cook Islands is now considered one of the best examples of the steady and effective development of national, legal and technical capacity aimed at the wise and sustainable development of a national seabed mineral resource in the waters of its vast Exclusive Economic Zone in the heart of the South Pacific.

END

Multi-criteria Decision Making Application for Sustainable Deep Sea Mining Transport Plan Selection

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ABSTRACT

Since the concept of deep sea mining (DSM) was proposed by J. L. Mero with his book, *The Mineral Resources of the Sea,* in the 1960s, many research and significant developments have been implemented. However, its commercial mining process still has not yet commenced. One of the most important issues is that a sustainable DSM transport plan is difficult to determine, taking into consideration the DSM technological, economic, and environmental aspects simultaneously. The objective of this paper is to propose a method to determine the sustainable DSM transport plan utilizing a fuzzy analytic network process method, which is a typical multi-criteria decision making method (MCDM). The DSM transport plans evaluating major criteria consist of technological, economic, environmental, and social aspects with both qualitative and quantitative attributes. Different major criteria include several sub-criteria, respectively:

- Technological aspect: energy consumption, proven technology, technology reliability, production rate, technology availability;
- Economic aspect: gross income, capital cost, operation and maintenance cost, investment recovery period;

- Environmental aspect: species disturbance variance, severity of ill effect, turbidity of ocean water, total organic carbon content, sedimentation thickness;
- Social aspect: social acceptability, policy support;

The weights for all evaluating criteria and sub-criteria are determined through a questionnaire survey interviewing experts at different research fields. All the transport plan candidates are ranked based on a comprehensive index. The conducted research in this paper is meaningful to promote the DSM commercialization process.

Keywords:

Deep sea mining, commercial mining process, sustainable, fuzzy, analytic network process, multi-criteria decision making method

Concentration of Pt, Au and Ag in Ferromanganese Deposits from the N-W Pacific: Preliminary Results

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ABSTRACT

At present, marine ferromanganese crusts of seamounts are of great interest as a source of high-tech metals. The metals most enriched in these deposits are essential for a wide variety of green-tech, emerging-tech, and energy applications (Hein et al., 2013). There is a grate number data on the content of major and minor metals (thousands analyses). However, information on the content of such elements as platinum, gold and silver in the world literature is limited. The concentrations (N – number of analyses) of platinum, gold and silver in the Pacific are 418 ppb (N = 105), 35 ppb (N = 72), 1.02 ppm (N = 26), respectively, and in the North Pacific Prime Zone - 477 ppb (N = 66), 55 ppb (N = 13), 0.1 ppm (N = 4); in the Atlantic Ocean is 567 ppb (N = 2), 6 ppb (N = 2), 0.20 ppm (N = 18), in the Indian Ocean, 211 ppb (N = 6), 21 ppb (N = 2), 0.37 ppm (N = 9) respectively; (Hein et al., 2013). The northern part of the Pacific is poorly studied in this question.

The samples of ferromanganese deposits (FMD) was recovered from the Govorov Guyot (Magellan seamounts), MZh-33 Guyot (Marshall Islands), as well as the Detroit Guyot (Imperor Ridge) and Yomei Guyot (Fe-Mn placer Holes 431 and 431A DSDP, Imperor Ridge).

For Au and Pt analyses, samples were decomposed using the acid solvents: $HF+HNO_3$ (2:1), then HCL+ HNO_3 (3:1), and concentrated HCl, with following precipitation together with Te. Gold and Pt content measurements were carried out in a graphite cuvette using and the electrothermal atomization mode of Shimadzu AA-6800 atomic absorption

spectrophotometer. For Ag analysis, samples were decomposed by the acid solvents: HCL+ HNO_3 (3:1), and concentrated HCl, by the HCAM-130-C procedure. Silver content was measured on fire in SolAAr M6 atomic absorption spectrophotometer.

The content of platinum, gold and silver is shown in the table. The average content (N = 14) of these noble metals at the four guyots of the N-W Pacific is 198 ppb, 152 ppb, 4.75 ppm, respectively. These average values indicate that the amount of platinum is close to its average concentration in the Indian Ocean, and gold and silver are much higher than all studied regions. An abnormally high gold content was established for the young Pliocene-Quaternary layer of the MZh-33 Guyot. Elevated gold concentrations (up to 110 ppb) were noted by us in the study of the ferromanganese crust of the Detroit Guyot (Mikhailik et al., 2013). The formation of high concentrations of gold is due to low-temperature hydrothermal activity during the Middle Miocene rejuvenated stage, with its subsequent redeposition in the microscales of the crust surface. It should be noted that this rejuvenated stage has also founded on the of the Magellan Guyots, where middle Miocene basanitic slag cones have been identified. Thus, the mechanism for accumulating such high concentrations of gold on the MZh-33 Guyot can be the same. It should be noted that we observe a correlation of gold and copper in the crusts of the MZh-33, Detroit, and Yomei Guyots. However, for Govorov Guyot Au vs Ag was not detected, but the concentration of copper in the crusts of this guyot is greatest. The concentrations of silver significantly exceed their average values in the World Ocean ferromanganese crusts, and the maximum values are determined in the FMD of the Imperor Ridge. At the moment we can not explain such a high concentration of silver, as well as the presence of its grains (up to 10 μm) in the FMD (Figure) of the Imperor Ridge.

The study was supported by project 18-17-00015 of Russian Science Foundation.

Table. Noble metals and copper concentration in ferromanganese deposits from the N-W Pacific

Sample	Age	Pt, ppb	Au, ppb	Ag, ppm	Cu, ppm
MZh-33 Guyot					
33D17-1-1	Paleocene-Eocene	110	<1	1.9	1212
33D17-1-2		360	<1	0.8	1059
33D17-1-3	Miocene	250	180	<0.5	1340
33D17-1-4	Pliocene -Quaternary	180	1390	5.5	1377
Govorov Guyot					
08D51-1-01	Paleocene-Eocene	220	<1	2.6	1422
08D51-1-03	Miocene	660	<1	0.9	2349
08D51-1-04	Pliocene -Quaternary	81	30	0.7	1026
08D51-1-05		50	<1	7.6	481
Detroit Guyots					
D13-1-7	Pliocene	100	67	3.8	384
D13-1-9	Miocene	230	68	17.6	730
Yomei Guyot					
431 001R 01W, 40-50 sm	Early Pleistocene	180	51	3.6	566
431 001R 02W, 0-10 sm	Middle Eocene	210	200	15.0	665
431A 001R 02W, 30-32 sm		54	78	1.2	282
431A 001R 02W, 53-55 sm		80	61	5.3	587

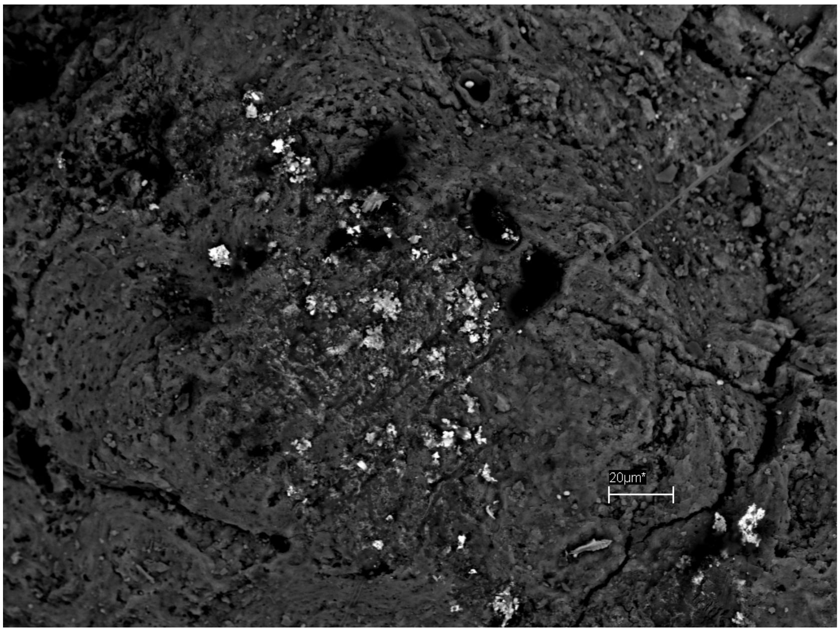

Figure. SEM image of Ag grains (light) into Fe-Mn crust from Yomei Guyot (sample 431 001R 02W, 0-10 sm).

Keywords: Nobel metals, ferromanganese deposits, Guyot, N-W Pacific.

REFERENCE

Hein, J.R., Mizell, K., Koschinsky, A., Conrad, T.A., 2013. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. Ore Geol. Rev. 51, 1–14.

Mikhailik, E.V., Khanchuk, A.I., Mikhailik, P.E., Barinov, N.N., Zarubina, N.V., 2013. The first find of visible gold in ferromanganese crusts of the Pacific Ocean. Dokl. Earth Sci. 449 (2), 422–426.

Main Author and or Speaker Name

Pavel Mikhailik

The field of scientific interests is concluded in the study of marine mineral resources of the Pacific region. The goal of research is to systematize the obtained data on mineral resources of the Far Eastern seas and the adjacent sector of the Pacific Ocean, detecting their genesis, as well as the creation and improvement of geological and geophysical complex for prove valuation of resources and their prospecting.

Coordinator of Russian Science Foundation project № 18-17-00015 “Sources and structure-chemical state of strategic elements in ferromanganese deposits of North West

Pacific and its marginal seas, as the basis of assessment criteria improvement and technologies for complex development of this deposit type."

Lead and other trace metal concentrations in the carbonate fluorapatite fraction of phosphatized FeMn crusts

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ABSTRACT

Ferromanganese (FeMn) crusts form by precipitation of iron and manganese oxides from seawater onto a rock substrate and are therefore considered hydrogenetic in origin. Diagenesis does occur however, through the process of phosphatization. During phosphatization, abundant dissolved phosphate in seawater replaces carbonate in the detrital fraction as well as directly precipitates within the FeMn matrix as carbonate fluorapatite (CFA). This process is likely accompanied by the partial dissolution or replacement of the oxide phases [1]. As a result of these diagenetic processes, trace elements adsorbed on the oxides are released and can either be depleted or enriched in the phosphatized FeMn crust layers. Pb, for example, has been shown in sequential leaching experiments to associate with the iron oxyhydroxide (FeOOH) phase in purely hydrogenetic layers, while >95% of Pb in phosphatized crust layers is found in the CFA fraction [2, 3]. However, previous sequential leaching studies analyzed bulk layers of phosphatized crusts and only a few crusts, from the Pacific Ocean. Here we present concentration data for Pb and other trace elements in the CFA fraction leached from thin stratigraphic intervals of the phosphatized portion of FeMn crusts from the Pacific and Atlantic oceans to confirm consistency of trace metal association with CFA both throughout the phosphatized section and in two ocean basins. The Pb and trace element concentration data from this study will also be compared with data from non-phosphatized crusts from the global ocean. We can then determine the effect of phosphatization on the concentration of Pb and other elements of greater economic

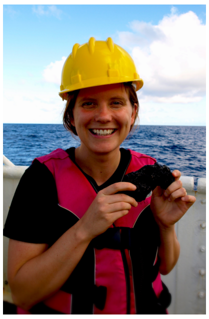
interest in FeMn crusts, specifically whether there is overall enrichment, depletion, or possibly even phase transfer of each metal in the phosphatized layers.

References

[1] Koschinsky et al. (1997) Geochim. Cosmochim. Acta 61, 4079-4094. [2] Koschinsky & Halbach (1995) Geochim. Cosmgchim. Acta 59, 5113-5132. [3] Koschinsky & Hein (2003) Mar. Geol. 198, 331-351.

Keywords: ferromanganese crusts, phosphatization, carbonate fluorapatite, lead enrichment, trace metal enrichment

Kira Mizell



I have worked as a research assistant at the U.S. Geological Survey with Dr. James Hein since 2011, the U.S. expert in marine minerals, and a cornerstone scientist to the international community. With Dr. Hein as a mentor, I honed skills at analyzing marine minerals deposits, learned their role in the mass balance of the earth and oceans, and become engrossed with their ability to accumulate economically viable quantities of metals that are critical to the advancement of high-tech, green energy, and military applications, as well as the potential social, political, and environmental impacts of marine mining. While working at USGS, I have co-authored 8 journal articles, 2 encyclopedia articles, and many oral presentations. In Fall 2015 I began a PhD at the University of California, Santa Cruz where I am being co-advised by Dr. James Hein and Dr. Phoebe Lam and working on a thesis project investigating controls on metal enrichment in ferromanganese crusts. I have also been a member of IMMS, the Secretary for the Executive Board of the IMMS, and editor for the IMMS Soundings newsletter since 2014.

The definition of morphotectonic domains in the Clarion-Clipperton Zone (CCZ): A step closer to understanding the controls behind nodule mineralisation?

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SUMMARY

The Clarion Clipperton Zone (CCZ) hosts the most valuable deposit of polymetallic nodules yet discovered. Understanding the geology of this deposit is key to its effective exploration and mining. Nautilus Minerals (via its subsidiary Tonga Offshore Mining Limited; TOML) has been progressing its understanding of the relationship between seafloor morphology/structure and nodule abundance/morphology, both locally (within its contract areas), and globally (across the CCZ and the span of its contract areas of almost 70% of the CCZ). We present the first results of a project with the aim of developing a method to quickly and accurately map seafloor morphology/structure (Tectonic Subcomponent scale) without the necessity for high resolution seafloor multibeam data. Furthermore, the results presented here will allow a first attempt in understanding the relationship between seafloor geomorphologically-defined zones and plate-scale tectonics of the CCZ and adjacent plate segments.

INTRODUCTION

A relationship between the type of geochemical active layer and nodule abundance/morphology has long been understood (ISA, 2010). Consideration of the range of differing nodule types found within, but especially between, the TOML contract areas allowed Parianos and Pomee (2017) to refine this relationship further via interpreted thickness and dynamism of the geochemically active layer. The scale of the deposit, both in terms of space and time is staggering (a 10-20 cm thick deposit, spanning almost 4500 km, varying within a circa 10 Ma period), but a segment wide geological map may one day prove to reflect controls on nodule formation and distribution.

To manage scale, a standard landform schema (modified Coastal and Marine Ecological Classification Standard (CMECS); FGDC, 2012; Watling, et al, 2013) is used.

Tectonic Setting Subcomponent (1,000s km^2)	**Physiographic Setting Subcomponent (100s km^2)**	**Geoform Level 1 (10s–1 km^2)**	**Geoform Level 2 (100s m^2)**	**Geoform Level 3 (10s m^2)**	**Geoform Level 4 (1s m^2)**
Mapped by TOML for the entire CCZ using GEBCO	*Mapped by TOML for TOML areas B to F using 12Kz MBES*	*Pertains to volcanic nodule bearing and nodule free sediment units*		*For example sections of towed photo profiles*	*Within individual photos*
Abyssal Plain (AP)	Abyssal Hills (AH)	Hill/Valley	Hill top	Sediment Bed – Nodule-free	Smooth Sediment
AP Plain / Transition	AH high smooth	Gently undulating hills	Side slope	–	Rippled Sediment
AP Rise	AH high rough	Undulating hills	Karstic sinkhole	–	Irregular Sediment (hummocks, waves, hills)
AP Low	AH low smooth	Graben-Horst range	–	Sediment Bed – Nodule-bearing	Smooth type
AP Step	AH low rough	–	–	–	Smooth-rough type
AP Trough	AH trough	Volcanic Flows	–	–	Rough type
	AH-plateau	Sediment Drifts	–	–	–
	Seamount Ranges	Seamount	–	–	–

Note each column above is effectively independent of each other.

GEBCO bathymetry is the only dataset currently available that spans the entire CCZ (Tectonic Setting scale). This was calibrated and verified against more detailed bathymetric data collected using typically 12 kz multibeam, in part collected by TOML and in part published by other workers in the area.

BACKGROUND

The Clarion-Clipperton zone is a segment of the Pacific Oceanic Plate extending between the East Pacific Rise and the Line Islands. It contains polymetallic nodules with unusually high base metals grades and in often consistently high abundances compared to other parts of the seafloor. The northern and southern boundaries of the zone are marked by the two major seafloor fractures (transforms) referred to as the Clarion Fracture Zone and the Clipperton Fracture Zone respectively. The two fractures are easily identified in datasets including satellite bathymetry (BODC, 2014).

The interpreted age of the seafloor over the extent of the CCZ increases from east to west (e.g. Muller et al 2008), consistent with increasing distance from the East Pacific Rise (active plate spreading center). In addition, seafloor plate segments, separated by major oceanic transforms, generally increase in depth from south to north (Figure 1).

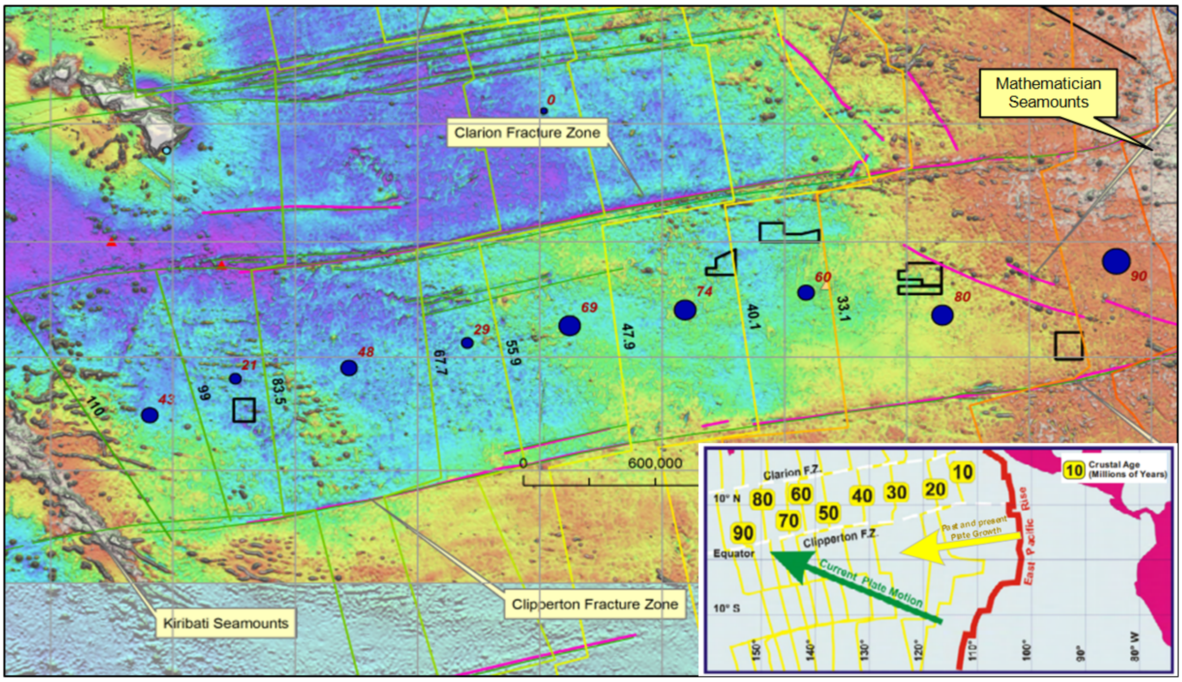

Figure 1. Polar reversals superimposed in green->yellow->orange with corresponding age (black) and associated average spreading rates per segment as indicated by the size of the circles in the center of each segment. The actual average value for spreading is shown as the red number accompanying each point. Tenement areas are shown in Black. Inset shows the location of the eat Pacific Rise spreading center to the east of the CCZ and also highlights increasing plate age with increasing distance from the spreading center (source: ISA (2003)).

METHODS AND RESULTS

GEBCO seafloor bathymetry data underwent internal processing to generate a detailed contour map (Figure 2) as well as a colour contoured image where colour gradients can be used to quickly visually discern the direction and steepness of gradient change. Combined visual and contour analysis of the raster image of the seafloor bathymetry was used to demarcate the boundary between units. The depth contours used to define the boundary between each zone was based on visual interpretation and is strictly qualitative at this point of the project.

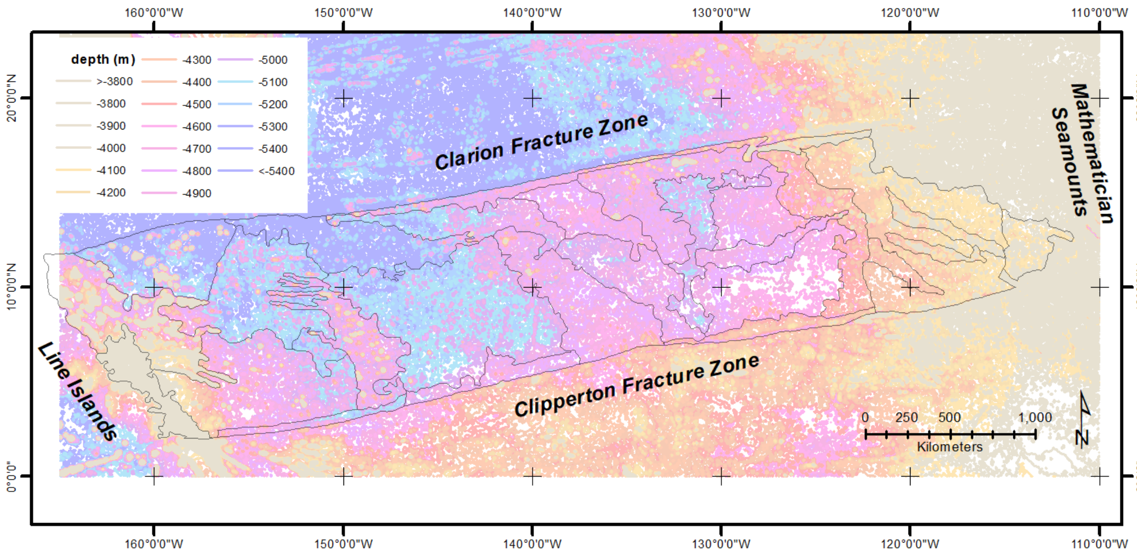

Figure 2. Interpreted contour map of the CCZ showing major boundaries.

Geomorphologic Units

Six types of tectonic setting units were defined (Figure 3):

1. Plains - abyssal hills and valleys comprise most of the seafloor
2. Transition - a type of plain that in one location the eastern and central parts of the CCZ
3. Lows - diffuse to distinct areas of abyssal hills at slightly greater depths
4. Rises - diffuse to distinct areas of abyssal hills at slight shallower depths
5. Steps - slightly shallower blocks aligned along the main fracture zones
6. Trough – narrow, slightly deeper area aligned along part of one of the main fracture zones

The absolute depth of the boundary below sea level (contour interval) between each zone was dependent on the location of the feature in the context of the CCZ. Accordingly, the precise depth below sea level of a boundary between two of the same zones will differ from east to west in order to accommodate the progressive increase in depth of the seafloor from east to west. The boundary between, for example a "low" and a "plain" in the Eastern CCZ may be some 500m shallower than the same boundary in the western, older and deeper part of the CCZ. At this stage of the project, the process cannot be automated but instead relies on visual interpretation of seafloor structure while using specific contour intervals as a guide. The resulting seafloor map is, therefore, a combination of both quantitative and qualitative interpretation.

For ease of reference, newly defined tectonic setting subcomponent level units are mostly named after the International Radiotelephony Spelling Alphabet, for example, Alpha, Bravo, Charlie etc. Already defined features names are maintained (ISA, 2010).

Most of the seabed is composed of ten discrete Abyssal Hill Plains which deepen from the eastern end of the CCZ to-wards the central-western part of the CCZ but then shallow again towards the Line Islands Rise. There is an eleventh plain-like unit termed a Transition for its unique characteristics in that it extends across the CCZ and marks a key change from the eastern to central CCZ. The Plains are dominated by abyssal hills but also include other smaller features such as volcanic cones, deeper trough grabens, collapse structures and sedimentary features.

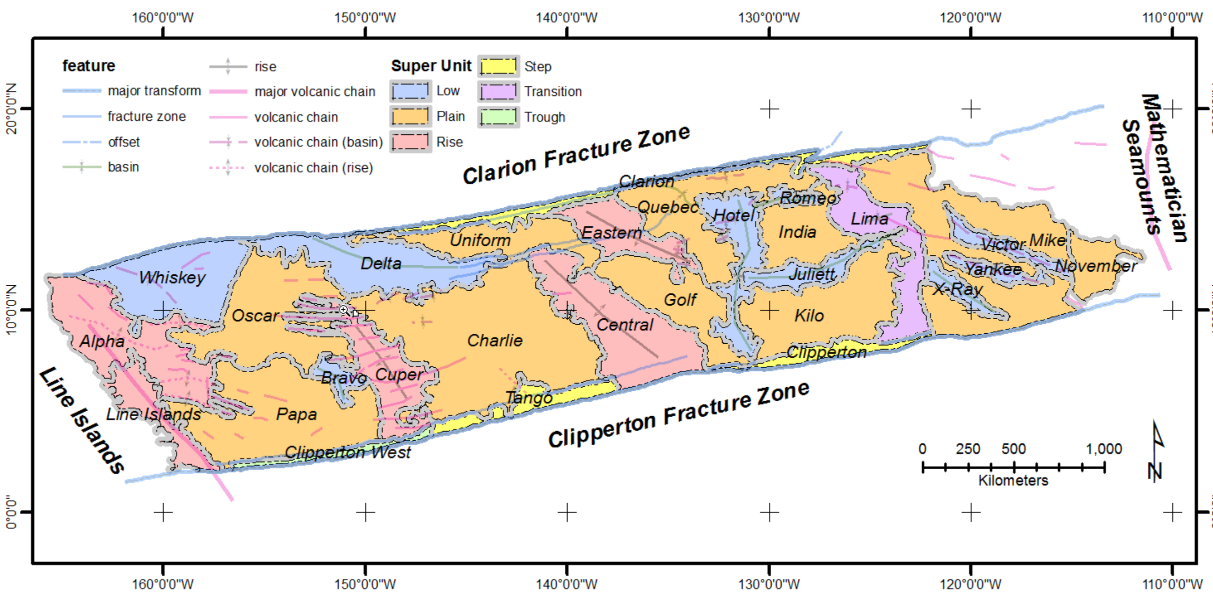

Figure 3. Interpreted geomorphological units.

The Plains are cross-cut by Rises and Lows which reflect shallower and deeper seabed regions respectively. Both may have seamount chains associated with them, but seamount chains are more a characteristic of the Lows. “Local” conditions are complex; for example the Cuper rise is distinctly different, being composed of numerous high angle seamount chains.

Near the main fracture zones are found Steps and a Trough. These narrow blocks typically have a smaller bounding fault inside the CCZ and likely reflect local uplift (or sinking) associated with the fracture zones, with changes associated with the intersection of Rises or major lows and/or with changes in strike of the fracture zone.

Correlation with high-resolution multibeam bathymetry

The boundaries between the six major morphotectonic settings interpreted using GEBCO data were checked against high-resolution multibeam bathymetry in order to check for accuracy in the interpretations. An example of this correlation is provided below where east-west trending ridges formed at the northwestern end of the Cuper Rise (Figure 4) were interpreted from GEBCO data. When the boundaries are overlain on higher-resolution multibeam data, the correlation between the ridges and the interpreted boundaries shows good visual corroboration thereby supporting the proposed suitability of the GEBCO data for interpreting seafloor features and accurately distinguishing between morphotectonic zones.

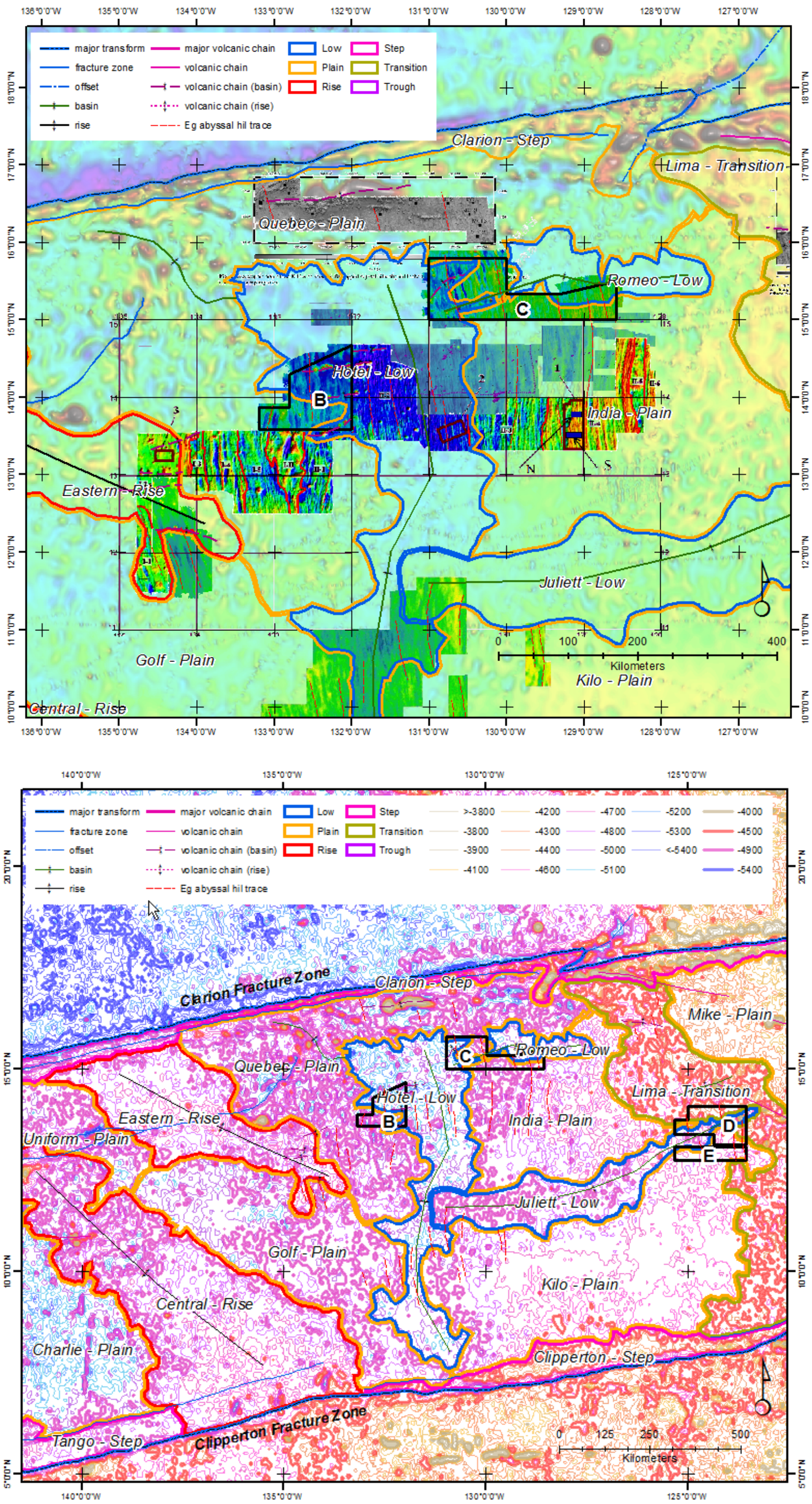

Figure 4. GEBCO vs MBES Bathymetry example

Structural elements

Following interpretation of the six major morphological zones, a structural map was generated in which nine major structural element types were defined. These elements (Figure 5) are:

1. Major transform fractures;
2. Fracture;
3. Offset Fracture;
4. Basin Axis;
5. Rise Axis;
6. Major Volcanic Chain;
7. Volcanic Chain;
8. Volcanic Chain in a basin; and
9. Volcanic Chain on a ridge

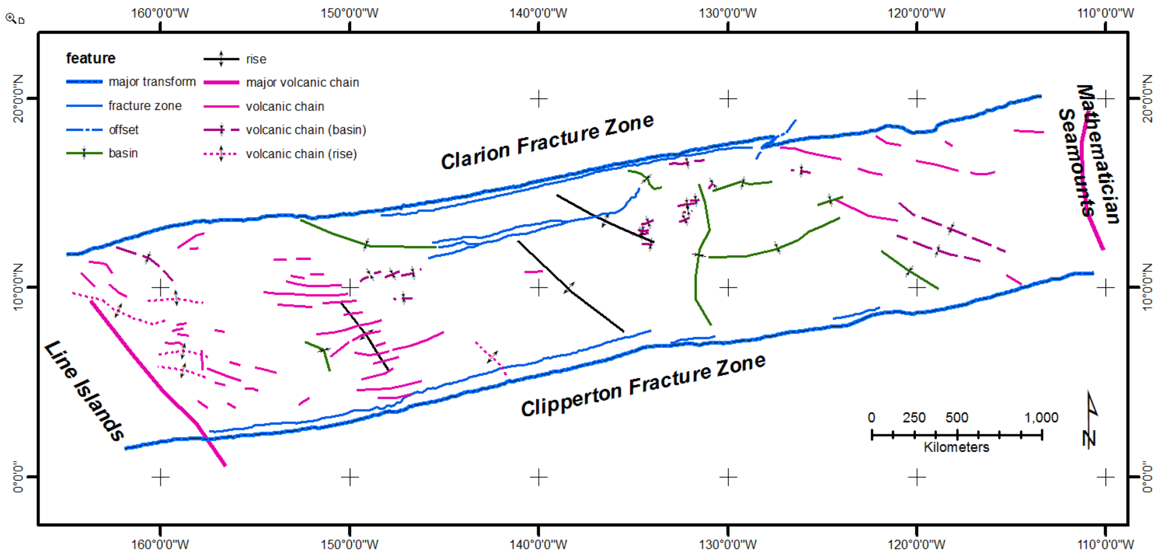

Figure 5. Interpreted structural elements

The Rises all aligned at approximately 30-40° from perpendicular with the main Clarion and Clipperton fracture zones. The Lows are in a range of orientations, but often parallel to the rises. It is proposed that extension and associated higher thermal gradient associated with the formation of the lows as trans tensional basins resulted in the processes leading to formation of volcanic seamount chains which are typically associated with the Lows.

It is interpreted and proposed here that the overall setting (Figure 1), and the nature of Rise and Low contact with the fracture zones formed due to the accommodation of transform-oblique principal, secondary and tertiary stress directions. Changes in the far-field stress directions linked primarily to the subduction, transfer and extensional plate margins to the north and east likely propagate through adjacent plate segments. The boundary between the plate segments accommodates part of this stress transfer in the form of deformation at and along the clarion and Clipperton fractures, however, due to partial coupling between adjacent segments, some of this deformation is accommodated by intraplate folding and extension. The recognition of the deformation regime and the tectonics of the plate segment may help resolve patterns of heat, metal and deformation.

FUTURE WORK

Ongoing improvements in the bathymetric data set (both for GEBCO and local MBES) should lead to improvements in the interpretation provided here. Certainly, more of the structural history of the segment may be able to be deduced, as more detailed data becomes available, not least in understanding the longitudinal trend of abyssal hills ridges.

Such interpretive work can also be extended to other plate segments, especially in conjunction with magnetic reversal dating of the seafloor.

Global maps of nodule grade and abundance, including priority areas for proposed mining can also perhaps benefit from analysis in the context of this segment wide interpretation. Aside from major controls relating to lysocline and primary productivity (e.g. Lipton et al 2016), it is likely that in some cases locally advantageous water depth or seabed conditions will relate to the prospectivity for polymetallic nodules.

REFERENCES

BODC (British Oceanographic Data Centre). 2014. GEBCO Gridded Bathymetric Data, URL: http://www.gebco.net/data_and_products/gridded_bathymetry_data/

FGDC (US Federal Geographic Data Committee), 2012, Coastal and Marine Ecological Classification Standard, Washington. http://www.fgdc.gov/standards/projects/cmecs-folder/CMECS_Version_06-2012_FINAL.pdf Downloaded May 2016.

ISA (International Seabed Authority), 2003. Establishment of a geological model of the polymetallic nodule resources in the Clarion-Clipperton Fracture Zone of the Equatorial North Pacific Ocean : Proceedings of the 13-20 May 2003 International Seabed Authority workshop held in Nadi, Fiji ISBN: 976-95217-3-6

ISA (International Seabed Authority), 2010. A Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone and Prospector's Guide for Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone. International Seabed Authority Technical Study: No. 6 ISBN: 978-976-95268-2-2

Lipton, I., Nimmo, M., & Parianos, J.M. 2016 TOML Clarion Clipperton Zone Project, Pacific Ocean. NI 43-101 Technical Report prepared for Nautilus Minerals . http://www.nautilusminerals.com/IRM/ShowCategory.aspx?CategoryId=306&FilterStyle=B&archive=true&masterpage=311&year=2016&RID=402 Downloaded 14th August 208

Müller, R.D., Sdrolias, M., Gaina, C. and Roest, W.R., 2008, Age spreading rates and spreading asymmetry of the world's ocean crust, Geochemistry, Geophysics, Geosystems, 9, Q04006, doi:10.1029/2007GC001743 Data from: http://www.earthbyte.org/Resources/agegrid2008.html

Parianos, J. M and Pomee C. 2017. Nodule types and genetic controls from the TOML Areas in the CCZ. Poster Abstract 46th Underwater Mining Conference Berlin 24-29 September 2017

Watling, L., Guinotte, J., Clark, M. R. & Smith, C. R. 2013. A proposed biogeography of the deep ocean floor. Progress in Oceanography, 111, 91-112.

Keywords: polymetallic nodules, seafloor, tectonics, minerals, structure, bathymetry, Clarion Clipperton Zone, CCZ, Nautilus Minerals.

John Parianos

John Parianos is Manager Exploration and Polymetallic Nodules at Nautilus Minerals.

Nautilus Minerals is adapting technology from the offshore oil & gas industry and the minerals industry, to prospect and develop offshore mineral deposits. Currently the company is focused on developing the Solwara 1 project in the territorial waters of Papua New Guinea, at a water depth of approximately 1600 m. To support its aggregation model of development, the company is also focused on exploring a large area of prospecting licenses in the South West Pacific. Exploration and engineering has also progressed on granted exploration tenements, within the Area administered by the International Seabed Authority, containing abundant copper, nickel, cobalt and manganese in polymetallic nodules. Nautilus' successes to date have come through applying innovative technology, often through collaboration with scientific and technological partners.

Electric motor drive systems for mobile mining equipment for deep-sea mining to maximize the productivity

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ABSTRACT

With the exponential growth of demand for minerals and need for diversification of supply channels, deep-sea mining is rapidly becoming inevitable. Productivity of underwater mining technology is salient to justify the deep-sea explorations. Methods for enhanced productivity of mobile mining equipment in a system level are investigated in this paper. Lessons learnt from the land-based mining has been the basis of this investigation.

In general, mining productivity can be enhanced in two ways; firstly, by maximizing the amount of recovered material per unit time and secondly, by minimizing the cost of operation per unit material. Equipment that enable faster excavation, loading and transport in the seabed contributes significantly in increasing the amount of slurry per unit time. Improved mean time between failures (MTBF) of mining equipment will reduce the operational down time, thereby, contribute to maximize the amount of mined material per unit time.

Several factors influence the operational cost minimization per ton of slurry. Higher efficient motor drive systems including the motor and PWM-fed inverter not only will save power but also will emit lesser heat thus the heat management can be less complex. This leads to more compact drive systems that allows higher power density, thus increased payload weight per empty vehicle weight. An energy storage method in the form of an utracapacitor in the electric drive system will also save the energy supply from the upstream.

Furthermore, the upstream components can be dimensioned only for the average power demand, therefore the cost of oversizing for peak demands can be curtailed.

Fault tolerant and encoder-less control methods coupled with modular inverter topologies will profoundly increase the mean time to repair (MTTR) of mining equipment on the seabed. Self and remote diagnostic methods and self-troubleshooting drive systems will largely help prevent fatal accidents or operational interruptions.

Keywords: deep-sea mining, mobile mining equipment, motor drives, PWM-fed inverter, mining productivity, energy storage, utracapacitor, Active Front End (AFE)

Main Author and or Speaker Name

Aravinda Perera received the B.Sc. Honors degree in electrical engineering from University of Moratuwa, Sri Lanka and M.Sc. degree in electrical engineering from Norwegian University of Science and Technology (NTNU), Trondheim, Norway in 2009 and 2012 respectively. Since May 2018, Aravinda is reading for his Ph.D. degree in electrical engineering at NTNU. He has nearly 10 years of industrial experience in product development, qualification and engineering applications in marine, offshore and subsea oil and gas sectors. Before starting his PhD research, Aravinda worked as a Senior Electrical Engineer in Subsea Systems Division in Siemens Norway, where he worked from 2012 to 2018. He has authored three patents at Siemens, which relate to power electronic systems for deep-sea applications. Aravinda's research interests include power electronics, motor drives and digital control design.

Permeability and fault control on seafloor massive sulfide deposits in the Lucky Strike hydrothermal field (Mid-Atlantic Ridge) using Leapfrog Geo software

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INTRODUCTION

Work by Humphris et al., (2002); Ondréas et al., (2009); Barreyre et al., (2012); and Escartín et al., (2015) has identified active and inactive hydrothermal sites along the Lucky Strike segment. The sites that contain the largest accumulation of known sulfides are located between the north and the southern zones (Figure 1), a vent site area that is referred to as the Main Lucky Strike hydrothermal field (Escartín et al., 2015). Hydrothermal fluid outflow has been linked to a shallow fault network (Barreyre et al., 2012). However, specific constraints on fault geometries have not been determined. Other off-axis sites at Lucky Strike, such as Capelinhos (high temperature vent), and Grunnus (inactive?), as well as a low temperature vent field (on-axis), Ewan, have been described by (Escartín et al., 2015).

Given the spatial relationship between the Main Lucky Strike hydrothermal field (MLSHF), and the intersection of northern rift faults with the southern rift faults, a structural analysis of this area can provide insight into the fault controls on fluid flow that leads to hydrothermal venting and sulfide precipitation.

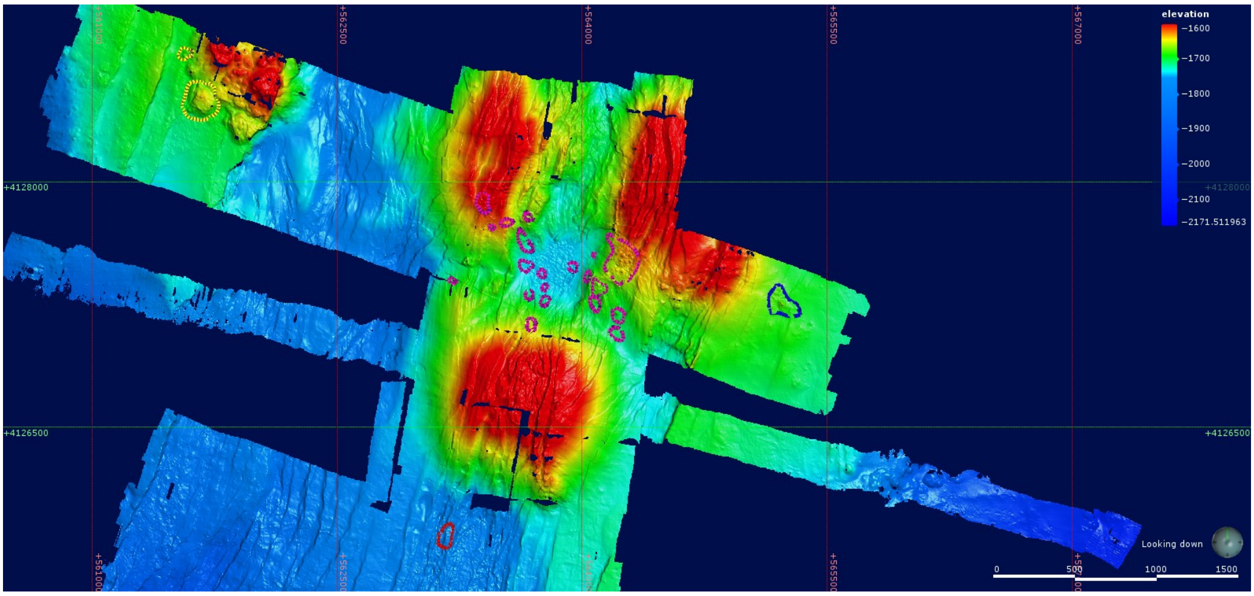

Figure 1. Hydrothermal sites in Lucky Strike, north is up. Main Lucky Strike hydrothermal field in pink polylines, Capelinhos in blue polylines to the east, Grunnus in yellow to the west, and Ewan to the south in red polylines.

METHODOLOGY

Structural data (dip direction and dip) was determined using Leapfrog Geo 4.0 software. Bathymetric data was obtained from Escartín et al., (2015) and references therein. The bathymetry was imported into Leapfrog Geo (in UTM format) and, using the structural modelling tool, individual measurements with dip direction and dip data were collected with a focus on the northern volcanic rift and the southern central volcano (Figure 2a). All measurements were taken from what the authors consider as normal faults, and to aid the determination of individual measurements a "face dip" map was constructed, where the bathymetry is colored by slope angle (Figure 2b). All measurements are simultaneously plotted on a stereonet generated by the Leapfrog Geo Software. Data were divided into northern and southern, and western and eastern zones to determine the relationship between hydrothermal venting and the structural geometries at Lucky Strike (Figure 2c).

Slip measurements for individual faults were determined along the dip of the fault with a measuring tool. Net slip, heave (horizontal displacement), and throw (vertical displacement) was calculated for each of the zones.

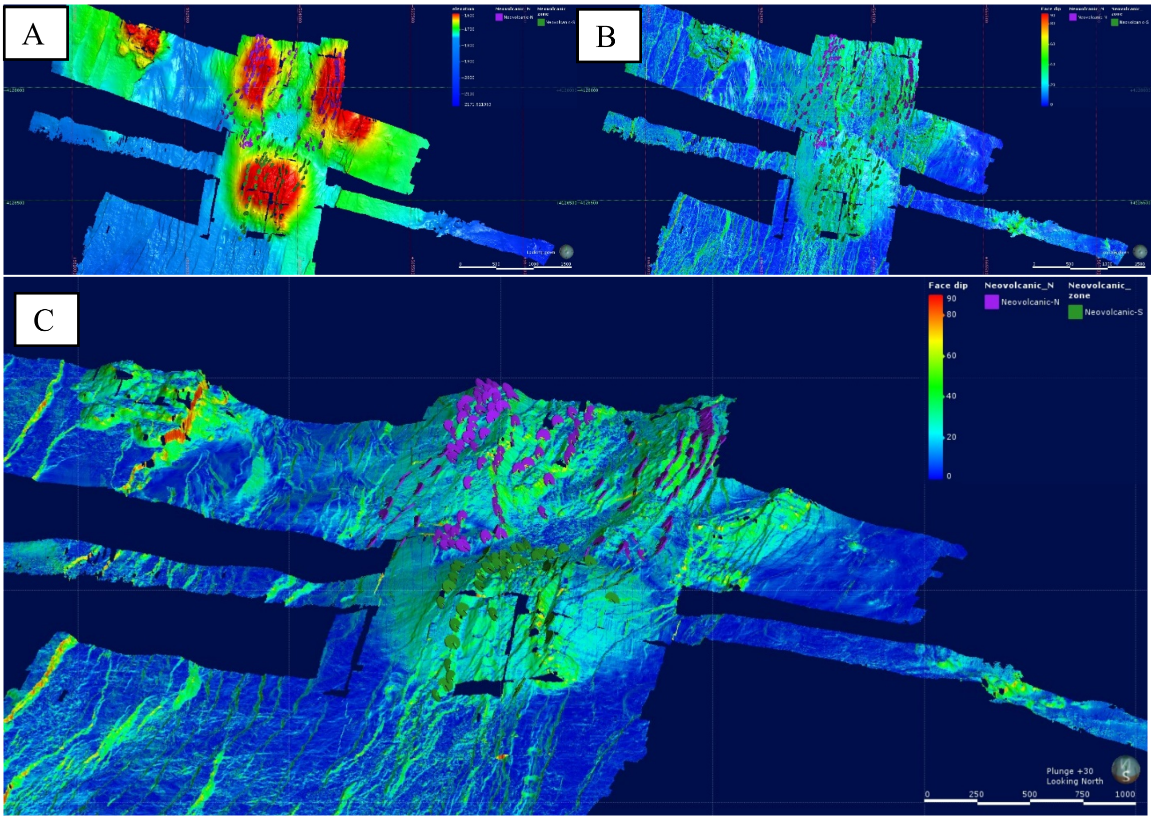

Figure 2. A) Bathymetric map with structural points measured, north is up. B) Face dip and structural points map, north is up. C) Same as B) but looking at a 30° angle. Individual measurements are in circular features, purple for the northern part of the rift and green in the southern part of the rift.

RESULTS

General structural trends

Mean orientations have been summarized in Table 1 and illustrated in Figure 3. Based on calculated stress orientations, significant differences exist between the northern and southern part of the rift. Using the orientations of σ_1 a clockwise rotation is determined.

Table 1. Mean structural orientations and stress regimes from the Lucky Strike segment in the Mid-Atlantic Ridge

	Northwest	Southwest	Northeast	Southeast
Mean principal orientation (Dip dir/dip)	107/51	107/43	278/48	289/51
Intersections N and S (plunge-trend)	0-197		46-255	
	North	South		
Calculated girdle (Dip dir/dip)	013/85	197/88		
Mean principal orientation (Dip dir/dip)	103/83	106/55		
Calculated beta axis (plunge-trend)	5-193	2-017		
Sigma 1 (plunge-trend)	82-064	55-110		
Sigma 2 (plunge-trend)	5-193	2-017		
Sigma 3 (plunge-trend)	6-283	35-286		

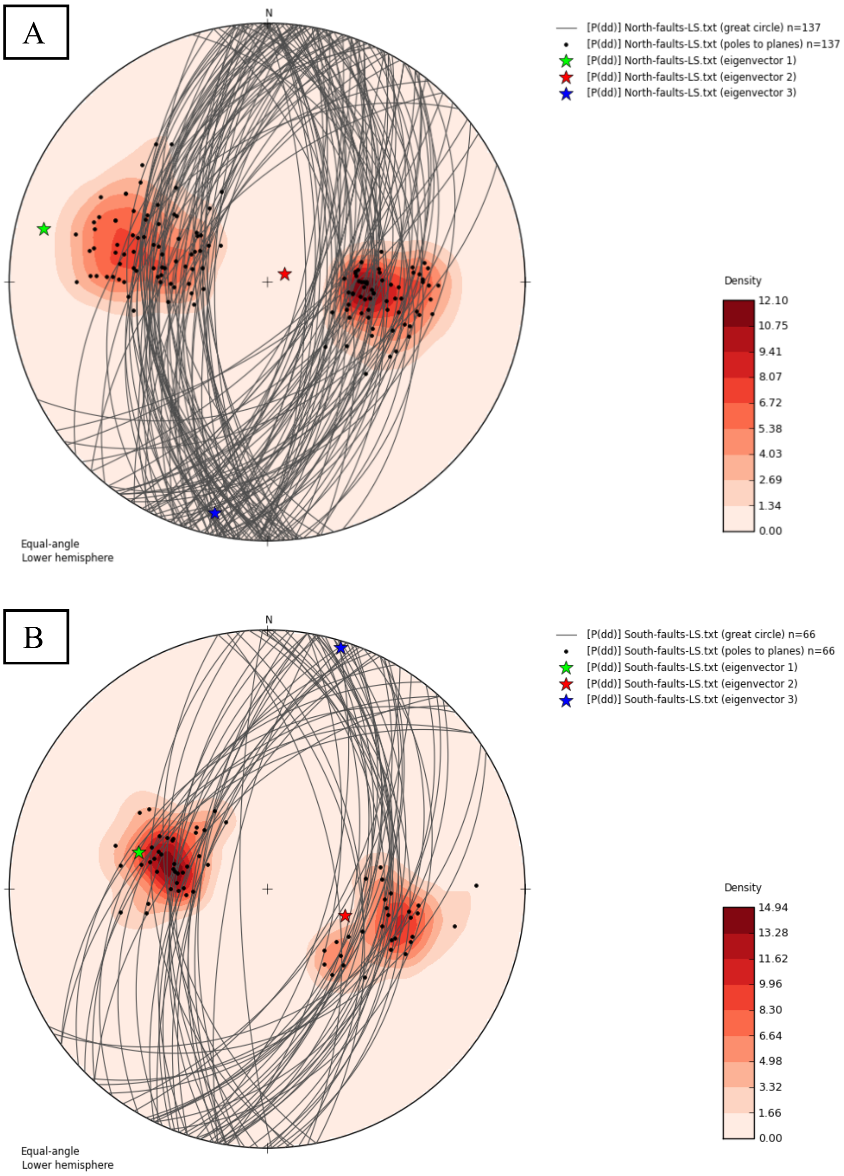

Figure 3. Equal angle stereonets from Lucky Strike. A) Poles to fault planes (n=137) in the northern rifted volcano. B) Poles to fault planes (n=66) in the southern neovolcanic zone. Principal stress orientations are represented by the stars: sigma 1 (red), sigma 2 (blue), and sigma 3 (green).

Fault slip

Fault slip at Lucky Strike was divided in four zones; northwest (NW), northeast (NE), southwest (SW), southeast (SE). Slip measurements are summarized in Table 2. Cumulative net slip, heave (horizontal displacement), and throw (vertical displacement) are a sum of all the faults measured at Lucky Strike. It is important to note that, in general, the northern areas have higher measured cumulative net slip and therefore also higher heave and throw.

Table 2. Measured net slip in faults.

	Cumulative net slip (m)	**Cumulative heave (m)**	**Cumulative throw (m)**
NW (n=24)	556.5	372.06	405.03
NE (n=22)	525	344.14	393.06
SW (n=12)	242	172.08	168.21
SE (n=11)	154	109.39	105.50

IMPLICATIONS OF FAULT GEOMETRY AND DISPLACEMENT AS A CONTROL ON LOCATIONS OF HYDROTHERMAL VENTING

Most of the sulfide deposits and hydrothermal vents are located between the northern and southern rifts. Fault geometries indicate significant differences between the north and south rift at this part of the Lucky Strike segment, mainly the change of principal stress σ_1 that changes from a direction of 81-064 in the north to 55-108 in the south, which implies a clockwise rotation of the stress field (Figure 4). The measured cumulative net slip, ranges in the north from 525-556 meters and in the south from 154-242 meters. Based on these parameters it is interpreted that fluid flow is focused in an accommodation zone that is perpendicular to the ridge axis. This is in agreement with an along-axis hydrothermal circulation interpretation made based on seismological data (Crawford et al., 2013) at Lucky Strike. In this interpretation, recharge of hydrothermal fluid comes from the north and south and discharges in the topographic depression (but shallower part of the axial magma chamber) located between the northern and southern volcanic structures. Similar processes have been described by Rowland and Sibson, (2004) in the Taupo Volcanic Zone in New Zealand to explain geothermal hydrothermal flow. Another characteristic of these faults that support this interpretation is the arcuate shape (in the northern rift) that have been reported in accommodation zones in the East African Rift by Rosendahl, (1987). Enhanced permeability perpendicular to the ridge axis has focused volcanism and hydrothermal circulation at the Lucky Strike volcano. Fault data (dip direction and dip) is therefore key to understand controls on hydrothermal flow and thus massive sulfide precipitation.

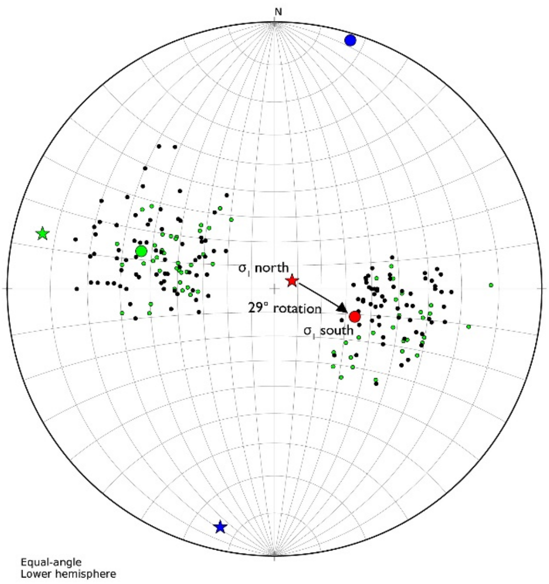

Figure 4. Stereonet of poles in the northern rift (black circles) and in the southern rift (green circles). Arrow shows a clockwise rotation of 29° from the northern rift to the southern rift. Stress orientations in stars (northern rift) and circles (southern rift), σ_1 (red), σ_2 (blue), σ_3 (green).

Keywords: Seafloor sulfides, faults, Leapfrog Geo, mid-ocean ridge, Mid-Atlantic Ridge.

REFERENCES

Barreyre, T., Escartín, J., Garcia, R., Cannat, M., Mittelstaedt, E., and Prados, R., 2012, Structure, temporal evolution, and heat flux estimates from the Lucky Strike deep-sea hydrothermal field derived from seafloor image mosaics: Geochemistry, Geophysics, Geosystems, v. 13, p. 1–29, doi: 10.1029/2011GC003990.

Crawford, W.C., Rai, A., Singh, S.C., Cannat, M., Escartin, J., Wang, H., Daniel, R., and Combier, V., 2013, Hydrothermal seismicity beneath the summit of Lucky Strike volcano, Mid-Atlantic Ridge: Earth and Planetary Science Letters, v. 373, p. 118–128, doi: 10.1016/j.epsl.2013.04.028.

Escartín, J., Barreyre, T., Cannat, M., Garcia, R., Gracias, N., Deschamps, A., Salocchi, A., Sarradin, P.M., and Ballu, V., 2015, Hydrothermal activity along the slow-spreading Lucky Strike ridge segment (Mid-Atlantic Ridge): Distribution, heatflux, and geological controls: Earth and Planetary Science Letters, v. 431, p. 173–185, doi: 10.1016/j.epsl.2015.09.025.

Humphris, S.E., Fornari, D.J., Scheirer, D.S., German, C.R., and Parson, L.M., 2002, Geotectonic setting of hydrothermal activity on the summit of Lucky Strike Seamount (37°17'N, Mid-Atlantic Ridge): Geochemistry, Geophysics, Geosystems, v. 3, p. 1–24, doi: 10.1029/2001GC000284.

Ondréas, H., Cannat, M., Fouquet, Y., Normand, A., Sarradin, P.M., and Sarrazin, J., 2009, Recent volcanic events and the distribution of hydrothermal venting at the Lucky Strike hydrothermal field, Mid-Atlantic Ridge: Geochemistry, Geophysics, Geosystems, v. 10, doi: 10.1029/2008GC002171.

Rosendahl, B.R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, v. 15, p. 445–503.

Rowland, J. V., and Sibson, R.H., 2004, Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand: Geofluids, v. 4, p. 259–283, doi: 10.1111/j.1468-8123.2004.00091.x.

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Assessment of impacts of deep-sea mining plumes to sediment biogeochemistry in polymetallic nodule fields: developing a modelling approach

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ABSTRACT

Polymetallic nodule mining in the deep sea is anticipated to produce plumes of sediment, which have been identified as being a top source of impact to the benthic environment (Ahnert and Borowski, 2000; Halfar and Fujita, 2007; Jones *et al.*, 2016; Oebius *et al.*, 2001). Methods for nodule mining are anticipated to produce plumes from two sources, one near the seabed from the mining vehicle, and a second higher in the water column from the process discharge (Oebius *et al.*, 2001). In addition to local impact, these plumes may transport sediment distant from the mining activity (Dale and Inall, 2015; Rolinski *et al.*, 2001), impacting undisturbed sediment. A concern is that these plumes may migrate across the boundaries of mining claims onto other claims, areas protected from mining (known as Areas of Particular Environmental Interest, APEIs, in the Area Beyond National Jurisdiction; International Seabed Authority, 2011; Lodge *et al.*, 2014), or into other jurisdictions (Halfar and Fujita, 2007). Thus, an understanding of the impacts of plume deposition to the benthic environment will be important to robust regional management (Jones in prep), coordination of multiple activities through ecosystem-based management (Danovaro *et al.*, 2017), and mining claim scale environmental impact assessment.

The material deposited from these plumes will largely constitute sediment that has been disturbed or gathered during nodule collection. Sediment deposition from mining plumes

will likely be orders of magnitude higher than the low natural sedimentation rates (e.g. 0.35-0.6 cm ky^{-1}; Mewes *et al.*, 2014) found on the low productivity abyssal plains where nodule fields exist. In addition to smothering and choking benthic fauna, material deposited from plumes will alter the sedimentary environment (Halfar and Fujita, 2007), since deposited material will have a different particle size and chemical composition compared to the existing surface sediment (Ahnert and Borowski, 2000; Oebius *et al.*, 2001). As such, these plumes have the potential to impact biogeochemical processes in the sediment.

Biogeochemical processes in the sediment are important to the benthic fauna, ecosystem function, and geochemical cycles at a wider scale (Levin and Gage, 1998). For example, redox conditions in deep-sea sediments are particularly important for microbial processes (Jorgensen *et al.*, 2012; Mogollón *et al.*, 2016), and bacteria are significant contributors to carbon cycling benthic communities on abyssal plains (Dunlop *et al.*, 2016; Durden *et al.*, 2017). Variations in the redox conditions in the water and sediment in nodule areas have been connected to nodule size and abundance, and microbial respiration (Mewes *et al.*, 2014). These findings suggest that perturbations to the redox environment, a likely outcome of alterations to sediment porosity and the oxygen penetration depth that may result from deposition of mining plume sediment, may have further effects on the benthic community. Models have been used to assess sediment biogeochemistry in nodule areas and the removal of surface sediment and nodules by mining (Haeckel *et al.*, 2001; König *et al.*, 2001), but do address the impacts of sedimentation from mining plumes, and were centred in an area of substantially higher surface productivity than much of the Clarion Clipperton Zone, where nodule mining is in the exploration phase.

Our aim is to model the differences in baseline sediment biogeochemistry at an APEI and a mining claim, and to model the changes to sedimentary conditions resulting from the deposition of material from DSM plumes at each site.

We adapt the Carbon and Nutrient Diagenesis (CANDI) sediment model. This model was developed by Boudreau (1996), and adaptations have previously been used to assess the removal of surface sediments for deep-sea mining (König *et al.*, 2001) and to assess impact of the accumulation of waste from aquaculture on the seabed (Paraska *et al.*, 2015), among other applications.

REFERENCES

Ahnert, A., Borowski, C., 2000. Environmental risk assessment of anthropogenic activity in the deep-sea. Journal of Aquatic Ecosystem Stress and Recovery 7 (4), 299-315.

Boudreau, B.P., 1996. A method-of-lines code for carbon and nutrient diagenesis in aquatic sediments. Computers & Geosciences 22 (5), 479-496.

Dale, A., Inall, M., 2015. Report on the effects of a range of characteristic hydrodynamic regimes on the three discharge methodologies in terms of near-field dilution. Managing Impacts of Deep Sea Resource Exploitation project.

Danovaro, R., Aguzzi, J., Fanelli, E., Billett, D., Gjerde, K., Jamieson, A., Ramirez-Llodra, E., Smith, C.R., Snelgrove, P.V.R., Thomsen, L., Dover, C.L.V., 2017. An ecosystem-based deep-ocean strategy. Science 355 (6324), 452-454.

Dunlop, K.M., van Oevelen, D., Ruhl, H.A., Huffard, C.L., Kuhnz, L.A., Smith Jr, K.L., 2016. Carbon cycling in the deep eastern North Pacific benthic food web: Investigating the effect of organic carbon input. Limnology and Oceanography 61 (6), 1956-1968.

Durden, J.M., Ruhl, H.A., Pebody, C., Blackbird, S.J., van Oevelen, D., 2017. Differences in the carbon flows in the benthic food webs of abyssal hills and the plain. Limnology and Oceanography 62, 1771-1782.

Haeckel, M., König, I., Riech, V., Weber, M.E., Suess, E., 2001. Pore water profiles and numerical modelling of biogeochemical processes in Peru Basin deep-sea sediments. Deep Sea Research Part II: Topical Studies in Oceanography 48 (17–18), 3713-3736.

Halfar, J., Fujita, R.M., 2007. Danger of Deep-Sea Mining. Science 316 (5827), 987-987.

International Seabed Authority, 2011. Environmental Management Plan for the Clarion-Clipperton Zone. ISBA/17/LTC/7. International Seabed Authority, Kingston, Jamaica.

Jones, D., Durden, J., Murphy, K., Ardron, J., Billett, D., Gjerde, K., Ortega, A., Colaço, A., Jaeckel, A., Christiansen, S., Khalid, L., Turner, P., Dover, C.L.V., Ng'etich, S., 2016. Protocols, tools and standards for environmental management of exploitation of deep-sea mineral resources. Managing Impacts of Deep Sea Resource Exploitation project.

Jones, D., Simon-Lledo, E., Lichtschlag, A., Huvenne, V., Robert, K., Connelly, D., Durden, J., Menendez, A., James, R., Young, C., Caulle, C., Tabaoda, S., Glover, A., Horton, T., Peel, K., Gates, A., Gooday, A., in prep. Landscape of the Pacific abyss: an area of particular environmental interest?

Jorgensen, S.L., Hannisdal, B., Lanzén, A., Baumberger, T., Flesland, K., Fonseca, R., Øvreås, L., Steen, I.H., Thorseth, I.H., Pedersen, R.B., Schleper, C., 2012. Correlating microbial community profiles with geochemical data in highly stratified sediments from the Arctic Mid-Ocean Ridge. Proceedings of the National Academy of Sciences 109 (42), E2846–E2855.

König, I., Haeckel, M., Lougear, A., Suess, E., Trautwein, A.X., 2001. A geochemical model of the Peru Basin deep-sea floor—and the response of the system to technical impacts. Deep Sea Research Part II: Topical Studies in Oceanography 48 (17–18), 3737-3756.

Levin, L.A., Gage, J.D., 1998. Relationships between oxygen, organic matter and the diversity of bathyal macrofauna. Deep-Sea Research Part II: Topical Studies in Oceanography 45 (1-3), 129-163.

Lodge, M., Johnson, D., Le Gurun, G., Wengler, M., Weaver, P., Gunn, V., 2014. Seabed mining: International Seabed Authority environmental management plan for the Clarion–Clipperton Zone. A partnership approach. Marine Policy 49 (0), 66-72.

Mewes, K., Mogollón, J.M., Picard, A., Rühlemann, C., Kuhn, T., Nöthen, K., Kasten, S., 2014. Impact of depositional and biogeochemical processes on small scale variations in nodule abundance in the Clarion-Clipperton Fracture Zone. Deep Sea Research Part I: Oceanographic Research Papers 91, 125-141.

Mogollón, J.M., Mewes, K., Kasten, S., 2016. Quantifying manganese and nitrogen cycle coupling in manganese-rich, organic carbon-starved marine sediments: Examples from the Clarion-Clipperton fracture zone. Geophysical Research Letters 43 (13), 7114-7123.

Oebius, H.U., Becker, H.J., Rolinski, S., Jankowski, J.A., 2001. Parametrization and evaluation of marine environmental impacts produced by deep-sea manganese nodule mining. Deep Sea Research Part II: Topical Studies in Oceanography 48 (17–18), 3453-3467.

Paraska, D.W., Bruce, L.C., Shiell, G., Hipsey, M.R., 2015. Predicting critical thresholds of aquaculture waste loading to coastal sediment. In: Weber, T., McPhee, M.J., Anderssen, R.S. (Eds.), 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Gold Coast, Australia, pp. 536-542.

Rolinski, S., Segschneider, J., Sündermann, J., 2001. Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. Deep Sea Research Part II: Topical Studies in Oceanography 48 (17), 3469-3485.

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Keywords: Redox; diagenetic processes; environmental impact

A poster presentation.

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Ocean Minerals' Cook Island Cobalt Project – Enabling the EV Revolution

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ABSTRACT

Experimental application of underwater hyperspectral imaging on seafloor massive sulphides from the Loki's Castle on the Arctic Mid-Ocean Ridge, Norway

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INTRODUCTION

Efficient exploration methodologies for base metal deposits have huge benefits for future deep sea mining endeavours, and underwater hyperspectral imaging (UHI) has been variably demonstrated to have applications in the identification and characterisation of mineralisation on the seafloor for both nodules and seafloor massive sulphides (SMS) (Dumke et al., 2018 and 2017 respectively). Due to growing resource requirements (Singer, 2017), SMS deposits are considered to be increasingly significant sources of copper and zinc, as well as silver and gold. This style of mineralisation is currently occurring at active hydrothermal vents (black and white smokers) but now-inactive sites also have the potential to be large mineral deposits. As such, the development of novel methodologies to detect both on-going and extinct mineralisations are of high importance.

Geological setting

During the MarMine cruise (Ludvigsen et al., 2016), non-mineralised host rock, low grade ore and high grade ore grab samples (Snook et al., 2018) was collected by ROV from the Loki's Castle deposit (Pedersen et al., 2010), located on the Mohn's/Knipovich junction on the ultra-slow spreading Arctic Mid-Ocean Ridge (AMOR), at a depth of approximately 2300 m. This material has been characterised as part of the MarMine project (e.g. Snook et al., 2017), and, by imaging compositionally constrained material, the measured hyperspectral responses can be used to generate a library for identification of deposits on the ocean floor.

UHI technology

Remote sensing with hyperspectral and multispectral technologies has seen wide use in prospecting for ores and hydrocarbons on land (Van der Meer et al., 2012). Iron oxides and sulphides have low blue reflectance and high red reflectance in the visible spectrum. The ratio between these two pairs has been used in exploration for terrestrial deposits of hydrothermal origin (Sabins, 1999). This discrimination typically also includes wavelengths exceeding the visible spectrum (1.5µm – 2.5µm). These wavelengths are typically not utilised underwater because infrared wavelengths and higher are rapidly attenuated in water. However, discrimination based on the full shape of the spectral response in the visible light (350nm – 800nm) may still be possible (Bolin and Moon, 2003). Resolving the endmembers from the spectral responses requires prior knowledge about the optical properties of the materials, i.e. their reflectance. These reflectances can be obtained in a controlled environment, where the spectra of the lamps, wavelength-dependent attenuation in water and scattering of light can be accounted for (Johnsen, 2013).

In this study, we report the methodologies used in tank experiments in order to generate a UHI spectral library of lithologies associated with SMS deposits (i.e. sediments/mudstone, basalt, low grade ore, high grade ore), we discuss the preliminary spectra results and their viability, and we recommend the experimental conditions for acquisition of valid UHI data pertaining to SMS identification.

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Keywords: UHI; SMS; hyperspectral; sulphides; exploration; AMOR; Norway.

REFERENCES

Bolin, B.J. and Moon, T.S., 2003. Sulfide detection in drill core from the Stillwater Complex
using visible/near-infrared imaging spectroscopy. Geophysics, 68, 1561–1568.

Dumke, I., Ludvigsen, M., Ellefmo, S.L., Søreide, F., Johnsen, G. and Murton, B.J., 2017. *Underwater hyperspectral imaging using a stationary platform in the Trans-Atlantic Geotraverse hydrothermal field*. IEEE Transactions on Geoscience and Remote Sensing, submitted.

Dumke, I., Nornes, S.M., Purser, A., Marcon, Y., Ludvigsen, M., Ellefmo, S.L., Johnsen, G. and Søreide, F., 2018. *First hyperspectral imaging survey of the deep seafloor: high-resolution mapping of manganese nodules*. Remote Sensing of Environment, 209, 19-30.

Johnsen, Geir, Volent, Zsolt, Dierssen, Heidi, Pettersen, Ragnhild, Van Ardelan, Murat, Søreide, Fredrik, Fearns, Peter, Ludvigsen, Martin & Moline, Mark, 2013. *Underwater hyperspectral imagery to create bio-geo-chemical maps of seafloor properties*, in Watson, J. & Zielinski, O. (eds), Subsea optics and imaging, Woodhead Publishing Ltd, Cambridge.

Ludvigsen M., Aasly K., Ellefemo S., Hilario A., Ramirez-Llodra E., Søreide F., Falcon-Suarez I., Juliani C., Kieswetter A., Lim A., Malmquist C., Nornes S.M., Paulsen E., Reimers H., and Sture Ø., 2016. *NTNU Cruise reports 2016 no 1 MarMine Arctic Mid ocean Ridge 15.08.16-05.09.16.*, Trondheim, Norway, ISSN 2535-2520.

Pedersen R.B., Rapp H.T., Thorseth I.H., Lilley M.D., Barriga F.J.A.S., Baumberger T., Flesland K., Fonseca R., Fruh-Green G.L., Jorgensen S.L., 2010. *Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge*. Nature Communications, 1:126.

Sabins, F.F., 1999. Remote sensing for mineral exploration. Ore Geology Reviews, 14(3), pp.157-183.

Singer, D.A., 2017. *Future copper resources*. Ore Geology Reviews, 86, 271-279.

Snook, B., Drivenes, K., Kowalczuk, P. B., Ellefmo, S. L., Kleiv, R. A. and Aasly, K., 2017. *Initial assessment of mineralogical properties of a seafloor massive sulphide deposit at the Arctic Mid-Ocean Ridge*. Underwater Mining Conference 2017, Berlin.

Snook, B., Drivenes, K., Aasly, K., and Rollinson, G., 2018. Preliminary characterisation of potential seafloor massive sulphide ore from the Loki's Castle deposit, on the Arctic Mid-Ocean Ridge. Nordic Geological Winter Meeting 2018, Copenhagen.

Van der Meer, F.D., Van der Werff, H.M., van Ruitenbeek, F.J., Hecker, C.A., Bakker, W.H., Noomen, M.F., van der Meijde, M., Carranza, E.J.M., de Smeth, J.B. and Woldai, T., 2012. *Multi-and hyperspectral geologic remote sensing: A review*. International Journal of Applied Earth Observation and Geoinformation, 14(1), 112-128.

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Abstract for UMC 2018 at Bergen, USA June 24, 2018 Akira Usui

On-site Observations and In-situ Experiments for the Ferromanganese Deposit at the Seamounts in the Northwestern Pacific: A Review for the ROV Geoscientific Exploration

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The small-scale observations, mapping, sampling, and in-situ experiments have been carried out since 2009 using JAMSTEC ROVs at some model seamounts in the Northwestern Pacific seamounts. Laboratory analysis on mineralogy, chemistry, chronology indicated a continuous slow precipitation since the Middle Miocene, at water-depths 1-6 km, and the modern hydrogenetic precipitation even in the oxygen minimum zones. Thus the variability in abundance and grade of the deposits on regional, small and microscopic scales are determined by geological, geochemical, and hydrological conditions, resulting in the stacked piles of tiny precipitates from the seawaters.