48TH CONFERENCE • UMC 2019 • CHINA

UNDERWATER MINING CONFERENCE

世界海洋矿产大会

PROGRAM AND ABSTRACTS

Sustainable Development of Seabed Mineral Resources: Environment, Regulations and Technology

海底矿产资源的可持续开采—环境、规则与科技

HOSTED BY

Institute of Deep-Sea Science and Engineering, Hainan

UMC 2019

September 22–27, 2019 • Sanya City, Hainan, China

www.underwatermining.org

INTRODUCTION

Welcome to the 48th Underwater Mining Conference, UMC 2019 – Sustainable Development of Seabed Mineral Resources: Environment, Regulations and Technology. We anticipate that we will hear new insights and many different perspectives from the world's leading experts who will share their thoughts on the current commercial, technological and environmental developments related to deep-sea minerals, deep-sea mining and metallurgical processing of marine mineral resources.

UMC 2019 in Sanya, China provides technical presentations consisting of a good balance among industrial, academic and government interests. The participants this year, as usual, represent a wide variety of nationalities, including presentations from Australia, Belgium, China, the Cook Islands, Denmark, France, Germany, India, Indonesia, Italy, Japan, Kiribati, Korea, The Netherlands, New Zealand, Norway, Papua New Guinea, Poland, Portugal, Russia, Singapore, the United Kingdom, and the USA.

Since the first conference (then called the Underwater Mining Institute), which took place in Milwaukee, Wisconsin, USA, in 1970, Founder Professor J. Robby Moore actively sought the combined participation of industry, academia, and government. After 45 years of that same successful formula, the Underwater Mining Conference remains the premier venue for bringing a diverse collection of experts together from around the globe to exchange ideas and collaborate in research and commercial projects relating to marine minerals.

The host organization for UMC 2019 is the Institute of Deep-Sea Science and Engineering (IDSSE), located in the tropical resort city of Sanya City, Hainan, China. In 2011 IDSSE was founded by the Chinese Academy of Sciences (CAS). IDSSE consists of three departments, the Deep-Sea Science Division, the Deep-Sea Engineering Division, and the Marine Equipment and Operations Management Center. The Deep-Sea Mining Subdivision and the Deep-Sea Resource Exploration Laboratory are key subdivisions within the Deep-Sea Engineering Division. In August 2017, CAS established the Institute of Deep-Sea Technology (IDST) within IDSSE. Our Technical Co-Chair for UMC 2019 is Dr. Yang Ning, the Deputy Director of IDSSE.

We extend our deepest gratitude to our Host, Local Host Sponsors, and Sponsors:

- Host: Institute of Deep-sea Science and Technology (IDSSE), Hainan
- Local Host Sponsor: China Academy of Sciences
- Local Host Sponsor: National Natural Science Foundation of China (NSFC)
- Local Host Sponsor: The People's Government of Sanya City
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We strive to bring you the very best experts engaged in marine minerals and mining from every corner of the globe. We trust that you will find professional benefit and personal camaraderie during your time with us. Listen, speak up, ask questions, make connections and friends, and enjoy yourselves in Sanya. We are so fortunate to be here together with such gracious and generous hosts.

Greg Stemm
President, International Marine Minerals Society

天涯何处无芳草，

琼州玉液迎客欢。

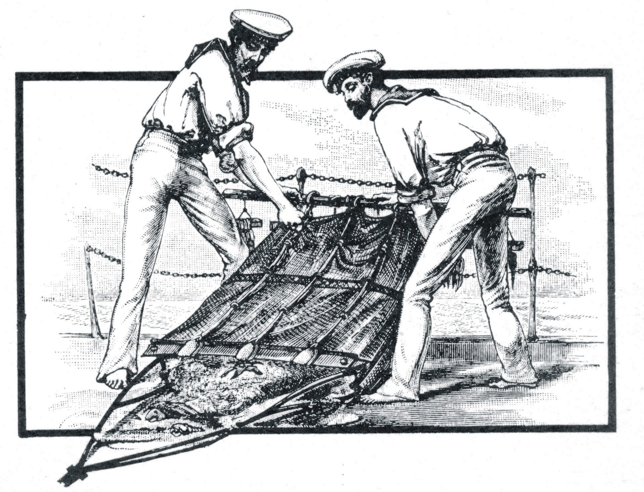
龙宫宝藏何处寻，

且听诸君细道来。

Yang Ning
Co-Chair, UMC 2019

UMC BACKGROUND

The Underwater Mining Conference (UMC)



The International Marine Minerals Society and the University of Hawai`i are the primary organizers of the UMC (formerly the Underwater Mining Institute) — an annual conference that draws on the worldwide expertise of researchers, industry professionals, and environmental, resource, and policy managers to provide the latest information relevant to seabed minerals. The UMC has come a long way since its first small gathering in 1970, led by founder Professor J. Robert Moore, through the Sea Grant College Program at the University of Wisconsin. Manganese nodule mining was the big impetus for the startup of the conference. During the intervening years, new research discoveries, technological advances, and commercial development have expanded the areas of interest to include much more than just nodules. Throughout this evolution one constant is the conference's goal, which is to encourage prudent and responsible development of marine mineral resources through technical presentations in venues that promote informal and free exchange.

The theme varies each year, as does the location and host. This collection of abstracts and brief biographical sketches of authors and or speakers is provided to participants. In the early days these were distributed in three-ring binders and, in recent years, as digital electronic files. These abstracts are now available through OneMine.org—an innovative service launched in April 2008 by the Society of Mining, Metallurgy, and Exploration that manages an extensive, online digital library for mining and minerals. Access to OneMine.org is made available to current members of professional societies, such as the International Marine Minerals Society. A significant benefit to UMC participants has been a one-year membership to the Society, which also includes access to OneMine.org.

To encourage the freedom of our speakers to share their ideas, which can include proprietary information, recording (sound or visual) of the technical sessions is not permitted, unless explicitly approved by the presenter. Presentations are scrutinized to ensure that the content and interactions of the UMC remain stimulating, fresh, and reflective of the latest scope of this industry. To date more than 25 nations have been represented at the **UMC.**

SPONSORS

We are grateful to our generous sponsors for supporting the efforts of the International Marine Minerals Society and the Underwater Mining Conference.

HOST

中国科学院 深海科学与工程研究所
Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences

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UNDERWATER SOLUTIONS WORLDWIDE

OCEAN MINERALS

FINAL PROGRAM

22 SEPTEMBER 2019 (SUNDAY)

JW Marriott Hotel Sanya Dadonghai Bay

WELCOMING RECEPTION & REGISTRATION

Outdoor Terrace, JW Kitchen, 2nd Floor

18:00 - 21:00 Registration (Restaurant Lobby 2nd Floor)

19:00 – 22:00 Cocktails and Buffet Dinner

UMC registered participants and spouses

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23 SEPTEMBER 2019 (MONDAY)

TECHNICAL SESSION I

Grand Ballroom

JW Marriott Hotel Sanya Dadonghai Bay

09:00 – 17:10

09:00 INTRODUCTION AND WELCOME

Call to Order

Charles L. Morgan, UMC Technical Program Chair
Moana Hohonu LLC, Hawaii

Host Welcome

Yang Ning
Deputy Director
Institute of Deep-sea Science and Engineering, China Academy of Science (CAS), Hainan, China

Lou Dongyang
Chief Financial Officer
China Merchants Industry Holdings CO., LTD.

Li Yunkai
Deputy Secretary-General
Sanya Municipal Government

Kang Xiangwu
Department of Social Development Technology
Ministry of Science and Technology

Li Linlin
Department of Treaty and Law
Ministry of Foreign Affairs

Program Introduction
Gregory Stemm, President
International Marine Minerals Society

Presentations

10:00 State Practices of China in the Area
Liu Feng, China Ocean Mineral Resources R&D Association, China

10:25 Break (30 minutes)

10:55 Developing New National Regulatory Frameworks and Standards for Sustainable Seabed Minerals development
Paul Lynch, Seabed Minerals Authority, Cook Islands

11:20 Sustainable Development of Mineral Resources in the Area
Pratima Jauhari, International Seabed Authority, Jamaica

11:45 An Unfinished Work: The Emerging Chinese Legal Regime and Management System of International Deep Seabed Mining
Zhang Guobin, Koguan School of Law, Shanghai Jiao Tong University, China

12:10 LUNCH – JW Kitchen – 2nd Floor West Wing (90 minutes)

13:40 An Economically and Environmentally Viable Underwater Mining Solution
Stef Kapusniak, Soil Machine Dynamics, United Kingdom

14:05 Progress of Chinese 1000m Deep Seabed Nodule Mining Test Project
Li Xiangyang, China Ocean Mineral Resources R&D Association, China

14:30 Field Testing: Improving Environmental Performance of Polymetallic Nodule Harvesting
Shi Wei, IHC Mining BV, China

14:55 Break (30 minutes)

15:20 Overview of a Pilot Study for Seabed Cobalt Mining
Xu Lixin, China Merchant Offshore Technology Research Center, China

15:45 The Sea Trials of the Second Generation of the Cobalt Mining Device
Chao Xie, Institute of Deep-sea Science and Engineering, CAS, Hainan, China

16:10 Development and Testing of a Hydraulic Nodule Collector While Minimizing Its Environmental Impact, Preliminary Results of Discharge Experiments (Blue Harvesting Project)
Rudy Helmons, Delft University of Technology, The Netherlands

16:35 Hazards and Risks in Deep-Seabed Mining
Sup Hong, Korea Research Institute of Ships & Ocean Engineering, Korea

17:00 Closing Remarks and End of Technical Session I

FREE EVENING (Dinner on Your Own)

19:30 Informal Boardwalk Exploration
From the JW Marriott front lobby, you'll be directed to the easy stroll along the beachfront to the mile-long Boardwalk where you can buy drinks and food at some of the colorful restaurants (weather permitting).

24 SEPTEMBER 2019 (TUESDAY)

TECHNICAL SESSION II

Grand Ballroom

JW Marriott Hotel Sanya Dadonghai Bay

09:30 OPENING REMARKS
Charles L. Morgan, UMC Technical Program Chair

Presentations

09:35 Promoting Cost-Effective Capture of Quality Environmental Data from the Outset through Integration: A Focus on the CCZ
Scott Breschkin, ERIAS Group, Australia

10:00 Deep-sea Mining Sediment Plumes: What We Know and What We Don't
Thomas Peacock, Massachusetts Institute of Technology, USA

10:25 Investigating Midwater Discharge Sediment Plumes Associated with Deep-Sea Nodule Mining
Carlos Munoz-Royo, Massachusetts Institute of Technology, USA

10:50 Break (30 minutes)

11:20 Establishing a Methodology to Define Criteria for a Risk Based Impact Assessment for Offshore Sea-floor Massive Sulphide Extraction
Marcel Rozemeijer, Wageningen Marine Research, The Netherlands

11:45 Can Patents be Considered Part of the Common Heritage of Mankind?
Andreas Kaede, Kanzlei, Germany

12:10 LUNCH – JW Kitchen – 2nd Floor West Wing (75 minutes)

13:25 POSTER SESSION (45 minutes)

Poster Presentations

Non-supervised Classification of Benthic Habitats Based on Seafloor Geomorphology in the French Exploration Contract for Polymetallic Nodules – Clarion-Clipperton Zone
Florian Besson, Ifremer, France

Acquiring Exploration Data from Polymetallic Sulphides on the Mohns Ridge on the Norwegian Continental Shelf
Harald Brekke, Norwegian Petroleum Directorate, Norway

Chatham Rock Phosphate – An Example of a Sustainable Development of Seabed Mineral Resources While Minimising the Environmental Impact and Using Ground Breaking Technology
Chris Castle, Chatham Rock Phosphate, New Zealand

Preparation of Bonded Super-hydrophobic Thin Film
Chen Ming and Ma Haoxiang, Institute of Deep-sea Science and Engineering, CAS, Hainan, China

Numerical Study on Settling and Floating Movements of a Sphere Particle Flowing in a Vertical Pipe
Xiong Hong, Institute of Deep-sea Science and Engineering, CAS, Hainan, China

The Estimation Study About the Amount of Collection in the Pick-Up Device for the Deep-Sea Mining System
Sugil Cho, Korea Research Institute of Ships & Ocean Engineering, Korea

Design and Implementation of Monitoring System for Deep Sea Cobalt-rich Crust Sampling Vehicle
Dong Donglei, Huazhong University of Science & Technology, China

Seabed Mineral Resources Extraction-ICCP
Feng Guojing, Shanghai FB Oil Equipment Technology, China University of Petroleum, China

Low Grades Ultramagic-hosted SMS Deposits: Case Study of Pobeda Hydrothermal Field
Anna Firstova, VNIIOkeangeologia, Saint Petersburg, Russia

GIS - based Approach to Define Permissive Areas for SMS Exploration Along the Slow-spreading Mid-Atlantic Ridge
Sebastian Graber, GEOMAR, Germany

A3D Method to Dynamically Model the Cutting of Submerged Rocks with Evaluation of Pore Pressure Effects
Rudy Helmons, Delft University of Technology, The Netherlands

Design of Oval Plane Mirror Component in Marine Remote Sensing Satellite for Mineral Resources
Hu Yongming, Xi'an Institute of Optics, CAS, China

Mineral Associations in the Crusts from Mendeleev Ridge Based on SEM-EDS and Microprobe Analyses
Natalia Konstantinova, VNIIOkeangeologia, Russia

Characteristics of the Polish contract area in the Mid-Atlantic Ridge
Agata Kozlowska-Roman, Polish Geological Institute, Poland

Assessment of Polymetallic Nodule Resources Using High-Resolution AUV Based Geophysical Imagery, Near-Bottom Photographs and Seabed Boxcore Sampling
Greg Kurras, Seafloor Investigations, USA

In situ Biomarker Discovery in Deep-sea Amphipods for Deep-sea Mining activities using TMT-based Comparative Proteomics
Kwan Yick Hang, Hong Kong University of Science & Technology, China

A Non-Metallic Riser Concept for the Ultra-Deep Seabed Mining Vertical Transport System
Frank Lim, 2H Offshore, United Kingdom

Research on Shipborne Dewatering Process Technology in Deep-sea Sulfide Mine
Liu Shimei, Changsha Research Institute of Mining and Metallurgy, China

Deep-sea Mining Equipment Researching in Marine Equipment and Technology Institute of Jiangsu University of Sci and Tech
Lu Daohua, Jiangsu University of Science & Technology, China

Determining and Communicating Marine Mineral Resource Estimates to the Broader Minerals Industry
Campbell McKenzie, RSC Mining, New Zealand

Titanium Concentration in the Mineral Phases of Ferromanganese Deposits from the N-W Pacific
Pavel Mikhailik, Far East Geological Institute, Russia

A Review of the Structural Health Monitoring for Marine Risers/Pipes
Cheonhong Min, Korea Research Institute of Ships & Ocean Engineering, Korea

A Study on the Simulation-Based Design Technology of the Subsea Equipment Using Dims Toolkit
Jaewon Oh, Korea Research Institute of Ships & Ocean Engineering, Korea

A Preliminary Study on the Geological Continuity of Polymetallic Nodules in the Deep-Sea Basin Between Guyots Suda and Scripps of the Western Pacific Based on Coverage from Towed Camera Sledge
Ren Xiangwen, First Institute of Oceanography, China

Uranium in Seafloor Massive Sulfides at the Mid-Atlantic Ridge
Anna Sukhanova, VNIIOkeangeologia, Russia

Copper-rich Disseminated Sulfides Near a Transform Fault on the Southern Carlsberg Ridge: Implications for Off-axis Seafloor Massive Sulfide Mineralization
Wang Yejian, Second Institute of Oceanography, China

Transparency, Public Participation and Access to Justice in the Context of Deep Sea Mining: Luxury or Legal Obligation?
Klaas Willaert, Ghent University, Belgium

Feasibility Study of Combined Mining of Rare-Earth Element Rich Mud and Manganese Nodules by Pulp-Lift in Japan's EEZ
Tetsuo Yamazaki, Osaka Prefecture University, Japan

CO2 Outgassing Suppressed by Enhanced Biological Pump in the Eastern Tropical Pacific
Chanmin Yoo, Korea Institute of Ocean Science and Technology, Korea

Visual Simulation of Deep-Sea Mining System
Zhang Guiping, Central South University, China

Current Situation and Prospect of Technological Development in Deep-sea Mining of China Minmetals Corporation
Zhuo Xiaojun, Minmetals, China

14:10 ORAL PRESENTATIONS

Oral Presentations – continued

14:10 Designing Logistic System for Deep Sea Mining
Govinder Singh Chopra, SeaTech Solutions, Singapore

14:35 Surface Support System Selection for Deepsea
Joe Zhou, China Merchants Offshore Research Center, China

15:00 Break (30 minutes)

15:30 Polymetallic Nodule Abundance Estimations based on High-Resolution AUV Data and Seabed Samples for DeepGreen's NORI Area D, Clarion Clipperton Zone
Christine Devine, Fugro, Australia

15:55 The Advances of Project of Investigation and Study on the Rare Earth Resources in Deep-Sea Sediments in the Pacific Ocean
Zhu Kechao, Guangzhou Marine Geological Survey

16:20 Closing Remarks and End of Technical Session II

17:45 IDSSE (Institute of Deep-Sea Science and Technology) Cocktail Reception

Featuring presentation by *Professor Dr. Mei Shenghua*, Director of the Key Laboratory of Deep-Sea Extreme Environment Simulation, Chinese Academy of Sciences

Meet at the JW Marriott front lobby for bus transport to IDSSE. Bus will return participants to the JW Marriott.

FREE EVENING (Dinner on Your Own)

21:00 NO-HOST GET TOGETHER – The Autograph Rooftop Pool Terrace (next door to the JW Marriott Hotel)

Take the short easy stroll to The Autograph for no-host UMC-discounted cocktails (weather permitting).

25 SEPTEMBER 2019 (WEDNESDAY)

TECHNICAL SESSION III

Grand Ballroom

JW Marriott Hotel Sanya Dadonghai Bay

09:00 – 17:10

09:30 OPENING REMARKS
Charles L. Morgan, UMC Technical Program Chair

09:35 ANNUAL GENERAL MEMBERSHIP MEETING: INTERNATIONAL MARINE MINERALS SOCIETY

Presentations

09:55 Research on Nodules Collecting in Deep-sea Mining: An Efficient and Environmentally Friendly Technology in Hydraulic Collection
Zhao Guocheng, Shanghai Jiao Tong University, China

10:20 Design Challenges of Riser & Lifting System
Andrew Lipman, American Bureau of Shipping, USA

10:45 Break (30 minutes)

11:15 Underwater Acoustic Positioning and Navigation System
Lv Chengcai, Institute of Deep-sea Science and Engineering, CAS, Hainan, China

11:40 Geochemical and Microbial Characteristics of Ferro-Manganese Crusts at Depths Ranging from 1100m to 5500m on the Seamount in the Northwestern Pacific
Katsuhiko Suzuki, Japan Agency for Marine-Earth Science & Technology, Japan

12:05 Geological Characterization of Cobalt-Rich Ferromanganese Crusts Using Deep-Sea Drill Cores in the NW Pacific Seamounts
Akira Usui, Kochi University, Japan

12:30 LUNCH – JW Kitchen – 2nd Floor West Wing (90 minutes)

14:00 Field Planning & Seafloor Production Tool Concept Review
Wilson Zheng, China Merchants Offshore Research Center, China

14:25 Assessing Hydrothermally Extinct Seafloor Massive Sulphide Deposits (eSMS): Lessons from the Blue Mining Project, Mid-Atlantic Ridge
Bramley Murton, National Oceanography Centre, University of Southampton, United Kingdom

14:50 Morphology and Formation of SMS Deposits in Different Geological Settings
Georgy Cherkashov, VNIIOkeangeologia (Institute for Geology and Mineral Resources of the Ocean), Russia

15:15 Break (30 minutes)

15:45 Seafloor Sulfide Mineral Deposition and Remobilization
Amy Gartman, U.S. Geological Survey, USA

16:10 HOMESIDE – An Advanced Tool for Hydrothermal Plume Hunting and Polymetallic Sulphide Exploration in the Indian Ocean
Ralf Freitag, Federal Institute for Geosciences and Natural Resources (BGR), Germany

16:35 APEIs: Some Thoughts About Designation for Crusts and Sulphides
Livia Ermakova, VNIIOkeangeologia (Institute for Geology and Mineral Resources of the Ocean), Russia

17:00 Closing Remarks - End of Technical Session III

17:45 OPTIONAL SUNSET WALK AND VIEW FROM DEER PARK (1.5 hours)
Meet at the JW Marriott front lobby for transport up the scenic hill to Deer Park (weather permitting). This bus will return participants to the JW Marriott.

19:15 FREE EVENING (Dinner on Your Own)

26 SEPTEMBER 2019 (THURSDAY)

WORKSHOP SESSION

Grand Ballroom

JW Marriott Hotel Sanya Dadonghai Bay

09:00 CALL TO ORDER

09:05 China Deepsea Mining Industry Development Workshop
中国深海采矿发展研讨会--招商工业集团
Hosted by China Merchants Industry Holdings CO., LTD.

10:30 Break (30 minutes)

CMI Workshop continues

12:00 LUNCH – JW Kitchen – 2nd Floor West Wing (90 minutes)

13:30 Panel on Ocean Mining Regulations, Permitting and Environmental Policy
Hosted by Odyssey Marine Exploration

14:25 Getting Out the Facts: The Role of Associations and the Private Sector in Promoting the Truth About Sustainable Ocean Mineral Development

16:30 Closing Remarks - End of Workshop Session

26 SEPTEMBER 2019 (THURSDAY)

UMC 2019 BANQUET

JW MARRIOTT – GRAND BALLROOM

19:00 – 22:00

Cocktails

***Welcome and Dinner** – Greg Stemm, IMMS President*

***Banquet Keynote Address** by Tom Albanese*

As a top executive in the mining industry, Tom Albanese brings a wealth of valuable experience to the UMC. He served as Chief Executive Officer of Rio Tinto, the second largest global diversified mining company, from May 2007 to January 2013. He is the former CEO of Vedanta Resources plc, a leading global diversified resources company, with metals and mining, oil and gas, and commercial power operations primarily in India and Africa. Tom has previously served on the Boards of Konkola Copper Mines, Ivanhoe Mines, Palabora Mining Company and Turquoise Hill Resources Limited. Early in 2018, Tom was appointed to the Advisory Board of Nevada Copper, which owns 100% of the Pumpkin Hollow Copper Development Property located in Nevada, United States of America. Tom currently serves as the Lead Independent Director of Nevada Copper.

In recognition of his distinguished leadership and service to the mining industry, Tom was conferred with the 'Mining Foundation of the Southwest' 2009 American Mining Hall of Fame Award. Tom holds a Bachelor's degree in Mineral Economics and a Master's in Mining Engineering from the University of Alaska.

UMC Geotechnical Field Tours I and II

27 September 2019

Shilu Iron Ore Mine

Departs 7:30 AM from the JW Marriott lobby; Lunch provided.
Tour will end at The Edition and eventually back at the hotel

Albanese, Tom	Huber, David	Moore, Chris and Beth
Brekke, Harald	Jamieson, John	Dettweiler, Tom
Castle, Chris	Jauhari, Pratima	Skaugset, Kjetil
Cherkashov, Georgy	Konstantinova, Natalia	Slobada, Elizabeth
Chou, Kent	Kurras, Greg	Sukhanova, Natalia
Ermakova, Livia	Mikhailik, Pavel	Wyatt, Christopher
Firstova, Anna	Miyata, Yoji	Yamazaki, Tetsuo
Freitag, Ralf	Murton, Bramley	
Gartman, Amy	Okamoto, Nobuyuki	
Goodden, Robert and Beatrice	OME 1, 2, 3 and 4	**TOTAL: 32 as 9/17/19**

Areca Valley Ethnic Village

Starts at 12:00 Noon with Lunch at Man Ho, JW Marriot.
13:30 Departure from the JW Marriott lobby; Arrival 14:30.
Tour will end at The Edition and eventually back at the hotel.

Barriga, Fernando	Kang, Jung-Keuk	Lynch, Paul and Shona
Chi, Sang-Bum	Cho, Sugil	McConnell, Dan and Beth
Chopra, Govinder	Hong, Sup	Mussett, Mark
Chopra, Daljeet	Kim, Hyung Woo	Stevenson, Ian
De Blaeij, Ko	Min, Cheonhong	Sukhanova, Natalia
Veldman, Alberta	Oh, Jaewon	Tapanes, Ernie and Julie
Hein, James	Luther, Mark	Yoo, Chan Min
Henry, Michael		**TOTAL: 25 as 9/17/19**

27 September 2019

CONCLUSION OF UMC 2019

UMC 2019 HAINAN CHINA

UMC Colleagues and Friends:

Thank you for your contributions and camaraderie at the 48th Underwater Mining Conference here in Sanya, Hainan China. We are deeply grateful to our host, Dr. Yang Ning and the Institute of Deep-Sea Science and Technology, Chinese Academy of Science. His associates and technical team (Xiao Jianyu, Chen Yuxiang and others) extended much effort toward the success of our conference. Valuable support was provided by the Chinese Academy of Science, National Natural Science Foundation of China, and the People's Government of Sanya City. We are very grateful to our Sponsors (Odyssey Marine Exploration, China Merchants Industry Holdings CO., LTD., Cooley LLP, Boskalis, Ocean Minerals LLC, Phoenix International) for their generous support. They and many others have done a wonderful job of planning for and executing this important event. We hope your experience with all of us has been professionally, and personally, rewarding and that you will join us again next year for UMC 2020 in St. Petersburg, Florida.

Greg Stemm
IMMS President
2019 thru 2020

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Promoting Cost-Effective Capture of Quality Environmental Data from the Outset through Integration: A Focus on the CCZ

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Abstract

The International Seabed Authority and a number of countries have, or are in the process of developing environmental impact assessment guidelines and legislation for seafloor mineral development. The formal decision to grant a project an environmental permit is based on an environmental and social impact assessment (ESIA). The ESIA needs to be supported by sufficient environmental data upon which an assessment of impacts can be made and mitigation measures developed. Given the remote locations of many seafloor prospects, including the Clarion Clipperton Zone (CCZ), collection of sufficient environmental data to inform an ESIA is often a logistically difficult, expensive and lengthy process. Integrating environmental data collection with resource exploration activities can ameliorate these challenges by ensuring the collection of environmental data of sufficient quality and quantity is achieved in a more cost-effective manner, early in the project and incrementally across all project stages.

Seafloor mineral exploration typically applies a phased approach, beginning with regional target identification, followed by prospect identification and then onto prospect evaluation and ultimately resource potential definition. At each exploration stage the level of commercial confidence in the resource potential of an area hopefully increases. Integration of environmental field surveys with mineral investigations allows environmental data to be opportunistically collected throughout each stage of exploration, and maximises the

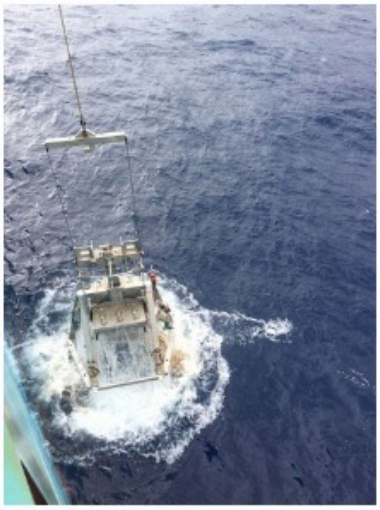
opportunity for collecting environmental data from the earliest stages of exploration. By applying this integrated approach, environmental data collection is captured from the onset of the seafloor mining project and throughout the project lifetime. This approach reduces costs associated with the conducting stand-alone surveys by consolidating mineral and environmental surveys into single cruises, reducing the need for re-mobilising to highly remote regions at significant expense.

An integrated approach was implemented during surveys in the eastern CCZ in 2018, where opportunistic environmental studies were conducted in conjunction with primary exploration surveys, with follow up surveys currently underway. The integrated surveys allowed for opportunistic environmental data collection at an early project stage, and consolidated the significant costs associated with vessel and equipment hire, mobilisation, and technical personnel. The program reduced the need to re-mobilise for separate environmental and resource surveys, and demonstrated the cost-effectiveness of developing a robust environmental baseline for a remote area such as the CCZ through an integrated approach.

In cases where exploration ceases in a particular area due to geological results indicating non-commercial resources, previously established environmental databases can be used in future analysis to build scientific knowledge and enable comparison to exploration areas in the same region that may be developed, as well as to improve data collection and analysis techniques.

This presentation will explore cost effective environmental data acquisition for seafloor mining project baseline and ESIAs, drawing on ERIAS Group's and the author's experience in coordinating baseline and ESIA studies for seafloor mineral deposits and mining proposals in the marine waters of Papua New Guinea, Solomon Islands, Mexico and the CCZ, within the context of a developing regulatory framework and whilst seafloor mining technology continues to evolve in this burgeoning industry.

Keywords: Environmental, assessment, ESIA, EIS, integrated, opportunistic, exploration, cost-effective.



Scott Breschkin

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Scott has worked on deep sea mining projects in Papua New Guinea, New Zealand and the Clarion Clipperton Zone. In particular, Scott has assisted deep sea mining clients in analysing and synthesising large environmental data sets to understand and characterise the existing environment and to identify data gaps to inform future environmental surveys. Scott has also been involved in deep sea massive sulfide exploration surveys in the Bismarck Sea, Papua New Guinea.

Scott is particularly interested in designing defensible and fit-for-purpose aquatic baseline surveys that allow for robust impact assessment and facilitate clients to obtain environmental approvals. Scott has worked on a number of international environmental and social impact assessments in Australia, Papua New Guinea and the Solomon Islands.

Morphology and formation of SMS deposits in different geological settings

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Abstract

Data collected during last year demonstrate diversity in morphology of SMS deposits formed in different geological settings. Variability in the shape of deposits is controlled by different styles of hydrothermal fluid discharge (focused or diffused), which in turn is determined by permeability of the host rocks: low in basalts and high in gabbro-peridotites. Transformation of ultramafic rocks to serpentinites during hydrothermal alteration processes contributes considerably to increasing permeability. As a result, classical mound-like structures are more typical for deposits with a basalt substrate whereas ultramafic rock settings are characterized by SMS deposits with a flatter morphology (fig. 1).

Flat mounds have been described at the ultramafic hosted Ashsadze-1 site and some fields of the Semenov cluster at the Mid-Atlantic Ridge (MAR). A chain of small mounds topped by black smokers were observed at the ultramafic rock-hosted Logatchev-1 hydrothermal field as well (Petersen et al., 2009).

Diffuse-flow hydrothermal discharge is represented by the accumulation of tens of small (up to 20-30 cm height) smokers (“chimney forest”) standing on a thin sulfide substrate, which has been detected at the Ashadze-1 field (fig. 2).

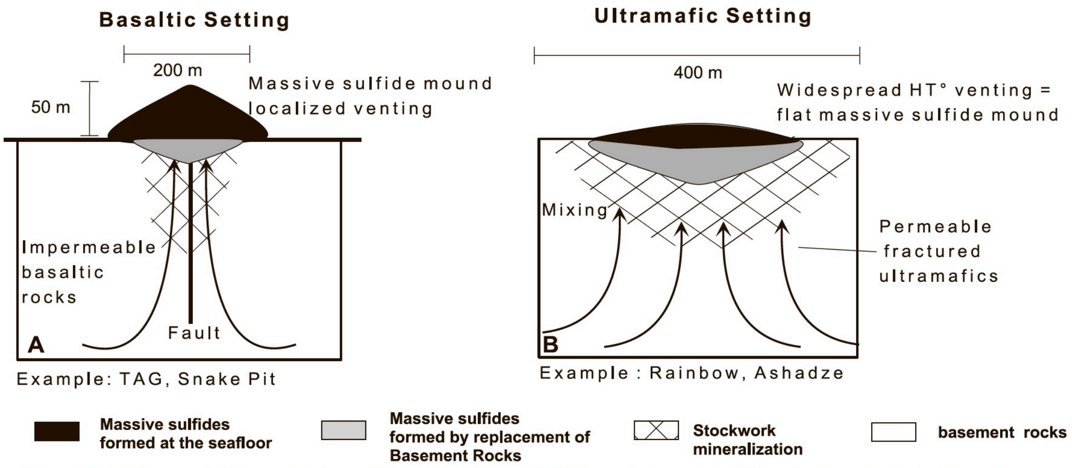

Figure. 1. Differences in the morphology of deposits and type of discharge between basaltic- and ultramafic-hosted hydrothermal deposits. Compared to (a) basaltic hosted fields, discharge is less focused in (b) ultramafic environments, where flatter mounds form (Fouquet et al., 2010).

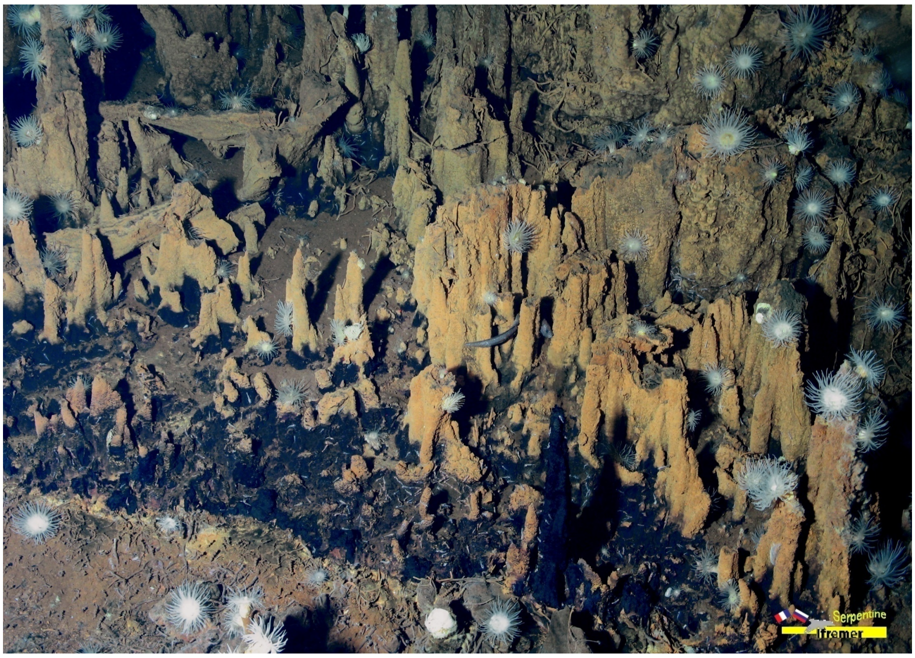

Figure 2. Ashadze-1 hydrothermal vent field (12°58’ N, MAR) weakly active site with combination of different structures (sulfide chimneys (“chimney forest”), crusts, metalliferous sediments) and hydrothermal vent fauna.

Mounds of different shape (higher or flatter) can be considered as **primary SMS structures** in ultramafic settings at the MAR. Further, evolution of mounds and formation of **secondary SMS structures** are illustrated by SMS bodies observed at the Ashadze-1 and

Ashadze-2 hydrothermal fields, studied during the French-Russian SERPENTINE cruise in 2007 (Fouquet et al., 2008; Ondreas et al., 2013; our data). The first secondary structure at the Ashadze-2 was described as a "smoking crater" (Fig. 3) and the second one at Ashadze-1 as a "broad-crust" (Fig. 4).

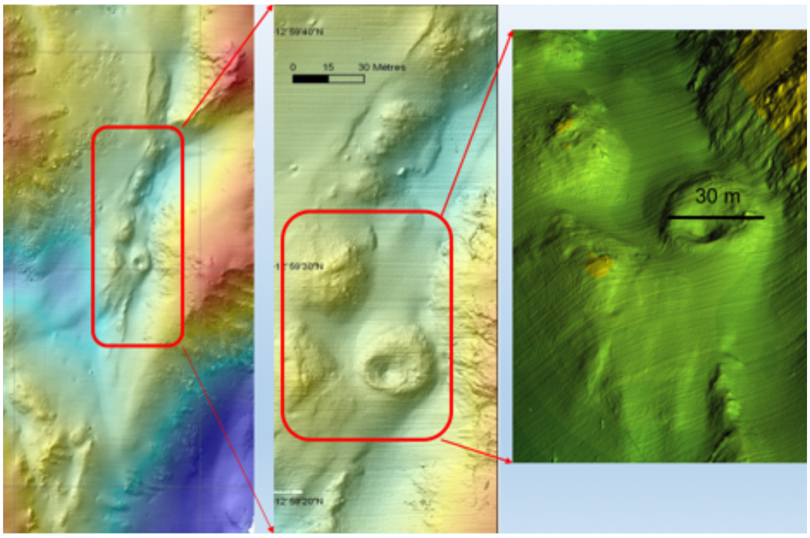

Figure 3. Chain of hydrothermal mounds and "smoking crater" at Ashadze-2 field (12° 59'N, MAR).

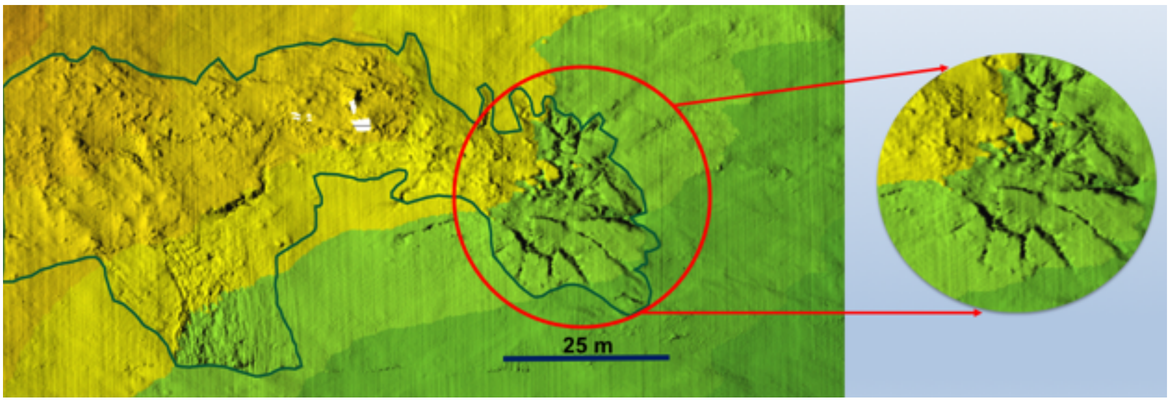

Figure 4. Contour of Ashadze-1 hydrothermal field (12°58' N, MAR) and "bread crust" structure.

It should be noted that the dimension of the crater and "bread crust" is similar (25-30 m in diameter).

Smoking craters were detected earlier at the Logatchev site (Bogdanov et al., 1997; Petersen et al., 2009) and at the Drachenschlund vent at the Nibelungen hydrothermal vent fields, both associated with ultramafic rocks (Koschinsky et al., 2006; Melchert et al., 2008).

The origin of craters has been interpreted as a result of an explosive process at the primary hydrothermal mound or, less likely, of dissolution of metastable anhydrite masses within the mound.

However, the process which resulted in the "bread crust" structure formation has not been explained yet.

We propose that the "smoking crater" and "bread crust" structures represent two possible scenarios of primary hydrothermal mound evolution. According to Bogdanov et al. (1997), Petersen et al. (2009) ,and Fouquet et al. (2010), the smoking crater could be the result of explosion due to overpressured fluids coming to the surface from the deep part of hydrothermal system. We suggest that the second structure could also be formed due to overpressured fluids. However, the result of the overpressuring was not expressed by aan explosion but by cracking/fracturing of the outer part of the primary mound and diffuse discharge of deeper fluids through the cracks. In other words, this process could be termed as a "failed crater".

Two scenarios of mound evolution are determined by different physical properties of surface mineralization: if it is strong enough and has no weak zones, overpressuring leads to explosion. Otherwise cracking will follow weakened zones of the mound with slow fluid discharge through the generated cracks. Two scenarios of secondary processes during hydrothermal mound evolution are illustrated at the fig. 5 (in plan) and fig. 6 (in cross section).

Current and future detailed study of ultramafic hydrothermal fields will result in the detection of many other morphological types of SMS deposits. It should also be noted that diversity of SMS deposits morphology is rather important for their resource estimation.

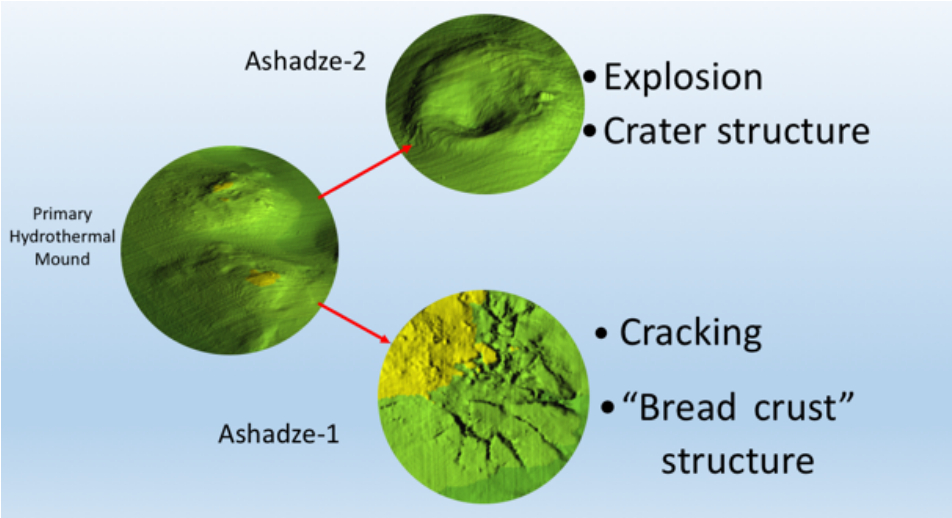

Figure 5. Two scenarios of hydrothermal mound evolution: plan view.

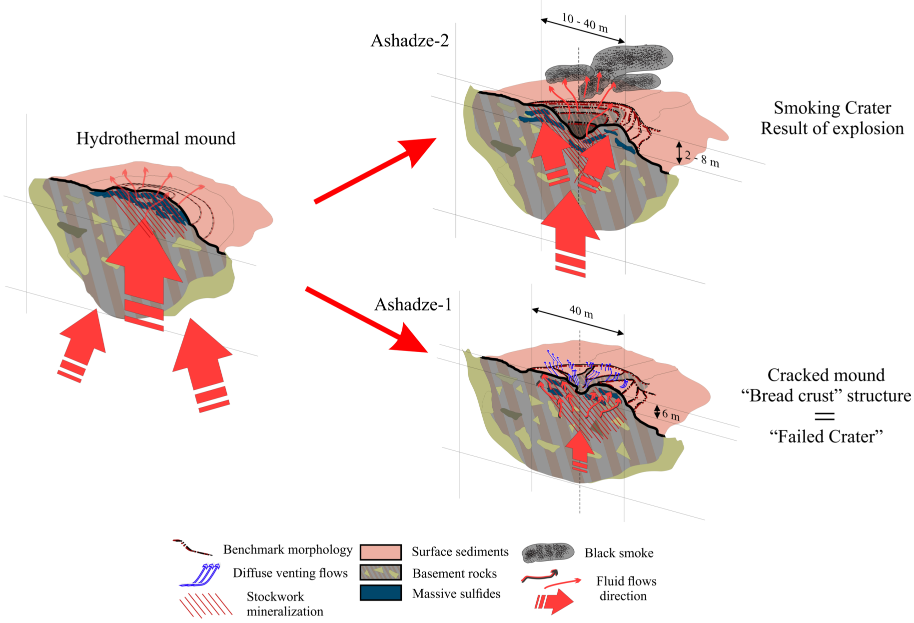

Figure 6. Two scenarios of hydrothermal mound evolution: cross-section view.

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Keywords: Deep-sea minerals, Seafloor massive sulfide deposits, Morphology, Geological setting, Mid-Atlantic ridge

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Designing Logistic System for Deep Sea Mining

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ABSTRACT

SeaTech Solutions International (S) Pte Ltd, Singapore are the designers of world's first Deep Seabed Mining ship. The ship is now under construction in China. The Deep Sea Mining industry is eagerly awaiting commencement of her seabed mining operations and the success of this story will go a far way in accelerating investment in the new industry of Deep Sea Mining.

Deep sea Mining ship is a entirely new ship type – a strange mix of an Offshore Support/Construction / SPS vessel with accommodation for 200+ persons, a Bulk Carrier, a Tanker, a Drill Ship, a FPSO for ore – all in one ship. The exact rule requirements that the Flag Administrations and Ship Classification societies should apply to such vessels need to be discussed in depth and agreed to by all stake-holders at an early stage. Similarly, there is to be an agreement on the environmental issues and the proposed means of addressing them through design of the ship and the mining process and operations.

The seabed mining Logistic System design should be simple and cost effective to optimize the vessel for intended operations at lower CAPEX and OPEX.

This paper aims to share our own experiences and some insight into the design process for the optimization of the complete logistic system for Deep Sea Mining.

Keywords: Ship Design, Deep Sea Mining, Ship Motion, Ship-to-Ship Transfer, Dynamic Positioning, Side-by-Side Mooring, Cargo Handling

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Polymetallic Nodule Abundance Estimations based on High-Resolution AUV Data and Seabed Samples for DeepGreen's NORI Area D, Clarion Clipperton Zone

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Introduction

During an offshore campaign for the Nauru Ocean Resources Inc. (NORI) Area D tenement in the Clarion Clipperton Zone, high-resolution geophysical data and seabed box core samples were acquired to provide crucial data for polymetallic nodule classification and selection and survey of a Collector Test Site for further detailed site investigation. Nodule abundances were estimated between physical sample site locations using a combination of image processing techniques, including GIS-based automated nodule mapping, and statistical comparison against actual box core abundances. These estimated abundances were used as input for mineral resource estimate calculations.

Background

In 2018 Nauru Ocean Resources Inc. (NORI) a subsidiary of DeepGreen Metals Inc., contracted Fugro to conduct an autonomous underwater vehicle (AUV) geosurvey and seabed sampling programme in its NORI Area D in the Clarion Clipperton Zone (CCZ). The key objectives of this programme were to acquire detailed multibeam echosounder (MBES) bathymetry and backscatter data, side scan sonar imaging, subbottom profiler data, and photogrammetry data to help facilitate:

- Identification and selection of enough suitable ground for a Collector Test Site.

• Provision of sufficient geological and geotechnical detail to make sure that sampling and Collector Test Site programmes are appropriately designed and provide a benchmark that future sampling and recovery efficiencies can be measured against.

• Provision of appropriate seafloor imagery to assist with selection of suitable environmental monitoring sites, particularly for metocean studies.

• Identification of smaller environmental baseline reference zones. An important consideration is that the habitats of these reference sites are similar in character to the site that will be selected for the Collector Test Site.

• Demonstration of a methodology to upgrade resource confidence from Inferred to Indicated and Measured categories.

High-Resolution AUV Geophysical Data

During the 2018 survey, over 14 TB of high-resolution bathymetry, backscatter, side scan sonar, and subbottom profiler geophysical data and camera imagery over a total area of 375.2 km^2 were acquired and processed during the 40-day offshore campaign. Initially, the AUV data were collected at an altitude of 35 m above the seabed along reconnaissance lines to assess the regional geological conditions and confirm no obstructions were present on the seabed. The AUV altitude was then lowered to 6 m above the seabed for collection of the camera imagery at a resolution suitable for identifying individual nodules. After assessing the reconnaissance geophysical data and associated camera imagery, and classifying the size and spatial distribution of nodules, a Collector Test Site was selected for a detailed geophysical survey and high-resolution data were collected over a continuous coverage area for further site investigations.

Nodule Classification based on Photogrammetry Data

Three broad facies of nodule distribution at the seafloor were identified based on camera imagery:

Type 1 are typically characterised by >50% nodules (by area of coverage). Type 1 was the most dominant type observed in the NORI Area D survey data during the 2018 campaign. The majority of these nodules are typically small-to-medium sized (~1 cm to 5 cm), with a normal size-frequency distribution. The distribution is predominately nodule-supported, characterised by frequent contact between neighbouring nodules, and are thus harder to discriminate individually.

Types 2 and 3 are characterised by lower nodule abundance, small-to-large size (~1 cm to 20 cm), and a bimodal size-frequency distribution. Type 2 have a more uniform distribution across the seafloor and are typically more abundant than Type 3 nodules which are more scattered and less abundant in the camera imagery. For both types 2 and 3, the distribution is predominately matrix (sediment) supported, with the nodules physically separated from one another, and are thus easier to discriminate individually.

Once the nodule types were defined, boundaries between the types were mapped throughout the study area. Facies boundaries between the nodule types are often well-defined and variable over short distances (<100 m).

Nodule Coverage Derived from AUV Camera Data

Nodule type boundaries correlated very well with the box core sampling results. Ninety-one percent of the nodules mapped and sampled throughout the 2018 NORI campaign were situated at the seabed surface. These include nodules on the surface and nodules with their top surfaces in the upper 1 cm of sediment. Based on all the box core data collected, the average nodule size (long-axis) was 2.95 cm.

Photographic data acquired by the AUV enabled nodule abundance to be estimated between physical box core locations, which were spaced on a pre-defined, 7-km rectilinear sampling grid.

In areas dominated by Type 2 and Type 3 nodule facies (i.e. where nodules are not closely-packed), automated image processing techniques were used to identify each nodule unambiguously and measure its long axis and short axis dimensions.

Type 1 facies constituted the dominant nodule distribution, averaging over 900 nodules per box core sample. Due to the closely-packed nature of Type 1 nodules, the automated image processing technique adopted was unable to reliably discriminate individual nodules. It was also not practical to manually measure long-axes lengths for each nodule in every AUV photo image.

Calculation of Percent Nodule Coverage

Once the survey area was classified by facies type, a systematic approach for isolating individual nodules was established. Mosaicked AUV camera images were imported and processed using proprietary Fugro scripts developed in ArcGIS. Individual nodules (Type 2 and Type 3) or delineating the spatial coverage of contiguous nodules (Type 1) were converted into polygon shapefiles, and the data were clipped to a 3 m by 3 m area every 100 m along the survey lines as representative locations across the extensive survey area. The percentage of nodule coverage was then calculated per subset location using the area of nodule coverage and the area of each polygon. For example, a 9 m^2 area polygon with nodule area of 7 m^2 would have 78% nodule coverage.

Calculation of Individual Nodules

Due to the contiguous nature of Type 1 nodules, it was not feasible to map individual nodules over the entire study area using the automated processing techniques. Individual Type 2 and Type 3 nodules (which are typically larger and isolated) were mapped inside the representative subset locations every 100 m. The area, perimeter, long axis, and short axis measurements of the individual nodules were calculated in ArcGIS, and subsequently exported to spreadsheet format for further statistical analyses.

Nodule Abundance Estimation

Photographic methods can be used to estimate nodule abundance. A key feature in the vertical distribution of nodules in the CCZ is that the majority appear to be located either on the seafloor or immediately below it (e.g. Felix, 1980). Techniques such as the Felix Method, used to derive the individual nodule weight estimation, rely upon measurement of the long-axes of individual nodules based on photo imagery. The nodule abundance is then derived by dividing the cumulative estimated weight of individual nodules by the image area. Whilst this approach can be used for estimating nodule abundance for Type 2 and Type 3 facies, it is not possible to adopt this method for Type 1 nodules, due to the difficulties in reliably discriminating individual nodules for this facies in the AUV camera imagery. Several nodule abundance estimation techniques were tested and an alternative methodology was developed using a combination of long-axis measurement and percentage nodule coverage.

A multiple linear regression (MLR) relationship using percentage nodule coverage and mean nodule long-axis measurement derived from AUV camera imagery for six Collector Test Site box core sample locations was found to provide a good correlation between estimated and actual nodule abundance.

The percentage nodule coverage was determined by thresholding the image and calculating the percentage area covered by nodules (versus matrix) in the image. Individual nodule long-axes were manually measured where possible, for each nodule in the image, using Image-J, an open-source image processing toolbox.

Measurements were obtained to calculate representative mean long-axis lengths in the photographs which compared favourably with the mean long-axis measurements from the actual box core samples. Because calibrated images were not taken at the exact box core sites (due to loss of the camera laser-calibration system mounted on the box corer), 1 m by 1 m subsets of the closest calibrated AUV camera data were used for this analysis. Extracted AUV camera imagery was within an average offset of 15 m from the selected box core sample locations. The offsets will have introduced some imprecision to the analysis and it is expected that future co-located photographs and box core samples will produce a better correlation.

The MLR method was applied to the entire box core data set with associated AUV camera imagery (a total of 29 box cores used, with an average of 228 nodules measured per image) to derive a more representative relationship using all available data. An acceptable correlation with an R^2 of 0.62 was obtained comparing estimated to actual nodule abundance.

Within the Collector Test Site, nodule abundance estimates were derived for each of the AUV camera transect intersection points, resulting in a 3.5 by 3.5 km grid of nodule estimation points over the Collector Test Site. These estimates were used to supplement the Mineral Resource estimate.

Conclusions

- Using high-resolution AUV camera imagery and image processing techniques, it is possible to define nodule types and estimate nodule abundances between physical sample site locations.

- Due to the closely-packed nature of Type 1 nodules, automated image processing techniques are currently unable to reliably discriminate each individual nodule. Future improvements could potentially be realised through the application of Machine Learning techniques.

- Geophysical data acquired by the AUV, together with the seabed sampling in the NORI Area D resulted in defining measured and indicated resources of 4.4 million tonnes and 33.7 million tonnes respectively. Importantly this validated the sampling and resource methodology implemented by NORI and resulted in a 51% increase in resource tonnage when compared with the previous inferred resource estimate for the same area.

Disclaimer

The purpose of this abstract is for consideration for selection for oral presentation at the 2019 Underwater Mining Conference and should not be used for any other purpose.

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participants during the offshore survey and others in Houston and Lafayette at Fugro for shore-based support.

Keywords

AUV, geophysical data, GIS, CCZ, polymetallic nodules, nodule abundance, resource estimation, AUV camera, image processing, Felix Method

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APEIs: Some thoughts about designation for crusts and sulphides

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Abstract

Active development of the exploration and further exploitation of deep-sea minerals requires special emphasis on the protection of the marine environment both by the Contractors and by the regulator body – the International Seabed Authority.

In accordance with article 145 the Convention, and with respect to activities in the Area, the Authority is mandated to take the measures necessary to ensure effective protection for the marine environment from harmful effects and to adopt appropriate rules, regulations and procedures for, inter alia, the prevention, reduction and control of pollution and other hazards to the marine environment, the protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna of the marine environment.

One way of the fulfillment of this mandate and implementation of the precautionary approach as well is development and adoption of the Regional Environment Management Plans (REMPs) for key provinces where exploration activities under contracts are carrying out.

In 2012, the Council approved an Environmental Management Plan for the Clarion-Clipperton Zone (CCZ) [ISBA/18/C/22] on the basis of recommendations made by the Legal and Technical Commission [ISBA/17/LTC/7].

At present, a work on the development of such plans for the Mid-Atlantic Ridge and the Indian Ocean (for polymetallic sulphide deposits) and for the North-West Pacific (for

cobalt-rich ferromanganese crusts) is started. Relevant workshops took place in 2018 in Szczecin, Poland, and Qingdao, China. A series of new ones is scheduled in the near future.

One of the key spatial (area-based) management tools for implementation of the REMPs is a designation of special protected areas - the Areas of Particular Environmental Interest (APEIs).

In case of the CCZ faunal communities vary from north to south and from east to west. For that reason, the Zone was divided into three east-west and three north-south strata, and for each of nine resulting subregions its own area of particular environmental interest with dimensions 400 x 400 km (the 200 x 200 km core area surrounded by a 100 km buffer zone) was designated [ISBA/17/LTC/7].

Ecosystems of seamounts and polymetallic sulphide deposits are fundamentally different from ecosystems of nodules provinces as from their size and three-dimensionality to variability of faunal communities. Combination of hydrothermal vent fauna and background fauna colonizing inactive deposits, dependence on a depth, presence of hard substrate, mosaic distribution and dissimilarities of sites are features of communities of polymetallic sulphide deposits [Boschen et al., 2013]. Dependence on a depth, impact of local hydrography and currents, hard substrate, discontinuous and patchy nature, large variations between different seamounts are characteristics of crusts communities [Pitcher T.J. et al. (eds), 2007].

Based on the above, designation of the APEIs for crusts and polymetallic sulphide deposits need another approach distinct from the one that applied for the CCZ.

In our study we tried to analyze the known patterns of faunal distribution for areas of crusts and polymetallic sulphide distribution and find some ideas about possible varies of the APEIs system.

One of such varies would be to create a network of local small-scale APEIs instead of huge ones, as in the CCZ. It allows to “catch” localized peculiarities and therefore would meet the objectives of representativeness and preservation of the marine environment. In addition, it would be rather flexible management tool that could be realizable in conditions when there are not enough large spaces "free" of exploration contracts.

The proposed change of the principle underlying the designation of the APEIs for seamounts and polymetallic sulphide deposits in the way of local small-scale areas as opposed the nodule-bearing provinces with their vast APEIs needs to be further developed. We're assuming that it could be a good solution allowing to reconcile the goal of protection of the marine environment and interests of contractors.

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Keywords: Regional Environment Management Plans (REMPs), Areas of Particular Environmental Interest (APEIs).

Livia Ermakova

Livia Ermakova works in the Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia) as oceanographer and lawyer. Scientific interests: oceanography of the Atlantic Ocean; environment and oceanography of Russian Exploration Areas on polymetallic sulphides, polymetallic nodules and cobalt-rich ferromanganese crusts; environmental issues and legal regulations of exploration and exploitation of deep-sea minerals.

HOMESIDE – An Advanced Tool for Hydrothermal Plume Hunting and Polymetallic Sulphide Exploration 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 took place in 1964, followed by several state-sponsored research cruises between 1983 and 1995 (GEMINO, HYDROTRUNC, HYDROCK) leading to the first finding of polymetallic sulphides in the Indian Ocean. The research included regional environmental investigations, particularly oceanographic and sedimentary base line studies. In 2010, BGR took the initiative for the preparation of an exploration claim for polymetallic sulphides, and prospecting started in 2011. After three years of resource-oriented and environmental base line studies, BGR applied for an exploration license, the contract with the International Seabed Authority (ISA) was signed in 2015 (Fig. 1). The exploration program will continue until 2030 with an option on five years extension.

To identify, locate and visualise economically feasible occurrences of Seafloor Massive Sulphides (SMS) along the Central Indian Ridge (CIR) and the Southeast Indian Ridge (SEIR), BGR developed the deep-towed multi-sensor platform HOMESIDE in 2015 (Fig. 2). Here we present some techniques of the exploration methods for active and inactive SMS.

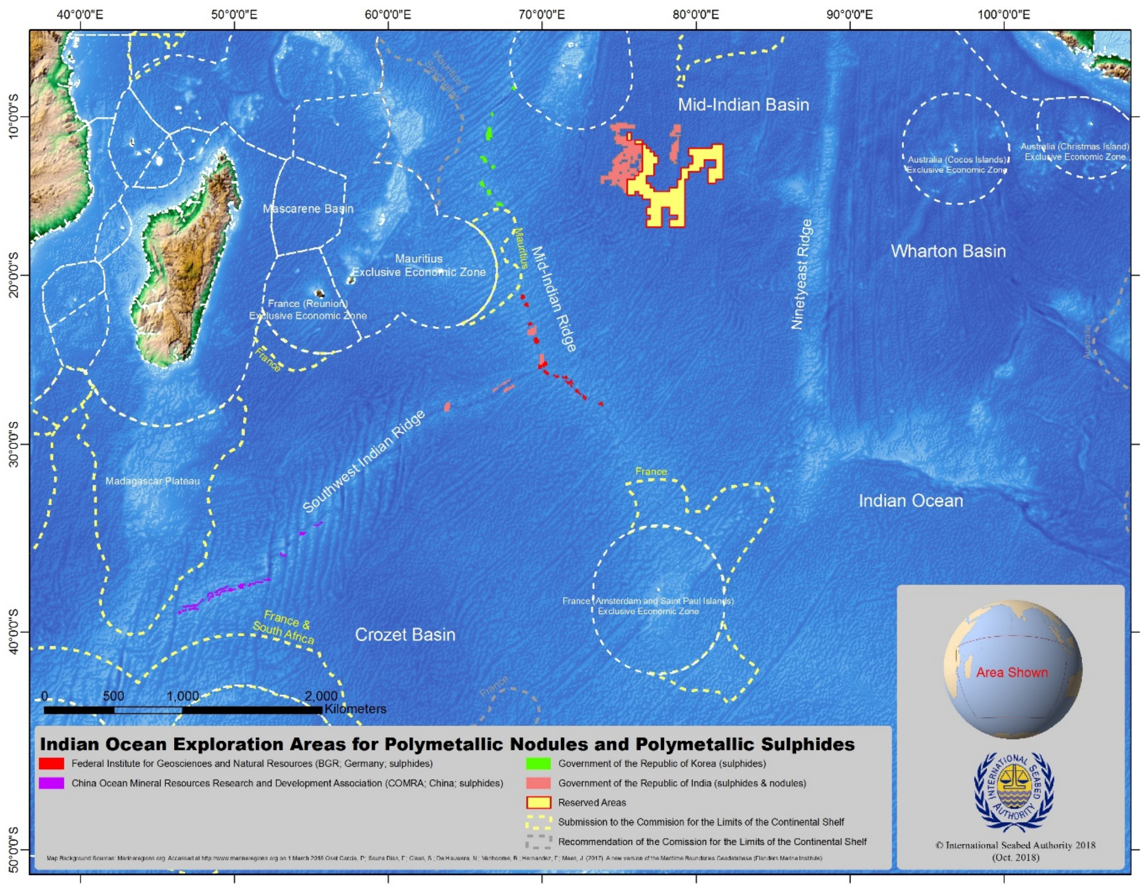

Fig. 1: Exploration areas of ISA contractors in the Indian Ocean.
(https://www.isa.org.jm/contractors/exploration-areas)

HOMESIDE

HOMESIDE is an acronym for the German term "**HO**chauflösendes **M**ultibeam-**E**cholot und **SI**descan **DE**pressor". It is a towed system for acquiring high-resolution multibeam bathymetry in a water depth up to 6000 m. Bathymetry resolution is very high (few cm) and the vessel requirements are low (except of a fibre-optic tow cable). The tool is easy to handle during deployment and recovery.

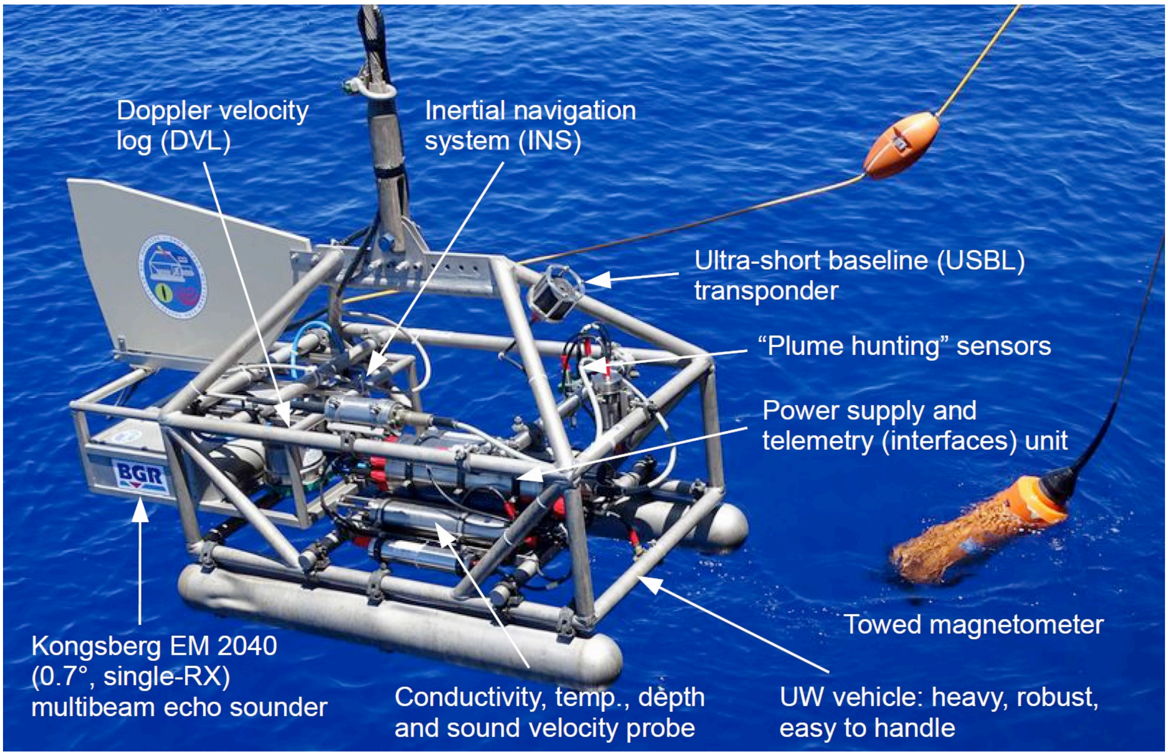

Fig. 2: BGR-HOMESIDE underwater vehicle: Main components.

Beside the bathymetry, HOMESIDE can acquire Water Colum reflections and can be equipped with several sensors as needed. For SMS exploration in the Indian Ocean, the integration of a magnetometer and a self-potential measurement array is standard, as well as sensors for retrieving physico-chemical parameters of the seawater like turbidity, redox potential, pH, temperature pressure and conductivity. Video, still cams and lights might be attached if needed.

The main advantages of the system are the unlimited deployment time (compared to an AUV) and the online control and availability of all acquired data. In addition, the "open" construction of the telemetry and interfaces allows for continuous improvements.

Inactive SMS sites are locatable by the shape and surface texture of the mounds, magnetic signature and their self-potential signal. Active sites are much easier to find as they are traceable by a relatively large plume and show typical edifices (“black smoker”). Nevertheless, the target size of the polymetallic sulphide mounds is much smaller than the resolution from shipborne bathymetry. The comparison (Fig. 3) between a “state of the art” Multibeam System (like Kongsberg EM122) in 3500 m water depth and our deep-towed system clearly reveals the benefit in resolution and information.

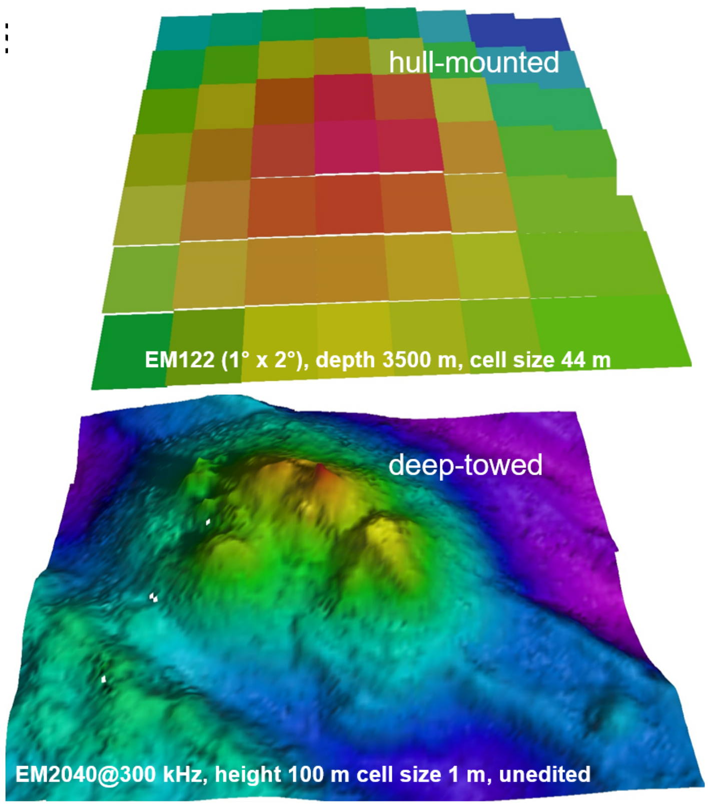

Fig. 3: Comparison of ship-borne (upper) and deep-towed (lower) multibeam bathymetry from the same area. Resolution of shipborne bathy is not sufficient to identify SMS. The lower image clearly shows a SMS mound and with several black smokers sitting on the top and the flanks (PENUMBRA main site, 2018).

In addition to the high-resolution mapping, the system is capable to obtain reflections of the ensonified water column. With a special data treatment, it is possible to extract the water column reflections and visualize them in 3D. Furthermore, it is possible to distinguish the reflections by amplitude, which gives us information about the acoustic attenuation properties of the hydrothermal plume. Additional information about near-bottom currents could be retrieved from the shape of the plume (Fig. 4).

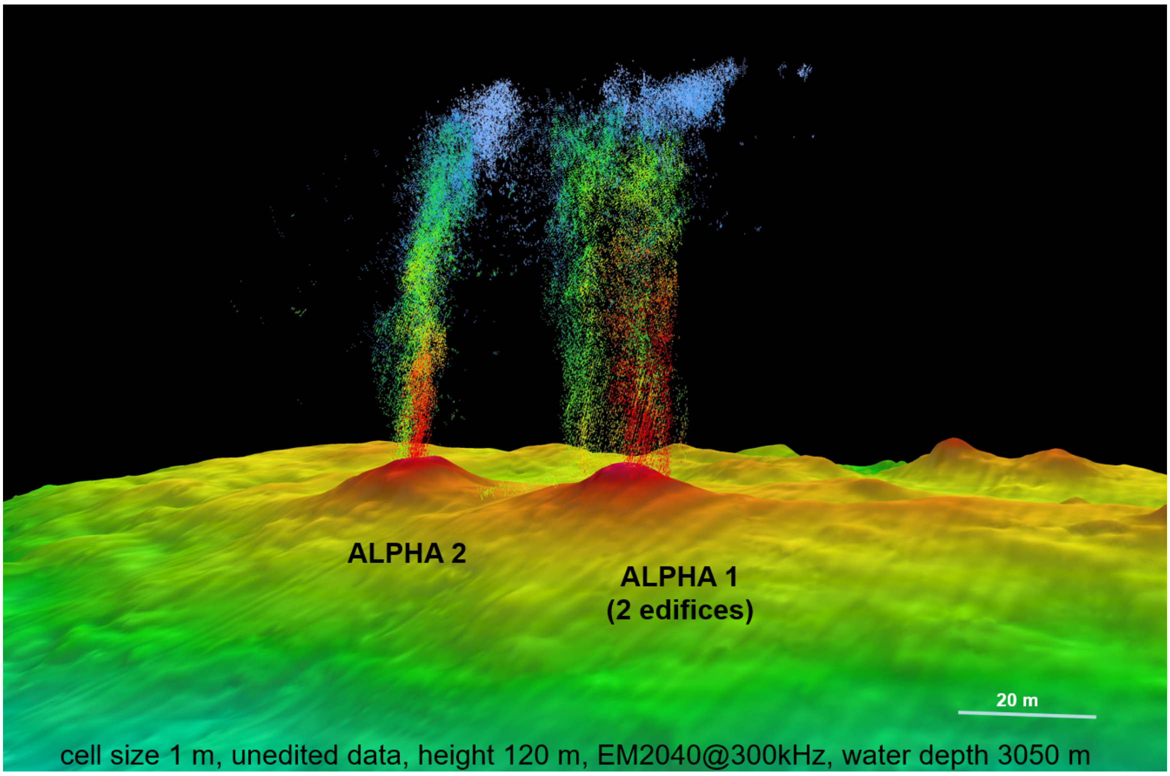

Fig. 4: Extracted water column reflections caused by a hydrothermal plume. The water column reflections are color-coded by attenuation and draped on a high-resolution bathymetry map (ALPHA area 2015 and 2017).

Keywords: Multi-beam, bathymetry, exploration, seafloor massive sulfides, hydrothermal plume

Ralf Freitag

After studying Geology/Paleontology in the early 1990s at University Heidelberg and University Kiel with emphasis on structural geology, I changed to the German research Centre for Geosciences (GFZ). Focusing on accretionary processes at convergent margins, I achieved PhD degree for research in Kamchatka and the Andes. After eight years of assistant professor at University of Jena starting to deal with divergent margins, I changed to the Federal Institute for Geosciences and Natural Resources (BGR) in 2011 to work in the Polymetallic Sulfide Exploration project.

Seafloor sulfide mineral deposition and remobilization

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Abstract

Element mobility is the defining feature of seafloor hydrothermal deposits, occurring from the onset of high temperature water-rock interactions, through eventual inactivity and burial. Metals that are mobilized by high temperature fluids at hydrothermal vents may precipitate in the subseafloor, at the seafloor surface as sulfide deposits, or be transported with ocean water in hydrothermal plumes, eventually being deposited in sediments or dissolving into the larger ocean basins. Factors controlling the location of sulfide mineral precipitation include the heat source, the initial chemistry of the fluids, as well as the rate of cooling and mixing with seawater. Although models for mineral saturation exist, recent research demonstrates that poorly understood processes, such as nanoparticle precipitation and colloidal transport can influence the location and timing of metal precipitation[1] and thus predictions of local element enrichment.

Even after deposition from hydrothermal fluids, element mobility within hydrothermal systems continues as sulfide minerals are unstable in contact with oxygen, which permeates deep-ocean water in varied concentrations. Whether the oxidation that occurs as a result of sulfide mineral aging remobilizes the metals within the sulfide minerals, or just changes their mineralogical environment, depends on the mineral in question and the oxidative process it undergoes. An understanding of metal remobilization and loss from oxidizing

sulfide deposits can be gained through integrating experimental results with studies of modern and ancient seafloor deposits. I will discuss element transport in hydrothermal sulfide environments as it leads to mineral formation, local deposition, and transport, as well as element mobility in aging hydrothermal deposits.

[1]Gartman A., Hannington M., Jamieson J.W., Peterkin B., Garbe-Schönberg D., Findlay A.J., Fuchs S. and Kwasnitschka T. (2018) Boiling-induced formation of colloidal gold in black smoker hydrothermal fluids. *Geology* **46**, 39-42.

Keywords: Seafloor massive sulfides, hydrothermal, oxidation, metal mobility

Amy Gartman

Amy is a Research Oceanographer studying marine minerals 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 minerals with an emphasis on metal sulfides and the role of nano-scale processes contributing to element fluxes. She has been a member of the U.S. delegation to the ISA as a scientific advisor since 2016.

Global Tonnage of Marine FeMn Nodules, Crusts, and Associated Metals: Comparisons with Terrestrial Resources

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Abstract

Many comparisons have been made for critical and base metals between global land-based reserves and global marine-based resources. This is not an informative comparison because marine reserves for these metals are not known. Comparisons between terrestrial reserve base (TRB)* and marine metal resources is also not adequate and those terrestrial data have not been compiled since 2009 (USGS, 2009). A better comparison for resource and metal tonnages is between terrestrial resources, which include known and inferred deposits, and marine deposits. The terrestrial resource for many elements has not been determined and in those cases TRB can be used as a minimum estimation. The marine deposits of consideration are predominantly ferromanganese (FeMn) crusts plus nodules, as seafloor massive sulfides (SMS) by comparison do not add significantly in critical and base metals to the total tonnages. This may change when tonnage estimates for extinct and undiscovered SMS systems can be determined. Marine FeMn-oxide crusts and nodules acquire vast quantities of rare, critical, and base metals from ocean water and also from pore water of sediment for some nodules. These oxide deposits control the concentrations of some elements in seawater, (e.g. Ce, Te) but the full extent of this sequestration and its contribution to the potential metal budget of marine oxides in the global ocean is not known. To partly address these issues, we estimated the total tonnage of crusts and nodules in the global ocean based on the known and inferred distributions, area of

permissive occurrence, crust thickness or nodule coverage, and dry bulk density. Crusts and nodules are estimated to have similar total estimated tonnages of $12x10^{10}$ dry metric tons, and $20x10^{10}$ dry tons respectively, for a combined total of $32x10^{10}$ tons. This estimate indicates that typical crust- and nodule-hosted elements (i.e. Mn, As, Bi, Co, Cu, Li, Mo, Nb, Ni, PGM, REE, Sb, Sc, Te, Th, Ti, Tl, V, W, Zr) are more abundant in crusts+nodules than in the TRB. Enrichment factors (EF) for marine mineral estimates over TRB values vary from 2.1 for Cu to 13,600 for Tl. Tl, Sc (EF 2500), Te (129), Y (89), Co (70), and As (41) are especially high in marine deposits and can be considered marine mineral deposit-dominant metals. The global terrestrial resource is known for Cu, Co, Mo, Li, PGM, Th, Ti, Tl, V, and Sc (USGS 2018, 2019); using these larger terrestrial metal tonnages, which are more appropriate than TRB, only Cu (EF 3.6), Li (EF 2.9), and PGM (EF 1.2) become terrestrial mineral deposit-dominant elements. These estimates clarify the importance of marine minerals as a potential resource and metals to target. *Terrestrial Reserve Base include resources that are currently economic (reserves), marginally economic, and sub-economic (USGS, 2009).

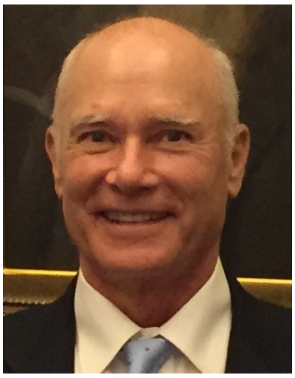
USGS 2009 Mineral Commodity Summaries 2009. U.S. Geological Survey, 195 p.

USGS 2018 Mineral Commodity Summaries 2018. U.S. Geological Survey, 200 p., https://doi.org/10.3133/70194932

USGS 2019 Mineral Commodity Summaries 2019. U.S. Geological Survey, 200 p., https://doi.org/10.3133/70202434

Keywords: global mineral tonnages, critical metals, base metals, marine-dominate metals, terrestrial-dominate 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 (twice) 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.

Development and Testing of a Hydraulic Nodule Collector while minimizing its Environmental Impact, Preliminary Results of Discharge Experiments (Blue Harvesting project)

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Introduction

One of the main challenges for deep-sea mining to minimize its environmental impact while maintaining a viable mining process. Technology development for sustainable, reliable and efficient mining of polymetallic nodules in the deep seas requires careful design, thorough understanding and integrated testing of all equipment, physical processes and systems involved (Dasselaar et al., 2018a). Within the EU H2020 program (2016-2020) Blue Nodules, the hydraulic nodule collector is tested at TRL 5. The next step will be to further develop, build and and to eventually test the hydraulic collector in an operational environment, aiming at TRL 7. The Blue Harvesting project entails the Improvement of the design, incorporating that design in a prototype and testing the new prototype both in the laboratory and in a nodule field in the deep-sea of the NE Atlantic Ocean. The Blue Harvesting project is funded by the Knowledge and Innovation Community (KIC) of EIT Raw Materials.

The Blue Harvesting consortium consists of 9 partners, from universities, research institutes and industry at various points of common interest for the development of a hydraulic nodule collector with a low environmental impact. Delft University of Technology, RWTH Aachen and Jakobs University Bremen and IHC Mining are responsible for the design optimization, development and testing of the collector, nodule separator, material detection based on acoustic emissions (AE), collector outlet and the vehicle itself. The deep-sea tests will be performed in the NE Atlantic Ocean with support of RV Sarmiento de Gamboa, operated by CSIC. This field test, the measurements and the analysis of these measurements will also be supported by the Dutch Institute for Sea Research, Aarhus University, Universitat de Polytecnica de Catalunya and Seascape Consultants.

The main objectives of the Blue Harvesting project are the following:

1. Development of a Go-To-Market strategy of deep-sea mining equipment, supporting the introduction of new products in a new market
2. Improve the design of the hydraulic collector to lower the clean water intake
3. Determine the ideal conditions in which to release the suspended sediment
4. Validation of the design and calculations through scaled and full scale laboratory tests
5. Deep-sea tests to demonstrate the performance of the hydraulic collector in a nodule field in the NE Atlantic Ocean in 2021, bringing it to TRL 7.
6. Assess the environmental performance of the hydraulic collector
7. Interact with other stakeholders, e.g. deep-sea biologists and scientists about reduction of the environmental pressures of the hydraulic collector.

Within the Blue Harvesting project, we will evaluate the design of the hydraulic collector, separator and sediment discharge (diffuser) and aim to minimize its environmental impact, while maintaining an economically viable production rate. The emphasis will be on reduction of the plume spread, as this is assumed to be the most severe environmental pressure. The generated plume might travel up to several kilometers distance from the mining activity before it has been sufficiently diluted to the background turbidity levels. See figure 1 for an overview of the typical length and time scales that are concerned with plumes (Roberts, 2013). The highest reduction of the environmental impact is expected through optimization of the mixture flows and reduction of the clean water intake, allowing to discharge the sediment at a higher concentration. In the project, all subsystems involved in the collection, separation and discharge processes will be optimized to reduce the environmental footprint of the hydraulic nodule collector.

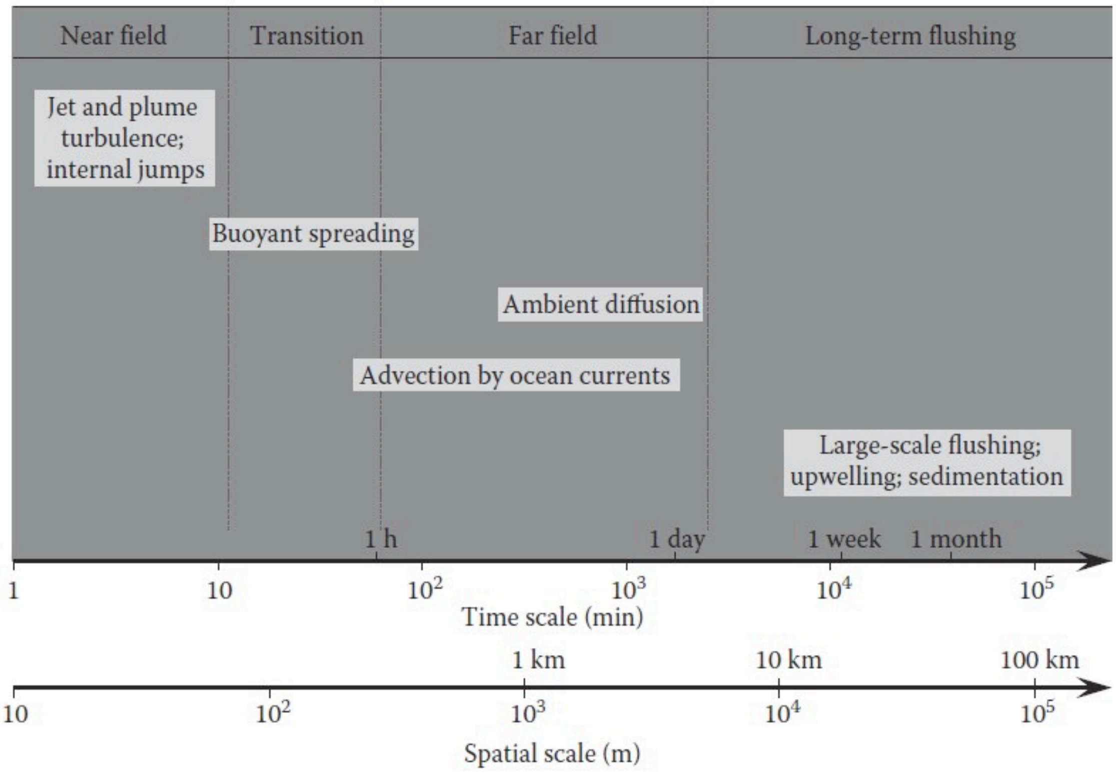

Figure 1:Main mixing zones and their corresponding length and time scales

Plume discharge laboratory experiments

Most of the processes related to plume dispersion depend on the local conditions, such as currents, sediment properties, topology, etc., aspects that we cannot influence. What we can influence is the source term of sediment plume, which depends on properties like initial momentum, concentration, shear, etc.. On the one hand, we might be able to minimize the amount of disturbed sediment through optimization of the hydraulic collector (intake). On the other hand, the design of the collector can be optimized for its sediment release conditions, aiming to minimize the plume spread and thus minimizing the affected area.

One of the options is to optimize the design of the discharge of the collector, often referred to as the diffuser. Such diffuser design optimization has been performed by IHC Mining within the Blue Nodules project (Dasselaar et al. 2018b). Horizontal plume dispersion experiments have been conducted by IHC Mining and Delft University of Technology. The main goal of these experiments is to simulate various sediment release conditions in a controlled laboratory environment, in order to quantify the near field performance of the released sediment plume for numerical model validation. The emphasis is on the settling response of the particles in the plume. The effect of ambient currents or transport of the collector vehicle is not studied within these experiments. Within this laboratory study, the aim is to visualize the plume trajectory and to measure velocity and concentration profiles along the centerline of the plume, at various distances with respect to the discharge position.

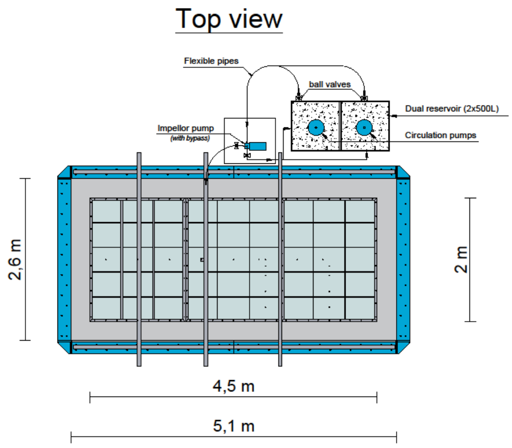

Figure 2:Top view of experimental setup

The rectangular tank with glass panels at the Dredging Laboratory of Delft University of Technology is used. For these experiments, the setup as used for the initial spreading of vertical turbidity plumes is used (van Grunsven, 2018). This flume measures 5.0 m in length, 2.5 m in width and 2.0 m in height. With a geometric scaling factor of 1:15, this would represent a volume of 75x37.5x30 m behind the mining vehicle. On the bottom of the tank, a large table measuring 4.5 x 2.0 m is placed to represent a simplified seafloor. This table is also equipped with LED-strips to provide lighting for visualization of the experiments. See figures 2 and 3 for an overview of the experimental setup.

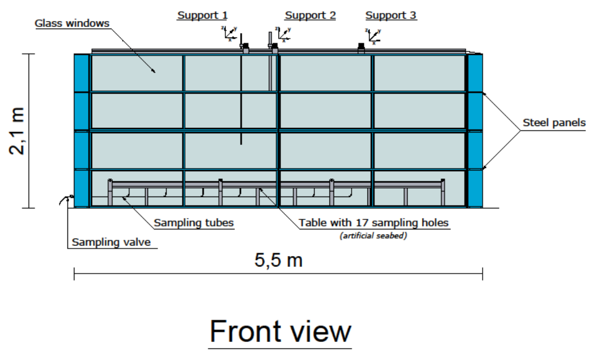

Figure 3:Front view of the experimental setup (glass windows)

A reservoir next to the tank is used to prepare the mixture of sediment and water that is to be discharged through the diffuser. The used sediment consists of fine glass beads with particle sizes in the range of 65-105 micron and these particles cannot flocculate. These particles are relatively large compared to the typical particle size found at nodule sites in the Clarion Clipperton Zone. However, these particle sizes are necessary for the experiments to allow for a sufficient amount of particles to be settled before the sediment plume hits the back of the tank and reflect (Lee et al., 2013) . Inside the mixing tank, multiple pumps are used to assure that the particles remain in suspension and are well mixed. A pump is added after the reservoir to pump the mixture through a flexible hose to the diffusers into the flume. The setup of the diffusers is shown in figure 4. The photographs in figure 5 give an impression of the plume generated in the experiments.

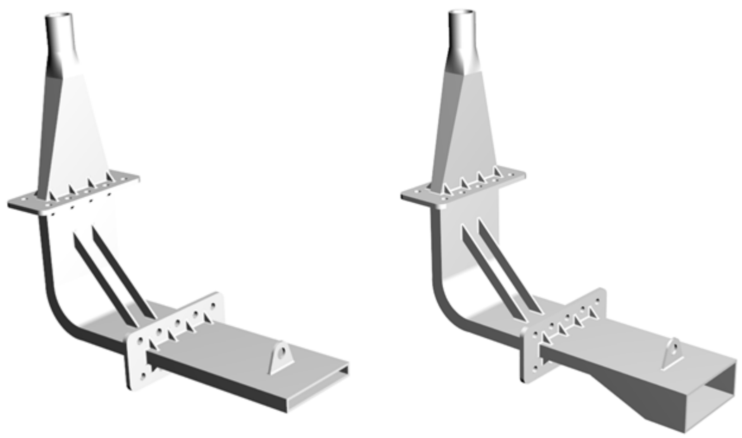

Figure 4:Three diffuser setups that are tested.

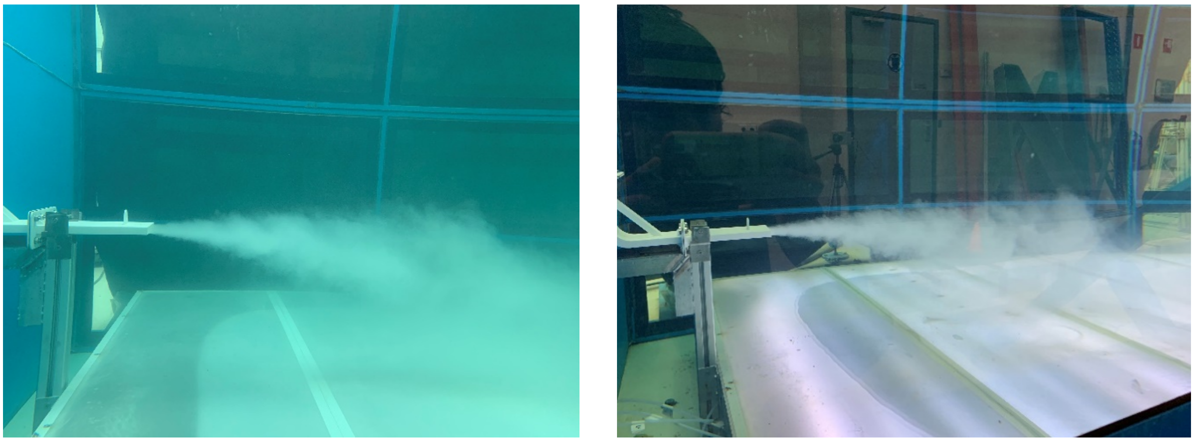

Figure 5:Example of a plume dispersion experiment

Concentration measurements are based on two measurement principles. 1) via 18 flexible sampling tubes connected along the centerline of the table, the turbidity current can be drained when passing with a sampling valve at the side of the flume. These samples are analyzed with an infrared turbidity sampler. 2) Optical Back Scatter sensors are used to generate concentration profiles (height) at various distances to the discharge. An additional OBS sensor is placed in the mixing tank next to the entrance of the flexible hose, assuring that we know what concentration is provided at the diffuser. An Acoustic Doppler Velocimetry profiler is used to measure velocity profiles along the centerline of the table, also at various distances to the diffuser.

The results obtained are useful for confirmation on the design of the diffuser, provides insight on the run-out length of the plume and to what extent it loses its mass along the length. Furthermore, video material and the velocity and concentration profiles can be used to support validation of the numerical plume dispersion models.

Acknowledgements

This work has been supported by and has received funding under 1) Blue Harvesting, supported by the European Union's EIT, EIT Raw Materials and has received funding under Framework Partnership Agreement No [FPA 2016/EIT/EIT Raw Materials], Specific Grant Agreement No. [EIT/RAW MATERIALS/SGA2019/1], project agreement 18138, 2) Blue Nodules, supported by European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 688975 and 3) the Netherlands Organization for the Advancement of Science (N.W.O.) under "Environmental Impacts and Risks of Deep-Sea Mining" of the JPI Oceans Project "Mining Impact II".

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Keywords: polymetalic nodules, turbidity, diffuser, plume generation, environmental impact

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. In 2012, Rudy started his PhD research in the Dredging Engineering group of the Delft University of Technology. 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. Currently, Rudy is employed there as Assistant Professor for Subsea Engineering and Deep-Sea Mining. He is also the project coordinator of the EIT Raw Materials Upscaling project ‘Blue Harvesting’. His main research interests are related to seabed interactions, e.g. excavation processes for sand, clay and rock, and the dispersion of turbidity plumes.

Hazards and Risks in Deep-Seabed Mining

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Abstract

Hazards and risks in deep-seabed mining (DSM) are linked with the concept of mining operation. Sustainable DSM requests that the intrinsic hazards are resolved and the associated risks are reduced by a proper concept of mining operation, development of technologies, utilization of proven technologies, and application of industrial standards, and so on.

Functional requirements for DSM is the fundament of mining operation concept. The functional requirements (FR) are expressed in form of a hierarchy structure, which shows relationships between various functions required to achieve comprehensive performances of DSM. The most important requirements are *annual production*, *safety* and *sustainability*.

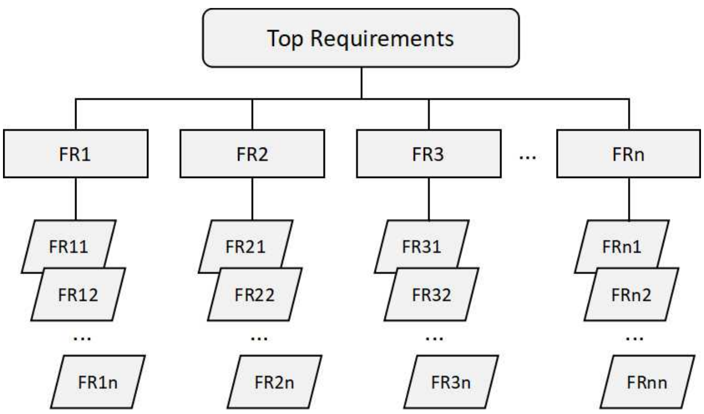

Figure 1 Hierarchy of functional requirements

The functional requirements for deep-seabed mining could be described as in Table 1, where FR are limited within three levels and the third level is expressed by representative feature.

Table 1: Functional requirements for deep-seabed mining

Level 1	Level 2	Level 3
To be capable of eco-friendly collecting ores from seafloors into buffering station	Moving on seafloors along designed paths	Automatic or remote control
	Dredging the ores from seafloors	Automatic or remote control
	Fragmentizing the dredged ores	Optimum fragmentizing of ores
	Discharging the fragmented ores to buffering station	Prevention of congestion/clogging
	Reducing the disturbances of benthic zones	Prevent excessive disturbances
To be capable of safe and effective vertical transportation of the collected ores to sea surface	Conveying the discharged ores into buffering station	Preventing clogging
	Optimum operation of vertical lifting system	Optimum design of lifting system
	Maximizing the mass flow rate of ore transportation	Feeding control of ores
	Avoiding failures in vertical transportation	Preventing overloading
To be capable of ore-seawater separation and of eco-friendly tailing	Separation of seawater matching with pump flowrate	Multi-stage separations
	Treatment of separated seawater to allowable criteria	Satisfaction of eco-criteria
	Eco-friendly tailing of treated seawater	Injection below thermocline depth
To be capable of storage and offloading of the separated ores	Conveying the separated ores into cargo holds	Loading procedure
	Storage management of the ores in cargo holds	Prevention from agglomeration
	Offloading ores to ore-carriers	Offloading with mining operation
To be capable of supporting the underwater mining operations	Launching and retrieval of underwater systems	Heave compensation, automation
	Power generation, supply and control	Maximizing efficiency
	Dynamic positioning relative to underwater systems	DP2-Class
	Maintenance and repairs	Regular inspection procedures
	Underwater navigation and tele-communication	High-precision, real-time comm.
	Provision of accommodation, foods, and fresh water	Two-shifts system

Hazard identification and risk assessment are needed prior to the development of not-existing (or unproven) technologies. Role and responsibility of experts group is utmost critical in this phase. Various kinds of design and analysis schemes, and concerned field experiences are required in order to find appropriate means and measures for reduction of risks and damage.

Qualitative description about hazards and risks is followed by risk assessment identifying levels and scopes of risks and damages. Table 2 is a qualitative descriptions of hazards and risks of a continuous mining scenario based on hydraulic lifting.

Table 2: A general description about hazards and risks in deep-seabed mining

Activity	Hazards	Risks	Damages
On-board operation	Handling heavy weights: moving, hanging	- Collision and/or drop accidents - Damage(s) of equipment - Mortality and/or injury accidents	Loss of costs and time
	Repeated launch-and-retrievals of underwater system	- Connection/disconnection failures of pipe units and cables - Loss of underwater system(s) - Damage(s) of equipment - Mortality and/or injury accidents	Loss of costs and time
	Use of high power capacity equipment and systems	- Power interruption or overload - Damage(s) of equipment and/or system - Fire and/or explosion accidents - Mortality and/or injury accidents	Loss of costs and time Environmental impact
	Necessity of a large number of various signals for communication and control	- Loss of signal(s) - Stop of mining operation - Damage(s) of equipment - Loss of system	Loss of costs and time
Collecting	Moving on soft and sticky sediment seafloor	- Excessive digging and penetration into sediments - Reduction and/or loss of mobility and production rate - Damage or loss of machine - Total stop of mining operation	Loss of costs Increase of down-time Environmental impact
	Dredging nodules half-buried in sediments	- Loss of dredging capability - Over-dredging - Reduction of production rate - Excessive generation of plumes	Loss of costs Environmental impact
	Necessity of crushing nodules	- Crushing failure - Clogging in collector - Damage of crusher/collector - Total stop of mining operation	Loss of costs Increase of down-time
	Necessity of discharging dredged nodules to prevent over-weight of collector	- Discharging failure - Clogging in collector - Clogging in flexible conduit - Total stop of mining operation	Loss of costs Increase of down-time
Lifting	Necessity to support the total weight and tension force of free-hanging lifting pipeline	- Failure of lifting pipeline - Loss of underwater system(s) - Damage of mining vessel - Total stop of mining operation - Mortality or injury accidents	Loss of costs and time Environmental impact
	Continuous vertical transportation of slurry through lifting pipeline	- Pipe and/or pump clogging - Damage of pump station(s) - Total stop of mining operation	Loss of costs and time

	Use of high power underwater pump stations	- Electric shortage - Occurring of water hammering - Damage and failure of pump station(s) - Total stop of mining operation	Loss of costs and time Environmental impact
Positioning	Keeping positions in harsh environmental conditions	- Failure in DPS - Total stop of mining operation - Damage and/or loss of underwater system - Damage of mining vessel (derrick)	Loss of costs and time Environmental impact
	Dependent on GPS and underwater localization system, and signal delay	- Irrelevant positioning - Decrease of production rate - Damage of flexible conduit and umbilical - Damage and/or loss of collector	Loss of costs and time Environmental impact
On-board treatments	Massive transportation of ores-seawater-sediment mixture	- Clogging or overflow in ores-seawater separation - Flooding of mining vessel - Total stop of mining operation - Damage of on-board facility - Accident of lives	Loss of costs and time Environmental impact
	Massive seawater amount to be treated	- Overflow in seawater treatment - Flooding of mining vessel - Total stop of mining operation - Damage of on-board facility - Accident of lives	Loss of costs and time Environmental impact
	Necessity of sediments separation from seawater	- Overload in sediment-caking [optional] - Delay of mining operation - Damage of on-board facility	Loss of costs and time Environmental impact
	Massive tailing amount to treat	- Overload and/or failure of tailing treatment - Flooding of mining vessel - Total stop of mining operation - Damage of on-board facility - Accident of lives	Loss of costs and time Environmental impact
	Dumping out tailing below thermocline water depth	- Loss of power for tailing treatment - Failure of tailing pipeline - Total stop of mining operation	Loss of costs and time Environmental impact
	Repeats of loading and offloading operations of huge amount of nodules in wet-and-dirty condition	- Congestion in ore storage - Agglomeration of ores in cargo holds - Delay and/or failure of offloading - Stop of mining operation	Loss of costs and time

The functional requirements, the hazard identification and the risk assessment, as well as the subsequent concept design are interrelated so that *iterative procedure* is inevitable until all kinds of risks are estimated as acceptable. Various and diverse kinds of countermeasures are required to reduce and manage the risks below certain levels.

Keywords: Deep-Seabed Mining, Functional Requirements, Hazards, Risks, Damages

Sup Hong

Dr. Sup Hong is a principal researcher at Korea Research Institute of Ships and Ocean Engineering (KRISO). He majored in Naval Architecture and Offshore Engineering at Seoul National University receiving Bachelors (1983) and Masters (1985) degrees. He holds a Doctorate for offshore engineering from Technical University of Aachen (1992). Since 1993, he has worked in the research field of deep-sea engineering. The main research focus is on development of deep-seabed mining technology. Based on the research and development works over past 20 years, his current interest is focused on sustainable mining of deep-seabed minerals.

Sustainable development of Mineral Resources in the Area

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Abstract

The International Seabed Authority (ISA) was established under the United Nations Convention on the Law of the Sea (UNCLOS) 1982 and the 1994 Agreement relating to the Implementation of Part XI of the UNCLOS. This year ISA is celebrating its 25th anniversary. The ISA now has 167 States + the European Union as members.

Since its establishment, the ISA is engaged in adopting rules, regulations and procedures for prospecting and exploration for mineral resources in the Area, namely polymetallic nodules (PMN), polymetallic sulphides (PMS) and cobalt-rich ferromanganese crusts (CFC). These regulations include *inter alia* regulation on prospecting, protection and preservation of the marine environment, contractors rights and obligations (such as submission of annual reports including data and information), size of the area and relinquishment, periodic review of the implementation of the plan of the work for exploration, standard clauses of exploration etc.

The ISA has issued twenty-nine contracts for the explorations, involving 20 contractors – 17 for PMN, seven for PMS and five for CFC. A new application for PMN was reviewed during March 2019 session. If approved, it will become the 30th contract.

In 2015, ISA has adopted standards for mineral exploration results assessments, mineral resources and mineral reserves. These standards are based on 2013 edition of the CRIRSCO (Committee for Mineral Reserves International Reporting Standards). These developments

indicate a transition from marine scientific research, towards commercialization of the discovered ore deposits. The classification of ore reserves implies that technology is available to mine the deposits and process the material into metals of interest and to have assessment of the mineable ore reserves in-situ.

Since 1978, when Ocean Management Incorporated (OMI) conducted a pilot mining test in the Clarion-Clipperton Zone (CCZ), and raised 800 tonnes of nodules to its mining ship; this is now that few contractors are ready with testing of renewed prototypes equipment or its components. In addition to proving their technology, such tests will provide contractors (and ISA) with information on the efficacy of the technologies they have developed, assessment of mineral reserves and assessment of impact on marine environment.

ISA is drafting a mining code for polymetallic nodules. Along with the development on drafting of mining code, it is also revising/developing recommendations and guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area to the environment.

The time now appears a new phase in the deep seabed mining industry. The demand for metals in the market and profitability of mining would perhaps determine the fate of the emerging industry.

Keywords: ISA, Mineral Resources, Seabed, Regulations, Emerging industry

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Disclaimer: The views expressed in this paper are of author's and do not necessarily reflect the views of the International Seabed Authority or any of its member States.

Pratima Jauhari

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.

She has several publications in peer reviewed journals, technical reports and popular scientific articles including a book in Hindi language. She has participated in several oceanographic cruises and spent about 800 days at sea.

Since 2013, she is employed with the International Seabed Authority, an UN entity seated in Jamaica.

Can Patents be considered part of the Common Heritage of Mankind?

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INTRODUCTION

Patents, e.g. on inventions of environment friendly mining methods and/or devices, may stand in the way of an exploitation of the ocean floor and subsoil without hindrance from individual interests. The presentation examines whether it would it not be appropriate to accord respective patents a status commensurate with the one given to the Area, namely Common Heritage of Mankind, even if innovation in sustainable mining would deserve substantial encouragement and thus call for “full patent strength”.

Challenging the signature feature of the patent as a monopoly, the presentation starts out by examining several examples of reduced patent strength in other areas, where, as it seems, the public expects freedom unimpeded by patents, such as open source software (OSS); fair, reasonable and non-discriminatory (FRAND) obligations to license patents on generally recognized publicly backed standards (e.g. cellphone); freedom of the high seas preventing acts of national legislation (which also may be patent enforcement).

Going on to take a closer look, the author notes that each of these examples, rather than allowing full freedom of action, comes with a set of rules which must nevertheless be complied with to enjoy the “freedom”. A view into how the applicable (and pending) regulatory frameworks, such as UNCLOS, the ISA draft exploitation rules, or even the BBNJ ILBI, deal with patents in the DSM context, reveals some reluctance to decide: Having the “established practices” govern patent use, may include a lot of different approaches.

The author takes the view that given the high concern for environmental safety accompanying the emergence of DSM, the creator of innovative solutions in this field should be substantially incentivized. Deviating from existing models, the solution is offered to allow the patent holder full enforceability of his patent in this field, as far as he can serve the markets and maintains the (always national) patent protection. However, for markets he probably cannot reach, it is proposed that he be obligated to grant royalty-free licenses to him who proves he can, and that only if the holder develops this capability later, he may charge a (FRAND) royalty from his competitor.

Keywords: Deepsea Mining, Common Heritage, Intellectual Property, Patents, Licenses, FRAND, 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 worldwide 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 deep-sea 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 deep-sea 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).

An economically and environmentally viable underwater mining solution

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ABSTRACT

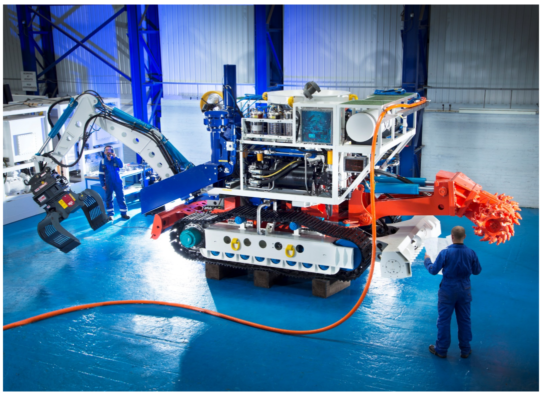
At UMC 2015 in Florida the authors presented on concepts for a project known as ¡VAMOS! (Viable Alternative Mine Operating System). This project, funded by the EU under the Horizon 2020 programme, involved the design, fabrication and testing of a remotely controlled prototype underwater mining system. At the time, the project was viewed in the EU as a safe and precautionary stepping stone towards future full scale underwater mining. The authors committed to a future presentation to demonstrate findings at the end of the project. This presentation fulfils that commitment.

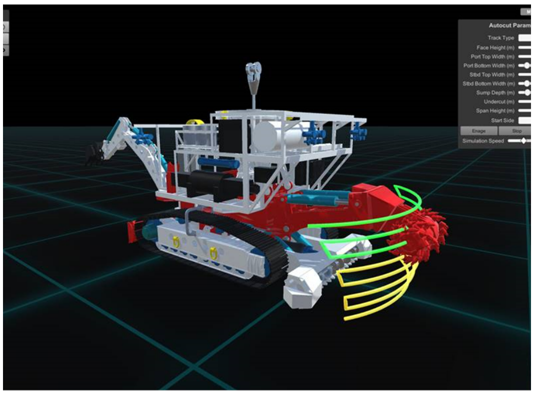
The project is now complete and the equipment has been successfully tested in flooded inland orebodies. The presentation covers…

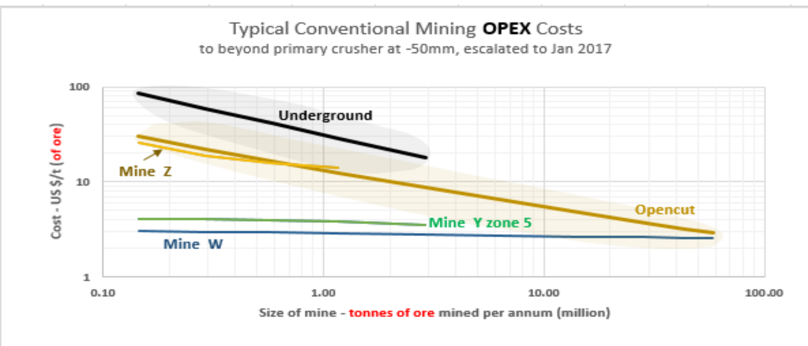
- the performance of the equipment and key sub-assemblies used,
- the results of environmental monitoring,
- extrapolated underwater mining costs compared to conventional mining costs.

A reliable positioning, navigation and awareness system has been developed which enables accurate virtual reality pilot views in highly turbid and reflective environments. An excavator arm which can disconnect and re-connect hydraulically powered tools underwater without leakage has been developed. The mining vehicle was successfully propelled in swampy and hard ground conditions. The cutting tool managed to cut rocks with a compressive strength of 220 MPa. A self-learning Laser Induced Breakdown Spectroscopy (LIBS) system was used for mineral and ore-grade assessment.

Keywords: Underwater, mining, environment, EU, robotics, AUV, ROV, LIBS, cuttability, capital costs, operating costs.







Stef Kapusniak

Stef is Business Development Manager – Mining with Specialist Machine Developments Ltd (SMD). Prior to joining SMD, Stef worked in the surface and underground mining industry, mainly in Australia. He has previously held roles in Australia as Mine Manager, Technical Services Manager, Preparation Plant Manager, Principal Mining Engineer, Senior Mining Engineer and Senior Geotechnical Engineer for a variety of companies. During his Australian career he received a ministerial appointment to the West Australian Coal Mines Examination Board. He gained a BSc in Mining Engineering and a PhD in Rock Mechanics from the University of Nottingham in the early eighties and holds both underground and opencut Mine Manager's tickets. He has also directed large construction Joint Ventures and framework contracts in the Transport and Utilities sectors in the UK.

Eduardo Silva

Eduardo is the Coordinator of the Robotics Centre at INESC TEC, has a PhD in Electrical and Computer Engineering and is professor "adjunto" within the school of Engineering at Porto Polytechnic Institute. His research interests are associated with areas of Field Robotics, in particular in the areas of perception (computer vision and multi-sensor fusion), navigation, control and coordination of mobile robots, with special emphasis on marine robotics. He has participated in more than 20 research projects and is the lead representative of INESC TEC in several key marine robotics research projects and related initiatives. These include: the EU FP7 project known as SUNNY - Smart UNmanned aerial vehicle sensor Network for detection of border crossing and illegal entrY; ICARUS - Integrated Components for Assisted Rescue and Unmanned Search operations and the EU H2020 project ¡VAMOS! - Viable Alternative Mine Operating System. He has more than 60 publications in the area of Field Robotics.

Progress of Chinese 1000m Deep Seabed Nodule Mining Test Project

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Abstract

This paper analyzes the latest development and situation of international deep seabed mining technology, and introduces the main progress of China's deep seabed polymetallic nodule mining test project from National Key R&D Programme of Thirteen-five Plan, including mining test vessel, surface launching & recovery system, underwater transportation system, underwater collection system, environmental monitoring and impact assessment. The follow-up work plan and contents are introduced.

Keywords: Deep seabed, Mining system, Environmental Impact Assessment

Li Xiangyang

Li Xiangyang, Ph.D, is dedicated to the development of deep-sea technology and facilities, the project leader of Chinese 1000m Deep Seabed Nodule Mining Test from the National Key R&D Programme, participated in the whole process of *Jiaolong* manned submersible research, development and sea trials, and served as deputy commander of *Jiaolong* cruise mission.

Design Challenges of Riser & Lifting System for Deepsea Mining

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Abstract

The history of underwater mining dates to the 1960s. It is well known that zinc deposit has been extracted in shallow protected waters for some time, but this is not directly comparable to the offshore world that needs to deal with the rigors of open seas. Also, a big intellectual effort was put forward by both the community and commercial interests in the 70's to investigate methods for extracting manganese nodules in waters over 4000 meters deep. These efforts, however, never progressed beyond preliminary testing and the interest faded in the late 80's when the investigators concluded that the endeavor was not commercially viable. In addition, experience at the time was limited to water depths of 450 meters or less and the technological gap was enormous. The discovery of seabed massive sulphides (SMS) in the exclusive economic zones along the Pacific Rim of Fire and on the mid-ocean ridges is correlated with a difficulty to find and develop new mining sites on land and with a surge in metals prices. Consequently, several small startup companies were initiated to explore these deposits. The deepsea minerals require artificial lifting from the seabed to the surface and this lift must be through a conduit called a riser. Other means of transporting minerals that were used in shallow water were proposed for deepwater but were not viable because of the efficiency and uncertain dynamic response of the overall lifting system. The riser and lifting system form the most crucial part of the deepsea mining system, particularly for seeking an efficient and sustainable harvesting method of deepwater mines. The oil and gas industry has developed various riser systems in the last 30 years for drilling in water depth in excess of 3,000 meters and producing close to that very successfully. However, the need for handling a lift system compounded with the need of constantly moving around to cover

the targeted field present challenges unique to deep water mining, particularly in harsh environments for the riser and lifting system. This presentation discusses design challenges of riser and lifting system for deepsea mining applications.

Deepsea mining is a mineral retrieval process that takes place from the seabed through the water column. As the application moves to deepwater and ultra-deepwater, the challenges of riser and lifting system development increase in terms of riser transport system design, analysis, installation and global performance and the need in handling the lifting system. This paper first introduces a typical riser and lifting system configuration in deepsea applications. Lifting methods and pumping systems' selection are key to the riser and lifting system design. This paper discusses the interim use of API codes for the design of dynamic riser system for the deepsea mining industry. It then addresses the design challenges of the riser and lifting system in deep sea mining applications. The system design issues cover riser wall thickness for various zones of risers, which is driven by the anticipated wear allowance from slurry particles, tension limits, and high payload. The installation concerns come from hook capacity limit, riser Vortex-Induced Vibration (VIV), and integration of hybrid riser segments. This paper further investigates the global performance of the riser system. Axial vibration may lead to extreme stress, snatching loading, or large fatigue damage when the axial natural period falls within the range of exciting wave periods. Flexible riser may offer alternatives to a vertical riser, however, the excessive wear and frictional loss on bends of flexible requires careful study and planning. This presentation provides a systematic approach for examining a proposed riser and lifting system through analytical means from examining the natural period for the first order axial vibration of the lifting system to global performance of the riser and lifting system in various operational conditions. In addition, this presentation also explores likely solutions to riser and lift system design challenges for deep sea mining applications in harsh environments.

Keywords: Deepsea Mining, Riser and Lifting System, Vortex-Induced Vibration (VIV), Riser Global Performance

Chenteh Alan Yu, PE

Biographical sketch of the main author(s)

Chenteh Alan Yu –

2017 to present, Director of Subsea, Global Offshore, ABS. Responsible for business development of subsea, umbilical, risers, and flowline work.
1997 to 2017, Technip USA - notable positions were the Riser Engineering Department Manager, Project Engineering Manager for the BP Holstein Spar Riser and Well System Project, Shell Perdido Spar DVA risers, Nautilus Minerals Salwara I Riser and Lift Systems.

1984 to 1996, Vetco Gray – notable positions were design/structural engineer for subsea equipment at R&D, testing engineer for Shell Auger tensioner, project engineer for Conoco Heidrun export riser systems, and Shell Mars/RamPowell drilling riser system.

Degree/Honor/Patents/Technical Sessions – MSME, Ohio University, early 80's. Awards – 2004 & 2009 Technip Jacques Franquelin Award for Innovation & Technology, 2010 & 2012 Technip Best Technical Paper Awards, and 2006 Dry Tree Forum Best Presenter Award. Five US Patents. OMAE session organizer/chairperson and technical paper reviewers. Published more than 10 technical papers in OMAE and OTC.

Yongming Cheng, PhD, PE

SURF Manager of Keppel FloaTEC in Subsea, Umbilical, Riser and Flowline

Over 20 years' offshore engineering experience in deepwater risers, umbilicals, and flexible risers. Technical lead and project manager in riser system design, global analysis, installation, life extension, and replacement. Widely involved in major deepwater projects in Gulf of Mexico, Brazil, West Africa, and South China Sea.

Extensive experience in all riser types: Top Tensioned Risers (TTRs), Steel Catenary Risers (SCRs), dynamic umbilical risers, flexible risers, and hybrid risers from concept evaluation to detailed engineering, procurement, construction, and installation (EPCI).

The recipient of Technip's Jacques Franquelin Award for outstanding technology development efforts and was named to Technip's college experts. Chair of International Associate of Offshore Engineering in 2012. Advisory Board member of Offshore Asia Conference 2013.

Owned three (3) patents in the application of riser technology including deepsea mining. Published over 50 technical papers in riser and VIV technology development and innovation. Expert in VIV hydrodynamic loads and response prediction for various offshore structures. Involved in the development of VIV prediction program SHEAR7 and the time domain VIV prediction program ABAVIV. Steering committee member for the VIV research and development JIPs including SHEAR7 and VIVA. OMAE Technical Reviewer and Session Chair on VIV and riser technology. Technical Reviewer for Journal of Fluid and Structures.

Andrew J. Lipman

2019- present
Director, Subsea and Mining Operations – ABS China Ltd. Responsible for Classification and Certification of deepsea equipment to ABS and International Standards. Oversight of EPCI for several deepwater installations as Third Party Certification as Authorized by PR China Maritime Emergency Management (MEM).

2008-2019
Surveyor, Manager - American Bureau of Shipping (ABS China Ltd.) Responsible for ABS activities including Operations and Training for Topside and Subsea Design, Construction and after-Construction.

Previous Subsea expertise as Commercial Diver and Operations Manager for Several International Marine Construction and Offshore Installation companies in US GOM and Worldwide.

State Practices of China in the Area

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Abstract

The presentation firstly introduces the national legislation of "**The Law of the People's Republic of China on Exploration for and Exploitation of Resources in the Deep Seabed Area**". Then the author describes the China's overall activities in the international deep seabed Area conducted in the last 30 years, including exploration work done in China's five contract areas, developments of technologies, endeavors for environmental protection and so on. Finally, the author presents China's contributions to the capacity building of the developing Countries to enhance their participation in deep sea activities.

Underwater acoustic positioning and navigation system

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Abstract

Underwater vehicle technology has developed rapidly with the strong demands of underwater mining applications in recent years. It is becoming more and more highly intelligent and automatic. High-precision positioning and navigation are indispensable technologies for underwater vehicles to implement underwater mining. GPS (Global Positioning System) is used widely by aerial or ground vehicles. However, it is used rarely on AUV due to the strong attenuation that the electromagnetic field suffers in water. In fact, underwater positioning and navigation usually combines INS (inertial navigation system), acoustic positioning, and navigation technology. INS can output navigation data stably in a short period; however, navigation accuracy will decrease with time. Acoustic positioning and navigation have high positioning accuracy and long-time stability that other positioning technology can't compare. Although the acoustic positioning and navigation system's frequency band is narrow and susceptible to environment. In all, underwater acoustic positioning and navigation will play an important role in underwater mining applications. Therefore, we will introduce the theory of underwater acoustic positioning and navigation system.

Underwater acoustic positioning and navigation utilize the concept of time of arrival ranging to determine target position. This concept entails measuring the time it takes for a ranging signal transmitted by a beacon to reach the target hydrophone, as shown in Fig. 1.

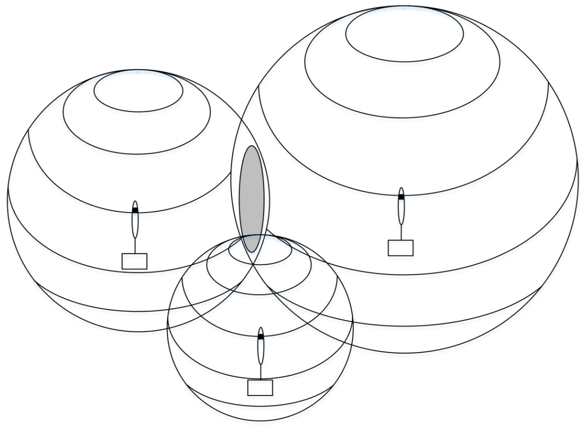

Fig.1. locate the target with three beacons

Assuming the coordinates of the beacon are (X_i, Y_i, Z_i), where i ranges from 1 to 3. The sound speed is c in water, Δt_i is the one way travel time between the ith beacon and the target, $r_i = c \times \Delta t_i$ is the range measurement between the ith beacon and the target. Range measurements are made to three beacons resulting in the system of equations:

$$\begin{cases} \sqrt{(X_1 - x)^2 + (Y_1 - y)^2 + (Z_1 - z)^2} = r_1 \\ \sqrt{(X_2 - x)^2 + (Y_2 - y)^2 + (Z_2 - z)^2} = r_2 \\ \sqrt{(X_3 - x)^2 + (Y_3 - y)^2 + (Z_3 - z)^2} = r_3 \end{cases} \tag{1}$$

If the beacons do not all lie in a plane, equation (1) can be simplified as:

$$\begin{bmatrix} X_2 - X_1 & Y_2 - Y_1 & Z_2 - Z_1 \\ X_3 - X_2 & Y_3 - Y_2 & Z_3 - Z_2 \\ X_1 - X_3 & Y_1 - Y_3 & Z_1 - Z_3 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \left(r_1^2 - r_2^2 + d_2^2 - d_1^2\right)/2 \\ \left(r_2^2 - r_3^2 + d_3^2 - d_2^2\right)/2 \\ \left(r_3^2 - r_1^2 + d_1^2 - d_3^2\right)/2 \end{bmatrix} \tag{2}$$

where $d_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2}$, $i = 1,2,3$. These equations can be put in matrix form by making the definitions:

$$\mathbf{A}=\begin{bmatrix} X_2-X_1 & Y_2-Y_1 & Z_2-Z_1 \\ X_3-X_2 & Y_3-Y_2 & Z_3-Z_2 \\ X_1-X_3 & Y_1-Y_3 & Z_1-Z_3 \end{bmatrix} \tag{3}$$

$$\mathbf{X}=\begin{bmatrix} x & y & z \end{bmatrix}^{\mathrm{T}} \tag{4}$$

$$\mathbf{B}=\begin{bmatrix} \left(r_1^2-r_2^2+d_2^2-d_1^2\right)/2 \\ \left(r_2^2-r_3^2+d_3^2-d_2^2\right)/2 \\ \left(r_3^2-r_1^2+d_1^2-d_3^2\right)/2 \end{bmatrix} \tag{5}$$

One obtains, finally:

$$\mathbf{AX}=\mathbf{B} \tag{6}$$

The matrix $\mathbf{A}$ will be invertible provided the beacons do not all lie in a plane, and equation (6) has the solution:

$$\mathbf{X}=\mathbf{A}^{-1}\mathbf{B} \tag{7}$$

If the beacons all lie in the same plane, equation (1) can be simplified as equation:

$$\begin{bmatrix} X_2-X_1 & Y_2-Y_1 \\ X_3-X_2 & Y_3-Y_2 \\ X_1-X_3 & Y_1-Y_3 \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}=\begin{bmatrix} \dfrac{r_1^2-r_2^2+d_2^2-d_1^2}{2} \\ \dfrac{r_2^2-r_3^2+d_3^2-d_2^2}{2} \\ \dfrac{r_3^2-r_1^2+d_1^2-d_3^2}{2} \end{bmatrix} \tag{8}$$

The coordinates (x, y) of the target can be calculated by equation (8), then the coordinate z of the target can be solved by equations (1).

The target velocity is defined as $\dot{\mathbf{u}}=\left(\dot{x}, \dot{y}, \dot{z}\right)$, at the hydrophone, the received frequency f_R can be approximated as follows:

$$f_R = f_T\left(1-\frac{\mathbf{v}_r\cdot\mathbf{a}}{c}\right) \tag{9}$$

where f_T is the transmitted beacon signal frequency, $\mathbf{v}_r$ is the beacon to target relative velocity vector, $\mathbf{a}$ is the unit vector pointing along the line of sight from the target to the beacon, and c is the sound speed in water. Vector $\mathbf{v}_r$ is given as:

$$\mathbf{v}_r = \mathbf{v} - \dot{\mathbf{u}} \tag{10}$$

where $\mathbf{v}$ is the velocity of the beacon, for the beacon on the seafloor, $\mathbf{v} = \mathbf{0}$.

For the ith beacon, substituting (10) into (9) yields:

$$f_{Ri} = f_{Ti}\left[1-\frac{1}{c}\left(-\dot{\mathbf{u}}\cdot\mathbf{a}_i\right)\right] \tag{11}$$

Then the dot products in terms of the vector components yields:

$$\frac{c\left(f_{Ri}-f_{Ti}\right)}{f_{Ti}} = \frac{c\Delta f_{Di}}{f_{Ti}} = \dot{x}a_{xi} + \dot{y}a_{yi} + \dot{z}a_{zi} \tag{12}$$

where Δf_{Di} is the Doppler frequency shift, $\mathbf{a}_i = \left(a_{xi}, a_{yi}, a_{zi}\right)$, and the components of $\mathbf{a}_i$ are obtained as follows:

$$\begin{aligned} a_{xi} &= \frac{(x_i - x)}{\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}} \\ a_{yi} &= \frac{(y_i - y)}{\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}} \\ a_{zi} &= \frac{(z_i - z)}{\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}} \end{aligned} \tag{13}$$

To simplify equation (12), the variable d_i is defined as:

$$d_i = \frac{c\Delta f_{Di}}{f_{Ti}} \tag{14}$$

Then the unknown quantities $\dot{\mathbf{u}}=(\dot{x}, \dot{y}, \dot{z})$ are calculated by solving the set of linear equations. The matrix and vector scheme are defined as:

$$\mathbf{d} = \begin{bmatrix} d_1 & d_2 & d_3 \end{bmatrix}^{\mathrm{T}} \tag{15}$$

$$\mathbf{H} = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} \\ a_{x2} & a_{y2} & a_{z2} \\ a_{x3} & a_{y3} & a_{z3} \end{bmatrix} \tag{16}$$

$$\mathbf{g} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} \end{bmatrix}^{\mathrm{T}} \tag{17}$$

The solution for the velocity is obtained as:

$$\mathbf{g} = \mathbf{H}^{-1}\mathbf{d} \tag{18}$$

Keywords: underwater positioning; underwater navigation; acoustic

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Lv Chengcai

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Developing new National Regulatory Frameworks and Standards for Sustainable Seabed Minerals development

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Cook Islands

Abstract

In the **2015 UMC** in Tampa, the South Pacific nation of the Cook Islands launched its first national Seabed Minerals Licencing process, based on a world class Regulatory Framework. This 2015 Regulatory Framework has now been updated and enhanced with a complete overhaul and repeal of the 2009 Seabed Minerals Act, with the passing on 13 June 2019 of the new Seabed Minerals Act 2019 of the Cook Islands, based on the latest and best international standards and practices.

The Cook Islands has a large Exclusive Economic Zone in the South Pacific, which contains a vast and unique seabed Manganese Nodule resource at 5,000m, estimated at 12 billion tonnes and a unique abundance of Rare Earth Elements in its Nodules and sediments.

This presentation will focus on the new Regulatory aspects to provide for a robust and world class Exploration Licencing process to progress for Deep Sea Minerals development in the Cook Islands EEZ and to comply with UNCLOS and ISA requirements as a new Sponsoring State.

New standards have been adopted for integrated decision-making and evaluation in the new Exploration Applications process, enhanced requirements for scientific exploration, collection and sharing of deep sea minerals resource information, data and samples.

This new focus will assist both investor/explorer and the resource owner to make informed decisions on the mineral and economic viability of seabed mineral areas, explored under the new Licencing process.

The new Seabed Minerals Regulatory Framework and Licencing process is being developed and coordinated by the **Cook Islands Seabed Minerals Authority**, under the Seabed Minerals Act 2019, together with the valuable collaboration of many international, regional and national stakeholders, including the Cook Islands NGOs, Marine Resources, Marine Park and National Environment Service.

Investigating Midwater Discharge Sediment Plumes Associated with Deep-Sea Nodule Mining

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Abstract

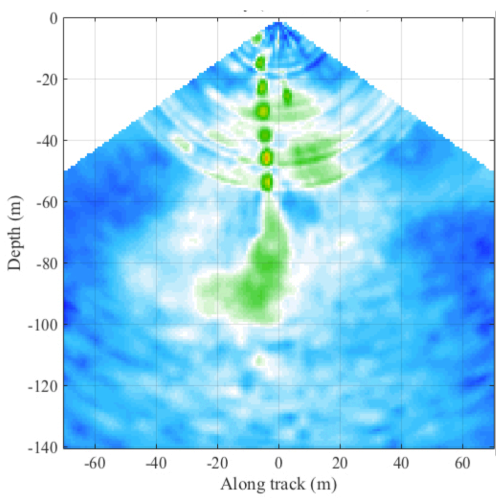
One of the most significant causes of concern associated with deep-sea polymetallic nodule mining activities is the discharge of sediment plumes into the ocean. These plumes constitute a significant threat to the highly diverse biology of the abyssal environment, which is used to a very low suspended solids concentration (0.01 mg/l) (Thiel et al., 2001) and sedimentation rates (1 μm/year) (Arrenhius, 1963). Therefore, it is expected that sediment plumes may generate issues such as suffocation and clogging of the feeding apparatus of many species, or even the local disruption of the vertical plankton migrations, which is a key aspect of the food chain (Amon et al., 2016; Glover et al., 2016). Consequently, it is essential to understand and assess the behavior of these plumes in order to develop informed environmental regulations, define protected areas and conduct adequate environmental impact assessment studies.

There are two main types of sediment plumes expected to be discharged during polymetallic nodule mining activities: a first one associated with the nodule collection vehicle in the seabed, and a second one with the sediment separated from the nodules in the mining vessel and returned back to the ocean. This second midwater discharge could eventually happen in the disphotic zone at depths of about 1,000 m. The understanding of the behavior of the midwater plumes starts with the study of the near-field dynamics: from the discharge depth until the plume reaches its neutrally buoyancy level. In the last decades, several semi-analytic and numeric plume models have been developed. One of

the most relevant models (Morton, Turner & Taylor 1956; Lee & Chu 2003) was recently applied to a polymetallic nodule mining discharge plume by Rzeznik, Flierl and Peacock (2019). The next step consists on the modeling of the ocean transport and settling of the sediment particles after the plume reaches its neutrally buoyancy level. Two main modeling efforts were conducted by Segschneider & Sundermann (1997) and Rolinski *et al* (2001). However, in these ocean transport simulations the near-field dynamics of the plume were not considered to define the initial parameters of the plumes. Regarding the field midwater sediment plume experiments, there is little field data available. In the 70s, at least three polymetallic nodule mining tests were conducted in the Atlantic and Pacific Oceans (Amos et al., 1977; Burns et al., 1980; Ozturgut et al., 1980). However, the sediment plumes were discharged directly to the ocean surface. There was a midwater sediment plume discharge associated with a metalliferous sediment extraction in the Red Sea, but the overall conclusion was that further research was required to study these plumes (Thiel et al., 2001).

Because of the lack of polymetallic nodule mining midwater discharge plumes field data, the PLUMEX field studies were conducted in during 8 days aboard *R/V Sally Ride* in 2018 in the Pacific Ocean as a collaboration between MIT and Scripps Institution of Oceanography. A plume creation system was designed to discharge a total of six midwater plumes with total volumes up to 670 m^3; one of them using actual seabed sediment from the Clarion Clipperton Fracture Zone. Additional four plume experiments were conducted using saltwater and one using limestone. PLUMEX was a unique opportunity to test different acoustic and optic technologies to monitor the plumes during and after the discharge for a period of up to six hours; such as optical backscatter sensors (OBS), fluorometers to detect the Rhodamine dye used as a tracer, a Phased Array Doppler Sonar (PADS), a prototype FastCTD and epsilometers. All them with the purpose of measuring the plume depth, width, thickness and dilution factors. Additionally, water samples of the plume were taken using Niskin bottles and analyzed afterwards in the laboratory. The results from the field experiments and a comparison with the near-field model predictions will be presented during the oral presentation. This is the first time a midwater sediment plume discharge using actual sediment from the CCFZ seabed is discharge and monitored in order to validate a plume near-field model which is the key for the development of informed environmental regulations. Figure 1 shows some of the key results from the sediment plume experiment.

a)



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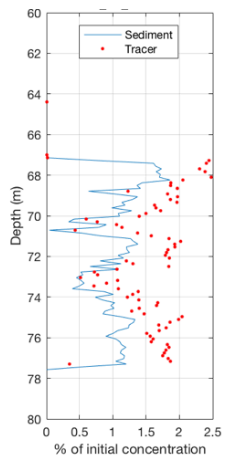

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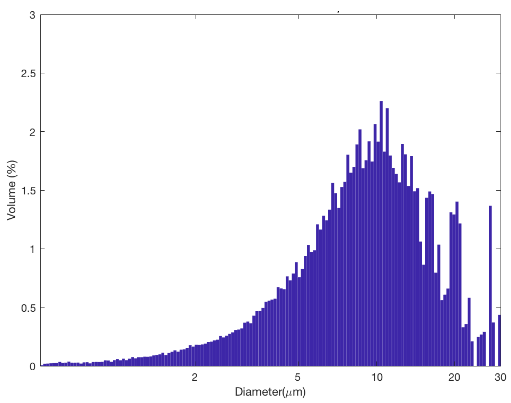

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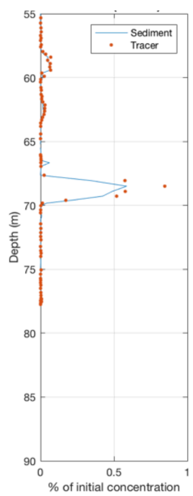

Figure 1. a) PADS backscatter intensity plot during a 60 m depth saltwater plume discharge. b) FCTD sediment and tracer inverse dilution factors profile measured during the plume discharge. c) Particle size distribution of one of the sediment plume experiment Niskin water samples. d) Sediment and tracer inverse dilution factors profile measured during the plume tracking one hour after the end of the plume discharge.

Keywords: Sediment Plumes, Polymetallic Nodule Mining, Field Experiments

Carlos Munoz-Royo

Carlos is a third year Ocean Engineering PhD student at the department of Mechanical Engineering at the Massachusetts Institute of Technology. His research is focused on the investigation of sediment plumes associated with Polymetallic Nodule Mining Operations. Carlos has led PLUMEX field studies, a collaboration between MIT and Scripps Institution of Oceanography to conduct midwater plume experiments in the Pacific Ocean aboard R/V Sally Ride in 2018. He is also involved in the study and field experimentation of sediment plumes associated with polymetallic nodule collection vehicles and in the development of near-field plume models. He has also made relevant contributions to the development of the MIT Economic Model of a Polymetallic Nodule Mining exploitation for the International Seabed Authority.

Assessing Hydrothermally Extinct Seafloor Massive Sulphide Deposits (eSMS): Lessons from the Blue Mining Project, Mid-Atlantic Ridge

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[5] https://cordis.europa.eu/docs/results/604/604500/periodic2-summary-blue-mining-project-p2.pdf

Introduction

Deep-sea mineral deposits potentially represent vast metal resources that could make a major contribution to future global raw material supply. These polymetallic deposits form a continuum from nodules and crusts, rich in the major industrial metals (e.g. nickel, copper, cobalt, manganese, titanium) and many minor elements (e.g. tellurium, platinum, molybdenum, niobium, bismuth, rare earth elements), to seafloor massive sulphide deposits containing abundant copper, zinc, gold and silver. Increasing demand for these elements, required to enable a low-carbon and high-technology society, and pressure on land-based resources, may necessitate the extraction of deep-sea minerals within the next decade.

Here, we describe the most comprehensive study to date of hydrothermally extinct seafloor massive sulphide deposits (eSMS), formed at a slow spreading ridge: the TAG hydrothermal field, 26°N, Mid-Atlantic Ridge. Our approach involved two research cruises and deployed a combination of high-resolution sonar swath bathymetry, self-potential mapping, surveying from an autonomous underwater vehicle, video surveying and sampling from a robotic underwater vehicle, and a variety of innovative geophysical imaging techniques including near-bottom ocean floor seismic and controlled-source electromagnetics, as well as seafloor drilling by diamond coring. The geological and geophysical data and their interpretation described in this contribution constitute the most detailed, three-dimensional characterisation of hydrothermally extinct seafloor massive sulphide deposits hosted by volcanic systems at slow spreading mid-ocean ridges. Together, these results that have allowed us to construct a new generic model for extinct seafloor massive sulphide deposits that indicate the presence of up to six times more massive sulphide on and below the seafloor than was previously thought.

Geological Setting

The Mid-Atlantic Ridge (MOR) is a slow-spreading (22mm/year) ridge[1], and the associated TAG hydrothermal field is one of the most intensively studied seafloor hydrothermal systems[1,2,3,4,5,6,7,8,9,10,11,12]. It lies at water depths ranging from 3,430 to 3,670 m on the eastern and shallowest part of a 75km-long, second-order spreading segment (Figure 1). The TAG segment is characteristic of most slow-spreading ridge segments forming a deep axial valley that hosts a neovolcanic zone comprising young lavas, hummocky volcanic ridges and isolated volcanoes[13].

The active TAG mound is the current locus of venting of high temperature (up to 363°C)

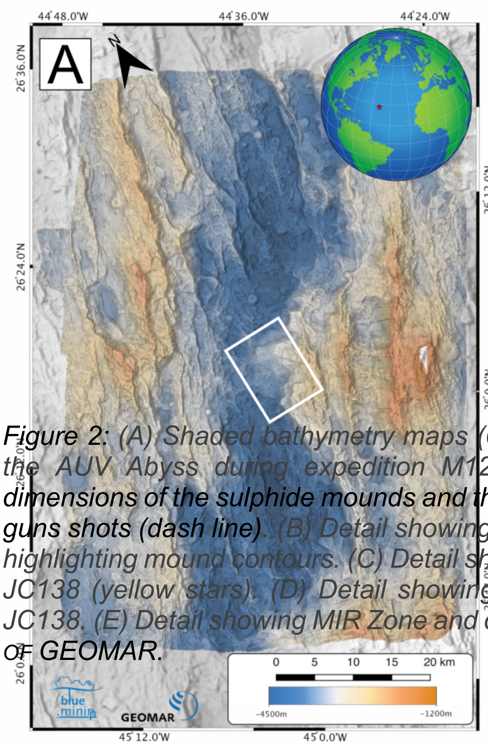
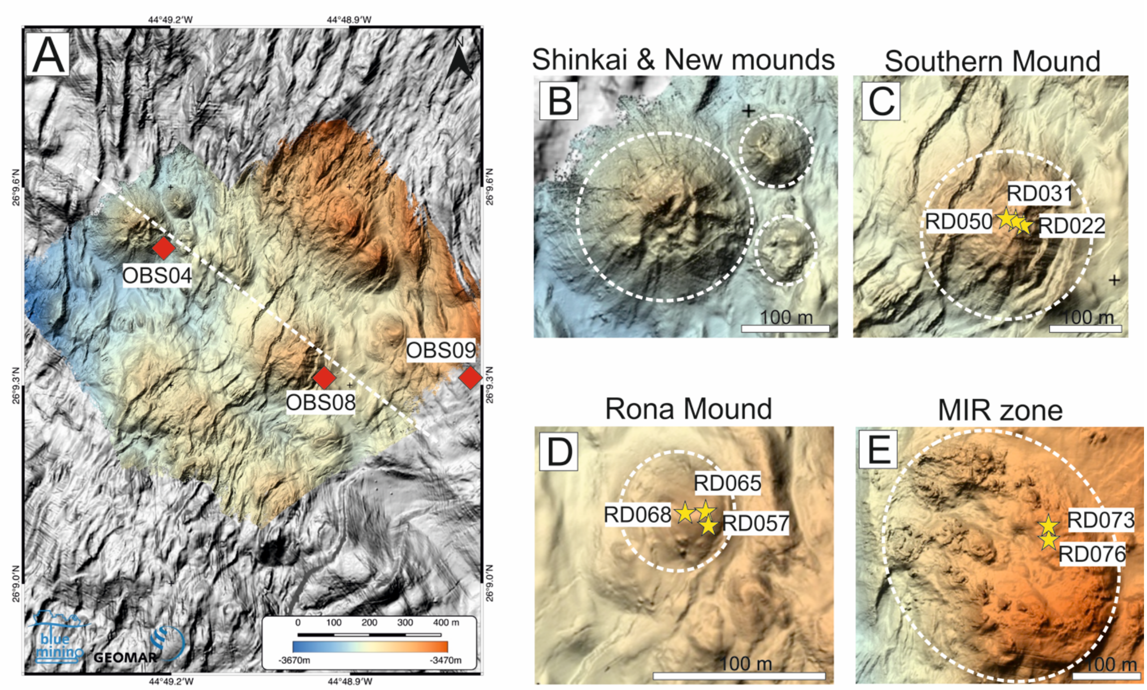


Figure 1: Location of the Trans-Atlantic Geotraverse (TAG) hydrothermal field, indicated by the red star on the inset globe, at 26°08'N on the Mid-Atlantic.

Figure 2: (A) Shaded bathymetry maps (0.5m resolution) of the 'Three Mounds' area surveyed by the AUV Abyss during expedition M127 and OBS positions (red diamonds) used to image dimensions of the sulphide mounds and their physical properties (P-velocity) while recording the air-guns shots (dash line). (B) Detail showing Shinkai Mound and New Mound #2 and #3; dashed lines highlighting mound contours. (C) Detail showing Southern Mound, its faults and drill locations during JC138 (yellow stars). (D) Detail showing Rona Mound and the location of the drill holes during JC138. (E) Detail showing MIR Zone and drill locations during JC138. BATHYMETRIC MAPS: COURTESY OF GEOMAR.

hydrothermal fluids that have resulted in the formation of a 200 m diameter, 50 m high circular deposit, topped by a number of 12m-tall black-smoker chimneys. In addition to the active TAG mound, at least seven other hydrothermally inactive or eSMS deposits have previously been identified in an area of ~2.5 km^2 [5,6] (Figure 2).



These include the Shinkai, Southern and Double eSMS mounds as well as the weakly active Shimmering Mound (Figure 2A) that are typically up to 60 m high, 100 to 300 m in diameter, variably covered in pelagic sediment and dated at between 6,000 to 75,000 years old[14]. In addition to the extensive Alvin Zone, a second hydrothermally inactive site occurs, called the MIR Zone (Figure 2E). This site is located two kilometres to the east-northeast of the active TAG Mound in water depths of 3,430 to 3,575 m.

Results

Our study finds the main differences between the TAG mound and the eSMS deposits are due to changes in hydrothermal activity. Anhydrite (calcium sulphate) dominates the interior of the active TAG mound that otherwise comprising massive sulphide overlying a silicified altered basalt-hosted stock-work of sulphide, to the eSMS deposits that have up to a 5m-thick carapace of iron-rich oxide sediments overlying a 3-6m thick silica cap that in turn overlies a highly conductive and dense massive sulphide ore body, of about 100m thickness, in which the anhydrite has been dissolved and lost. Importantly, we find the massive sulphide body overlies a lower conductive yet moderate density stock-work zone of sulphide and altered basalt that extends another 100m and which is surrounded by a low density, resistive host of altered basaltic lava.

Our new data give insight into the processes leading to the formation of the eSMS deposits, and especially those that occur at the closing stages of the hydrothermal cycle. High-resolution AUV-bathymetry (0.5 m resolution) and RUV surveys show that the eSMS mounds are often dissected by shallow inward dipping (20°-30°) normal faults that are interpreted to be a response to anhydrite dissolution and the resulting volumetric contraction within the main ore body (Figures 3&4). This has led to brecciation of the upper 10-20m of the ore body with late stage silicification overprinting the sulphide and precipitating a silica cap. Despite the silica cap acting to restrict oxidation by seawater penetrating into the ore body, remobilisation and recrystallisation of the massive sulphide, especially the copper-rich phases such as chalcopyrite, have led to an enrichment in the upper few metres of the ore body but the impact on metal tenor at depth remains unknown (Figure 5). The presence of highly conducting and high-seismic velocity material down to 50-100mbsf indicates that the main ore body forms a lens that is massive in character, probably with little gangue material. None of the controlled source electromagnetic data penetrate below the main ore body, but the seismic evidence for relatively high velocity material below the main ore lens extends to 200mbsf where it forms a downwards-narrowing cone. We interpret this as a stock-work of sulphide in an altered basalt matrix, possibly with some silica overprint that reduces the conductivity without making a significant impact on the velocity. Both the main ore body and stock-work highlight a volumetric space problem in their formation process.

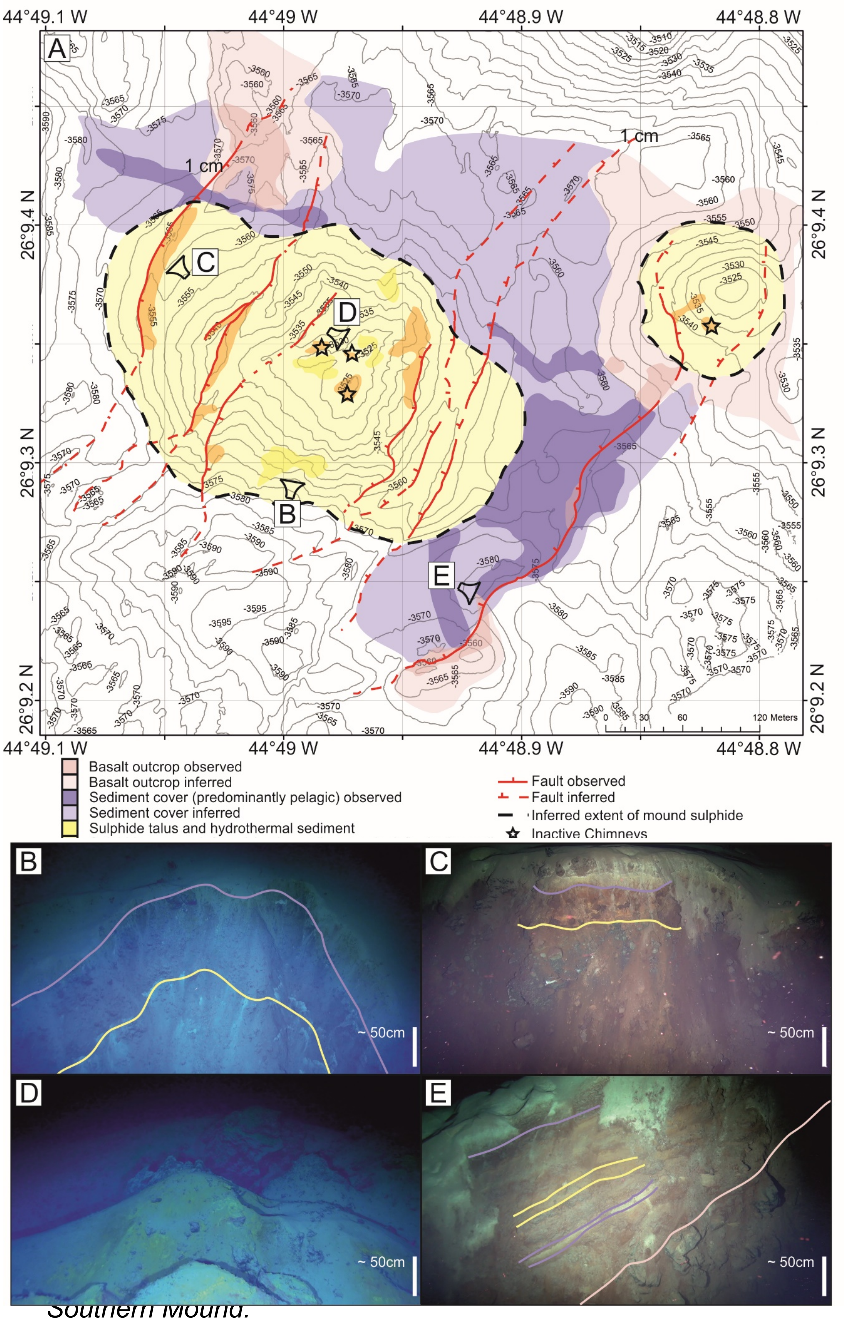


Figure 3: *Geological map of Southern Mound and Rona Mound, interpreted from the surface geology and locations of photographs of features from Southern Mound.*

Southern Mound.

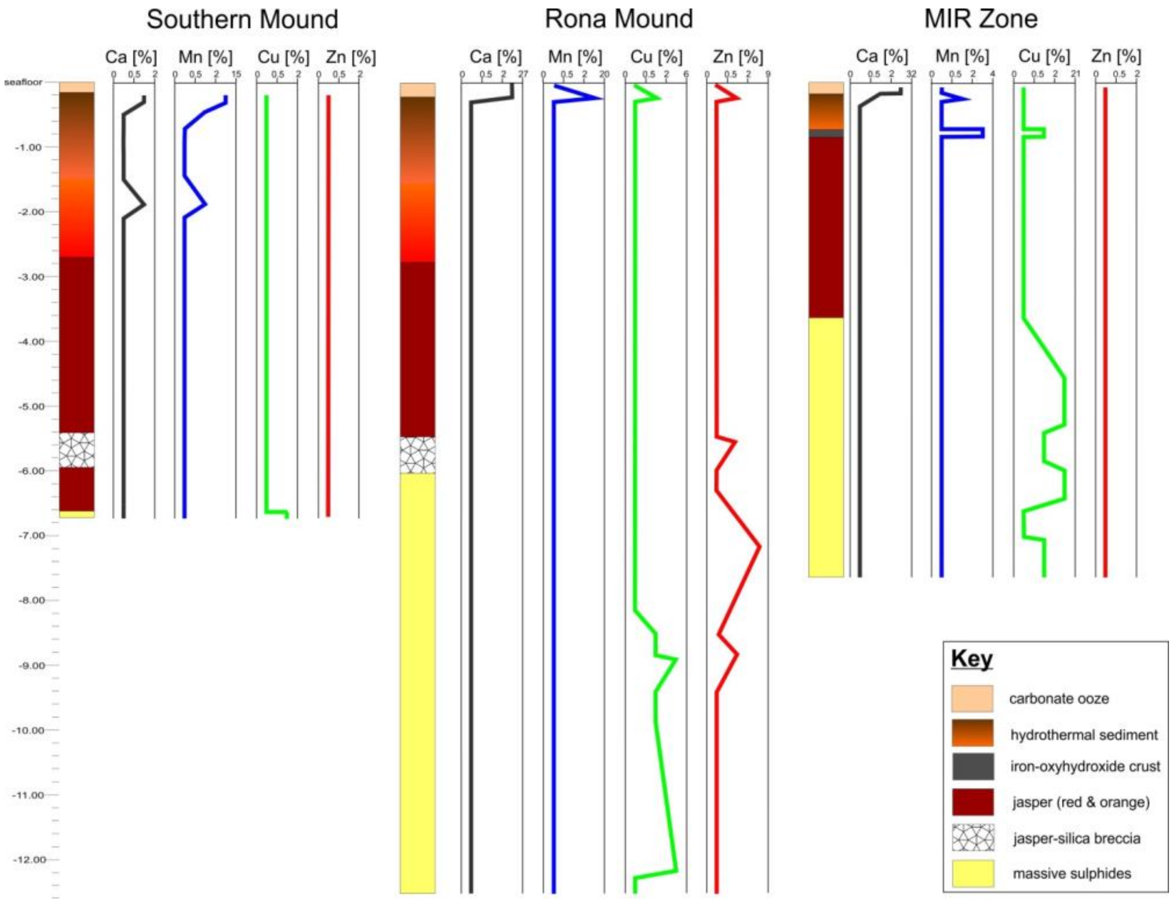


Figure 5: Composite stratigraphy for Southern mound, Rona mound, and MIR Zone and downhole geochemical trends for calcium, manganese, copper and zinc.

Previous geological models for SMS mounds interpret their formation as a process driven by sulphide precipitation in the form of chimneys, the subsequent collapse and accumulation of sulphide building a positive morphological feature that we see today as the mounds. However, our data show that a volume of massive sulphide, at least twice that expressed by the surface mounds, is precipitated beneath the seafloor and within the host rock (Figure 6). How this occurs remains unknown, although replacement of altered basaltic host rocks is a possibility. Alternatively, the mounds may grow by tectonic subsidence driven by progressive faulting. In the latter scenario, some of the shallow faulting affecting the mounds may also be a response to progressive extension and subsidence.

From a resource perspective, we have been able to combine the geophysics data with the boundaries and volumes to yield an estimate of the metal content of the eSMS. Our data show that the main ore body extends to a sub-seafloor depth of about 100 m and comprises an average of about 79% sulphide with abundances increasing with depth. The underlying stock-work extends to another 100m and comprises up to 17% sulphide with a host rock likely to comprise silicified and altered basalt. This grades into an altered basalt host rock. In general, our data indicate a resource that is 3 to 6 times larger than that predicted from the surface expression of the deposits alone. This is even larger if we include the metal rich sediment-apron that surrounds the eSMS mounds.

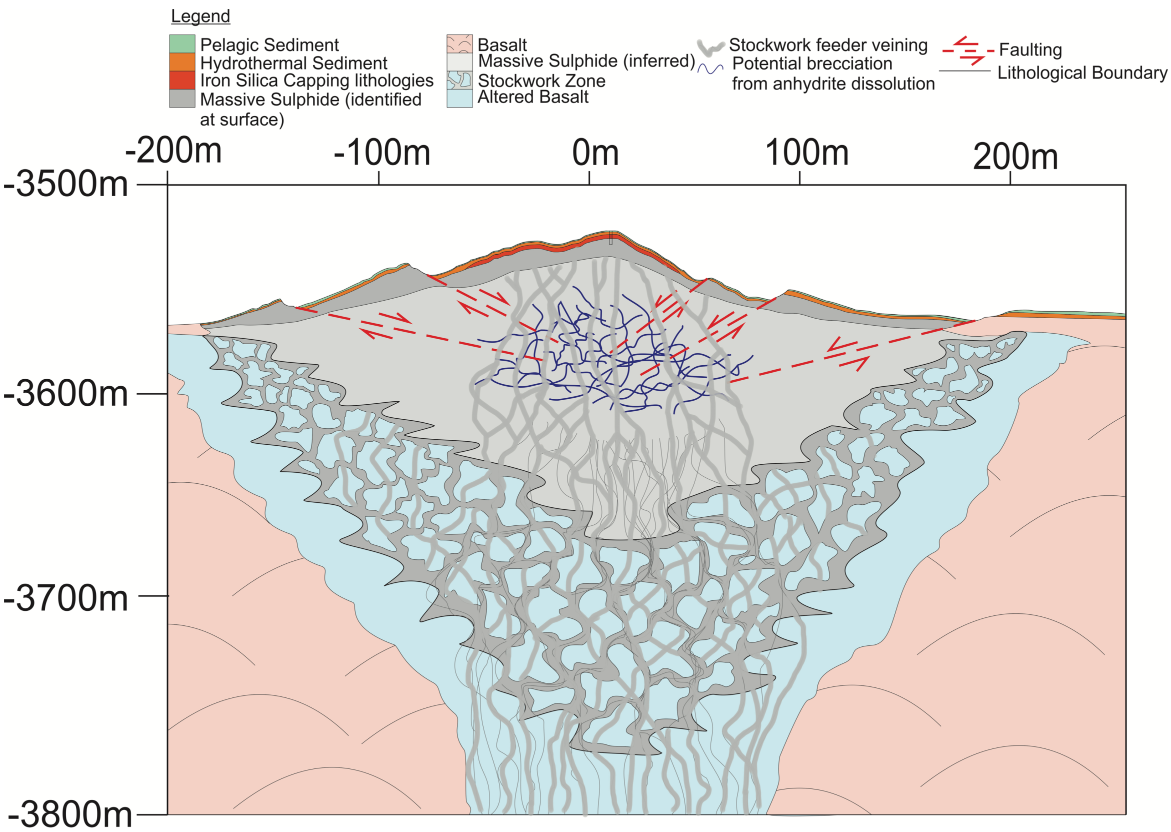


Figure 6: Composite 3D geological model of the TAG eSMS mounds based on a synthesis of the surface geology, drilling and geophysics showing sediment covered mounds with an interior comprising an uppermost jasper layer underlain by massive sulphide that merges downwards into a stockwork. The interior of the massive sulphide body is brecciated as a result of dissolution of anhydrite that in turn leaves open pore space and causes contraction of the volume of the mound resulting in inward faulting. Note the significant presence of ore

material lies beneath the mound at a depth that is at least twice the height of the mound itself.

Estimates by members of the Blue Mining consortium indicate that there are about ten times more eSMS deposits exposed on the seafloor or under a few metres of sediment, within 20km each side of the mid-ocean ridge axis, compared with the number of known hydrothermally active systems. Of these, 350 are known globally, with another 1000 estimated yet to be discovered. If we consider the number of undiscovered eSMS deposits, then the accessible inventory may be of the order of 15,000 worldwide.

Keywords: ***resource assessment, extinct seafloor massive sulphide, high-resolution mapping, seismic, electromagnetic, seafloor drilling.***

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Bramley J Murton

Prof. Bramley Murton is the Associate Head of Marine Geosciences at the National Oceanography Centre in Southampton. Bramley has over 25 years of experience leading research in to the formation of oceanic crust, exploring hydrothermal activity and, more recently, leads the UK research effort into discovering new deep-sea minerals. Bramley has been chief scientist on numerous national and internationally-funded research programmes including an EU-funded study (the 'Blue Mining Programme') of extinct seafloor massive sulphides, a UK-funded study (the 'MarineE-tech Project) on tellurium and cobalt-rich ferromanganese crusts, and he is chief scientist on a new four-year study ('Project ULTRA') of tellurium, platinum and gold-rich hydrothermal deposits on the Mid-Atlantic Ridge. The motives for this deep-sea mineral research is to provide the raw materials for high-tech and low-carbon technologies including renewable energy. In support of his deep-ocean exploration, Bramley has developed several deep-sea technologies including the deep-diving robotic vehicle 'HyBIS' that found the world's deepest hydrothermal vents at a depth of 5,000m in the Caribbean.

Deep-sea mining sediment plumes: what we know and what we don't.

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Abstract

Developing an understanding of the dynamics and scale of the sediment plumes that will be created by deep-sea mining underpins all capability to make reliable predictions of the impact of such activities on the ocean environment. This presentation reviews current understanding, and knowledge gaps, regarding the sediment plumes that will be created by collector vehicles and by potential midwater column discharges.

To begin, we will outline the key underlying physics of midwater discharge plumes, detailing the established modelling, and prior laboratory and field experiments that can be drawn upon to validate these models as applied to deep-sea mining. We will present the results of our recent *PLUMEX* field experiment in which a midwater discharge plume with the characteristics of a proposed commercial plume was created and studied using sediment obtained from the Clarion Clipperton Fracture Zone. The outcomes of the *PLUMEX* studies provide the basis on which a regional scale numerical simulation of a commercial discharge plume has been run, and we present the results of this modelling.

Thereafter, our presentation will provide an overview of gravity current dynamics as applied to the sediment plumes created by collector vehicles. The results of a numerical

model are compared with well-established analytical models and laboratory experimentation to support this understanding. We outline what features of the collector plume dynamics will be the most important to characterize in order to assess the environmental footprint, considering, among other things, the roles of flocculation and resuspension of sediment.

Our presentation concludes by providing a roadmap to the deep-sea mining community regarding what measurements need to be made, and what modelling needs to be performed, in order to achieve reliable predictions of the extent of sediment plumes that will underpin considerations of environmental impact.

Keywords: deep-sea nodule mining; sediment plumes.

Thomas Peacock

Professor Thomas Peacock is a faculty member in Mechanical Engineering at MIT. His research focuses on Physical Oceanography and Environmental Fluid Dynamics and involves running major field experiments in combination with laboratory experiments and modeling. He is overseeing the development of a deep-sea mining research program at MIT, and his research focuses on the dynamics of sediment plumes potentially generated by deep-sea mining. In 2018, as part of a collaborative effort, his group oversaw the *PLUMEX* field experimental study of a simulated deep-sea mining discharge plume. Funding of deep-sea mining research at MIT is currently through the MIT Environmental Solutions Initiative, The 11th Hour Foundation, and The Benioff Foundation.

Establishing a methodology to define criteria for a risk-based impact assessment for offshore sea-floor massive sulphide extraction

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Abstract

Metal-rich seafloor massive (polymetallic) sulphide (SMS) deposits around hydrothermal vents offer a potential of ore resources and are prone to extraction in the near future. The International Seabed Authority (ISA) is currently drafting legislation for the exploitation of various forms of metal reserves in international waters, e.g. outline of legal procedures and how to prepare an Environmental Impact Assessment (EIA) for mining. Little attention is paid to the actual criteria for an EIA for e.g. extracting SMS deposits. When analysing literature it appears that there is a wide variety of criteria to evaluate the impacts of exploitation. Whilst there is a common basis in activities performed, there are also important differences in criteria which authors judged to be important. In this study we have designed a methodology to generate a comprehensive overview of potential criteria and select criteria for an EIA for SMS deposit exploitation, using existing literature. Such an approach, with criteria based on broad literature evaluation following a structured methodology, ensures both the Competent Authority and the relevant stakeholders that the starting point of the EIA is well established in the scientific literature. This research makes no statement about the acceptance or non-acceptance of ecological impacts or the evaluations done. It provides an overview of what should be assessed to generate a good EIA that is more likely to meet general acceptance, facilitating decision making.

Introduction

Due to economic developments in rising economies like China and India and worldwide in general, new technological developments and the transition to sustainable energy, the demands on metal ores are rising. Metal-rich seafloor massive (polymetallic) sulphide (SMS) deposits around hydrothermal vents offer a potential of ore resources and are prone to extraction in the near future. Deep-sea hydrothermal vents are found at mid-ocean ridges and back-arc basins between -150 and -5000 m. The most likely zone to be mined is between -150 and -1800 m. The SMS deposits are rich in iron, zinc, copper, lead and numerous other elements, including gold, silver, arsenic, cobalt, molybdenum and platinum (Boschen et al., 2013, 2016, Rozemeijer et al., 2015, 2018).

The chimney-shaped vents (black smokers) emit smoke-like plumes of dark particles and chemicals like H_2S. That H_2S is the energy source for a vent-adapted biological ecosystem relying on chemosynthetic primary production. The complex vent-communities are characterised by high biomasses and relatively low number of species with high numbers of endemicity. Animals like large clams, tubeworms, shrimp, and other undiscovered creatures rely on chemosynthetic bacteria for their survival, often in symbiotic relationships (International Seabed Authority (ISA), 2011, Boschen et al, 2013, 2016, van Dover, 2014, Van Dover et al., 2018).

Offshore, most initiatives to exploit SMS deposits are still in the preparatory stages (Rozemeijer et al., 2018, Miller et al., 2018). Seven contracts have been granted by the ISA for SMS deposit exploration at specified locations[1]. Japan has a lead in test mining SMS deposits at extinct hydrothermal vents in deep water (approximately 1.6 km)[2] (Narita et al., 2015). At 1.9-2.2 km water depth in the Red Sea, the metalliferous sediments of Atlantis II Deep are near exploitation[3]. Recently a potential project on the extraction of SMS deposits at the hydrothermal vent system Solwara, Bismarck Sea, Papua New Guinea, was stopped because the company Nautilus was not able to gather sufficient funding[4]. In addition, there was a lot of criticism of national and international stakeholders based on the mere fact of offshore SMS mining, the quality of the EIA, and the participation of stakeholders (Steiner, 2011, Luick, 2012, Filer and Gabriel (2018). The Environmental Impact Assessment (EIA) was written by Coffey Natural Systems (CNS), 2008.

Legislation and EIA

In order to be able to mine the seabed, a permit is necessary. The seabed spreads both over areas within national jurisdiction (EEZ, Continental shelf) and the area beyond national jurisdiction (called the Area). There are thus two different levels of regulatory framework depending on the specific location of mining activities: 1) domestic law, within national jurisdiction. Coastal States are sovereign and can regulate seabed mining occurring on their continental shelf taking international conventions into account and 2) International law, regulating the Area and its mineral resources by the United Nations Convention in the Law of the Sea (LOSC, 1982), managed by the ISA (Rozemeijer et al., 2015, 2018).

Environmental Impact Assessment
Irrespective of domestic or international legislation, in most legislation an EIA is a legal requirement in planning application for any large-scale development (on land or sea) (Guerra et al., 2014, Smart et al., 2014 Tang et al., 2016, Clark et al., 2017, 2019, Durden et al., 2018, ISA 2019). One major objective of EIA is to support project licensing with sound and social responsive technical and scientific knowledge on the likely environmental effects including potential mitigation measures and Environmental Management Plan (EMP) in order to reduce the impacts. When the often obligatory stakeholder participation and evaluation are applied correctly, the establishment of an EIA can also have an important contribution to achieve more acceptance of the initiative and potentially contribute to a Social License to Operate (Smart et al., 2014, Leeuwerik et al., 2019).

In order to establish an EIA numerous frameworks have been developed. E.g. Guerra et al. (2014), Smart et al. (2014), Tang et al. (2016), Tamis et al. (2015) describe how to position the EIA in the total process of licensing. Others, (e.g. Lee et al., 1995, Phylip-Jones and Fischer, 2013, Clark et al., 2017, 2019, Oesterman et al., 2016, Kaikkonen et al., 2018) describe how to establish evaluation criteria to in a coherent framework. Especially on the upcoming domain of seabed mining oversights are given how to position and generate the baseline data and the structure of the EIA by both independent authors (Collins et al., 2013, Knight et al., 2013, 2015, Clark et al., 2017, 2019, Piet et al., 2017, Durden et al., 2018, Kaikkonen et al., 2018) and official bodies like the ISA (ISA, 2002, 2010, 2016, 2019).

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[1] https://www.isa.org.jm/deep-seabed-minerals-contractors D.d. 16-05-19
[2] http://www.meti.go.jp/english/press/2017/0926_004.html d.d. 16-02-2018
[3] http://www.manafai.com/index.php d.d 10-01-2018
[4] http://www.nautilusminerals.com/irm/PDF/2086_0/NautilusMineralschangeindirectorsandofficers D.d 16-05-19

All these papers do not define what aspects and which evaluation criteria should be included in an EIA. In general the approach is i) to make an inventory of the anticipated impacts by an expert team, ii) supplement those by the legal requirements and criteria, and iii) complement this overview by consulting stakeholders from the scientific communities, NGO's, other users and decision makers and area managers (Lee et al., 1995, CNS, 2008, Durden et al., 2018). Despite that approach, EIAs in the marine environment receive fundamental criticism and projects are hampered by fierce environmental discussions (Sharma, 2017, 2019, Filer and Gabriel, 2017, Miller et al., 2018, Rozemeijer et al., 2018, Durden et al., 2018).

Therefore, a transparent and objective approach for assigning the evaluation criteria for an EIA for the marine environment is necessary, preferably using an ecosystem approach and possibilities for accumulation of impacts across sectors (King et al., 2013, 2015, Piet et al., 2017). The marine environment is heavily exploited by different industrial sectors in the same regions (e.g. shipping, mining etc.). Different activities[5] (within or across sectors) can exhibit similar pressures[6] exhibiting an alike impact on the ecosystem components[7]. The approach should enable cumulating of alike pressures across sectors: e.g. the underwater sound that is generated by shipping, fishing and seismic research. A cumulative Linkage framework method is offered by the ODEMM approach[8] which is designed to evaluate management measures in the context of the Marine Strategy Framework Directive (MSFD) (Figure 1, White et al., 2013, Knight et al., 2013, 2015, Tamis et al., 2015, Piet et al., 2017). In essence it is an integrated Risk Based Impact Assessment (iRBIA). This iRBIA methodology is applicable in scoping evaluation criteria by a Linkage Framework, risk assessment on impacts and assessing data quality of any level of EA from EIA to Strategic EA.

Since lack of knowledge is an important argument for non-acceptance of especially offshore mining projects, it is important to determine not only impact/risks but also the validity and confidence level of the estimates. Based on potential importance of impact and actual data availability, a prioritization can be made on what to monitor with more emphasis and what could receive lesser attention.

Research question

In this manuscript we intend to study the first step of the iRBIA: the generation of a generic iRBIA linkage framework for EIAs for offshore seabed mining. The case of SMS deposit mining will be elaborated since this type projects is about to start in Japan[2] or was just cancelled (Solwara, CNS, 2008,[4]) at the same time enduring significant public debate on acceptability (e.g. Rosenbaum and Grey, 2015, Filer and Gabriel, 2017). Comparison of several literature sources reveals that marked differences exist in nomenclature and definitions with regards to activities, pressures and ecosystem components. Therefore we aim to develop a methodology to construct a generalized first overview of relevant activities, pressures and ecosystem components that can serve as a starting point for an EIA to be discussed with relevant stakeholders. This generalised approach could be helpful in facilitating comparability in EIAs on SMS deposits and offshore mining in general. The sequel of this paper will involve a comparison of risk and data availabilities estimates by different methodologies.

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5 Activity: an activity, action, process, or physical works intended to enhance human welfare; alternative terms used are e.g., driver, sector. Activity is used at the highest level (driver from society) to lower levels like sector and the activity of particular machines or gears (Tamis et al., 2015, Kaikkonen et al., 2018).

6 Pressure: the mechanism through which an activity has an effect on any part of the ecosystem (Robinson and Knight, 2011); alternative terms used may be stressor, impact, effect (Tamis et al., 2015)

7 Ecosystem components: ecologically coherent elements of an ecosystem that group together more disparate taxonomic groups into the minimum number of elements, based on the view that the lower the number of elements, the easier it is to gain a coherent and integrated assessment across the ecosystem (Robinson and Knight, 2011); alternative terms used may be valued ecosystem component (VEC), ecological component, receptor, indicator (Tamis et al., 2015).

8 https://odemm.com/content/linkage-framework D.d. 20-5-19

Material and methods

The starting point of the exercise is the ODEMM methodology[8] (*Figure 1A,B*, White et al., 2013). The advantage of ODEMM is its foundation in the MSFD. E.g. marine aggregates extraction, fishing or shipping represent sectors, that undertake specific activities[5] (e.g. extraction of ores with a seafloor mining tool, SMT,) during their exploitation of marine resources. Each sector activity can generate many different pressures[6] that impact one or more ecological components[7]. Pressures have a direct impact on the ecological components. The impacts on that ecological components can have a derived impacts on ecosystem structures, functions and services that are depending on those ecological components. E.g. the activity of "Aggregate extraction" causes the pressure "Smothering". "Smothering" has an impact on benthic fauna and the changes in that benthic fauna can have an effect on the ecosystem structure "Biodiversity". The same pressures from different sectors can be cumulated, e.g. the "Smothering" caused by extraction and by bottom trawling (*Figure 1*).

Starting point for the methodology is an literature survey. Extensive literature is available on SMS deposit exploitation. For this publication the following were selected: next to the ODEMM approach (White et al., 2013), a genuine EIA (Coffey Natural Systems, CNS, 2008) and two independent reviewers on that EIA (Steiner, 2011, Luick, 2012), and EIAs methodology approaches Ortega (2014), Ministry for the Environment (MFE, 2011) and Narita et al. (2015). Van Dover (2014), ISA (2011), Armstrong et al. (2012), Kaikkonen et al. (2018, on nodules but principles are valid) and Turner et al. (2019) yielded broader background.

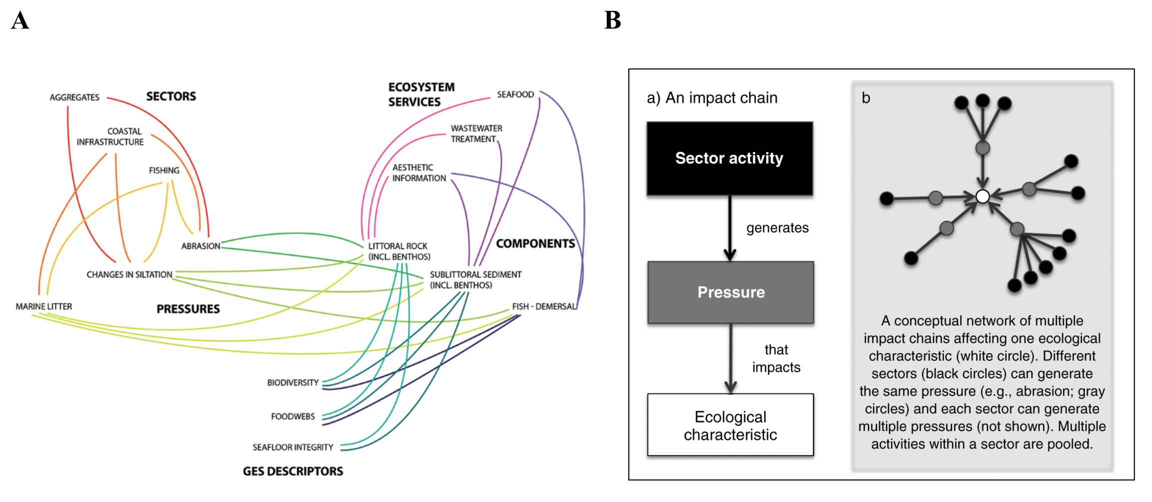

Figure 1 ***A:*** *An illustration of the full linkage framework of the ODEMM approach showing linkages between a subset of elements of the ecosystem (White et al., 2013).*

B: *Impact chains. (a) A generic hierarchical impact chain linking sectors and activities to an ecological characteristic via a specific pressure. A separate impact chain is generated for every combination of sector (black circles), pressure (grey circles), and ecological characteristic (central white circle).*

Description of the selected case to study

The exploitation of SMS deposits is variable in its execution, compare e.g. the different scenarios in Ortega (2014). For testing our methodology, the operation form proposed by Nautilus Minerals for Solwara was selected as a starting point because it is the first complete EIA on SMS mining (*Figure 2*, CNS, 2008). The mining site is a predominantly extinct vent with some active vent chimneys. The actual project site is 0.112 km^2 at a volcanic summit of an estimated 6.3 km^2 at 1,500-1,600 metres water depth. The to be mined patches are e.g. ~100*50 m.

A SMT harvests the SMS deposits, which are pumped to the mining vessel through a riser pipe. The ores are retained and the wastewater including fines is returned to the sea (release depth under discussion, see e.g. Ortega, 2014). In short, the pressures are: 1) removal of substrate (and animals); 2) sediment plume; 3) toxic compound release; 4) disturbance by tools and ships. In the Nautilus approach the sediment water and other effluents (SWOE) were intended to be released at 50 m above the seabed with the return pipe opening directed upward.

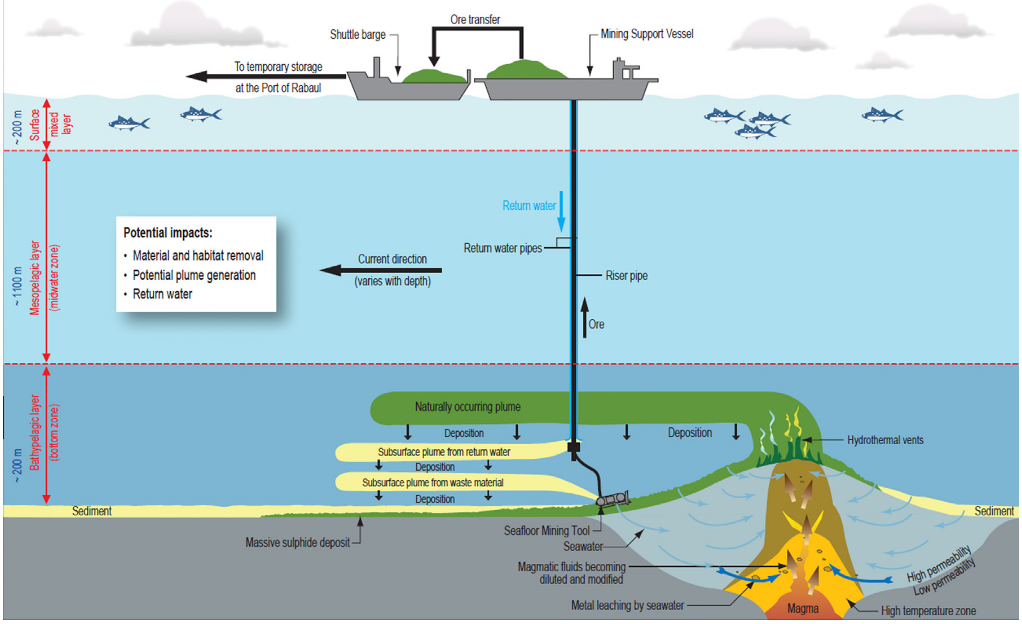

Figure 2 Schematic showing proposed mining process proposed for the Solwara 1 project and perceived potential impacts (figure from CNS, 2008).

Results

In a stepwise approach the linkage framework is constructed. Conform White et al. (2013) an overview of pressures, activities, ecosystem components, ecosystem structure, functions, services were made using the selected literature. Per type of entity the approach is explained together with results and a short discussion.

Activities

A complete EIA linkage frame is rather extensive (see e.g. Appendix A in CNS, 2008), and beyond the scope of this publication which intends to demonstrate principles. Therefore, those activities were selected that are most specific for SMS mining: the cutting and removal of SMS deposits by the SMT and the release of SWOE (conform Ortega, 2014). The overview of activities, including labelling and definition, was primarily based on Ortega (2014), completed with CNS (2008) and MFE (2011).

Table 1 gives an overview on the activities encountered. Ortega (2014) compiled the activities based on discussions between scientists and a group of industrial stakeholders. CNS (2008) determined the linkage framework based and activities through stakeholder meetings, both public stakeholders and the relevant scientific community. What they called hazards are 'activities' in the current terminology. In MFE (2011) activities and pressures are defined less precisely. Some aspects that are pressures according to our definitions are designated activities in their approach.

In total eleven activities were established (Table 1). Most activities were mentioned by at least two scources. The high similarity in activities demonstrates that there is a common ground for a generalised approach. Two activities “Seafloor installations” and “Jet stream hitting bottom floor” were only mentioned once. CNS (2008) evaluated most activities (10 out of 11 total).

Pressures

Literature was investigated on all pressures involved in SMS deposit mining mentioned. These were assembled into a longlist and subsequently selected on their relevance for SMT activities and SWOE (Table 2). White et al. (2013) give a gross list of the pressures used and defined in the ODEMM approach. The first seventeen pressures were derived from the MSFD. Pressures 18-24 were added to that set by White et al. (2013). Pressures 25-37 were derived from the other sources considered. Ortega (2014) deviated at some points from White at al. (2013). Ortega (2014) defined the pressure “Waste generation” (# 25 in Table 1). It was registered in the approach but subsequently omitted because it was not enough distinctive from the ODEMM pressure “Marine Litter” (# 7). The ODEMM pressure sealing (# 2). was defined as “substrate loss” by Ortega (# 26 in Table 2). This seems more an impact of e.g. “Smothering, Abrasion, Selective extraction”.

Seven out of 37 pressures, all MSFD defined pressures, were encountered in ≥80% in the literature: “Smothering”, “Changes in siltation”, “Selective extraction of non-living resources”, “Underwater sound”, “Introduction of non-synthetic compounds”, “Selective extraction of species”. Next, 15 out 37 pressures were mentioned in only 30% or less of the references. The lack of agreement between these formally reviewed impact studies clearly demonstrates the need for a common, comprehensive approach.

CNS (2008, being a genuine EIA) discussed 33 of all 37 encountered pressures, Ortega (2014, being a methodology demonstration for an EIA approach) discussed 32 of all 37 encountered pressures. MFE (2011) and Narita et al., (2015), both methodology demonstration for an EIA approach as well, discussed 16 and 14 pressures respectively. The other publications in Table 2 were more focussed on highlighting aspects of SMS deposit mining rather than elaborating the entire scope of a mining operation and EIA.

Linking activities to pressures

Next it was checked in the three selected sources whether a pressure was coupled to an activity (Table 3). To this extend, only Ortega (2014), CNS (2008) and MFE (2011) were analysed. Only those pressures were selected that were associated to the selected activities. A pressure was omitted if at this point it was already apparent that no impacts could be assigned (reducing the amount of pressures from 37 to 21, Table 3, Table 1).

Most of the pressures were attributed to the excavation of materials by the SMT, especially the cutting of the soil (Table 3). SWOE had much less pressures. The pressures most mentioned were “Smothering” and “Changes in siltation (sediment concentration)”, followed by “Underwater sound” and “Selective extraction of species”. The pressures least mentioned were “Electromagnetic changes” and “Entanglement”. Remarkably only 15% of the pressures coupled to a activity were mentioned by Ortega (2014), CNS (2008) and MFE (2011), 23% by two sources. A high 62% was mentioned by only one source, demonstrating large differences in interpretation and thereby a need for a general approach and guideline. The activities “Seafloor installations” and “Umbilicals” had the least pressures linked.

The activities of the SMT also had the most impacts estimated to be of relevance. As compared to SWOE the activities of the SMT have more pressures associated due to the alteration of the local system due to the removal of the active vent chimneys. This could lead to generation of new chimneys at other locations and an “Emergence regime change” leading to local extinction of vent dependent associations.

Linking pressures to ecosystem components

Reducing much of the actual complexity of SMS-associated ecosystems, mining pressures were linked to the following first order ecological components: benthos, zooplankton and fish (the latter two subdivided for epi-, meso- and bathypelagic layers following CNS (2008), Steiner (2011), Luick (2012), MFE (2011). Considering the ODEMM linkage of ecosystem components with pressures insufficiently detailed for SMS mining, we took Ortega (2014) as a basis and extended this following CNS (2008) and MFE (2011) (Table 4).

Ortega (2014) split up the vent benthos and non-vent benthos in functional groups like vent bivalves (e.g. *Bathymodiolus azoricus*), vent shrimps (*Mirocaris, Chorocaris, Rimicaris*), vestimentifera (vent worms) and non-vent benthos like stony corals (e.g. *Lophelia pertusa*), octocorals, large snails (*Buccinids, Turrids*), crinoids (sea-feathers) but CNS (2008) and MFE (2011) mainly distinguished the higher functional groups of "Vent benthos" and "Non-vent benthos", making an exception for the non-vent corals ("Stony corals and octocorals"). Those were particularized because of their vulnerabilities and estimated impacts. Since for Ortega (2014) the impacts are also assignable to the higher level functional groups of "Vent benthos" and "Non-vent benthos", it was decided to continue at that level. An exception are the aforementioned "Stony corals and octocorals". The ecosystem components "Habitat" and "Habitat types" are difficult to define. Taking e.g. the project area, can be considered as one habitat type "Massive sulphides" (consolidated SMS deposits). On the other hand, the project site is a heterogeneous and pachty assemblages of habitat types as "Actively venting chimneys", "Extinct chimneys", "Massive sulphides sediments", "Unconsolidated sediments" and "Faecal pellets". Adding to the complexity, the "Non-vent benthos" and "Stony corals and octocorals" can be encountered in this project site starting from 20-50 m distance from an "Actively venting chimneys" (CNS, 2008). In order to reduce complexity a proxy for "Habitat types" was defined in the form of "Substrate", focussing more on species for this exercise.

Table 4 shows that authors do not generally agree in assigning impacts to Pressure : Ecosystem component linkages. Exceptions are "Selective extraction of non-living resources" and "Selective extraction of species" which all authors considered to have a significant impact on "Stony corals and octocorals". This discrepancy between authors urges for a more unifying approach. Surprisingly the impacts of pressures on "Vent benthos" was evaluated differently. Ortega (2014) and MFE (2011) stressed the unique nature of this type of benthos. CNS (2008) emphasised the robust nature of this type of communities since these species are present in very stressful circumstance and they are able to recolonise the substrates after disastrous events like a volcano burst.

Pressures which were most commonly considered to have significant impact on Ecosystem components were those initially recognised in the MSFD in relation to benthos and habitat (Table 4). The added pressures by White et al. (2013) and others (Table a, Table 3) seem of less importance. In addition, zooplankton and fish at any pelagic layer are in general considered not to be significantly affected.

Pressures "Nitrogen and Phosphorus enrichment", "Death or injury by collision", "Entanglement" and "Salinity regime change", considered not relevant for the selected targets or perceived not to be harmful, were eliminated, leaving a total of 17 pressures in Table 4.

Linking ecosystem components to ecosystem structure, functions and services

Ecosystem components like (non-)vent benthos or zooplankton contribute to Ecosystem structures, functions and services like biodiversity, food web functioning, etc. In the approach of ODEMM the ecosystem services are translated to services which are closely linked to human society or to indicators of the MSFD describing the state of the system. At current knowledge level for SMS deposit mining the discussion on ecosystem functioning and EIAs is still at the beginning stages. Therefore, it was thought more important to emphasise the basic structures, functions and services, rather than the derived, society and policy related services. Millennium Ecosystem

Assessment (2005), Armstrong et al. (2012) and Kaikkonen et al. (2018) define provisioning services (harvestable aspects, like biomass, genetic treasure), regulating services (ecosystem aspects that regulate the benefits for human being like CO_2 absorption) and supporting services (that maintain the ecosystem to come to services, like chemosynthetic primary production, nutrient recycling, habitat availability etc.) and cultural services (the often non-material benefits that people obtain, in this case only one evaluated "Protected species", Table 5). Turner et al. (2019) clearly distinguished structural elements, functions and services. In the present linkage framework MFE (2011) was taken as starting point because it defines readily available ecosystem functions and services. The framework was then supplemented with Armstrong et al. (2012), Kaikkonen et al. (2018) and Turner et al., (2019), Ortega (2014) and CNS (2008).

Twelve structures, functions and services were encountered (Table 5). Analysing more literature would yield more functions, still this is already sufficient to demonstrate our methodology. "Habitat" to "Key species" are typically structures. "Nutrient recycling" to "Recovery and resilience" are functions and/or supporting services. "Genetic diversity" and "Harvestable biomass" are provisioning services. "Protected species" was interpreted as a cultural function, finding its origin in legal and policy considerations. "Food web functioning" and "Ecosystem functioning" seem alike functions. In the description of MFE (2011) "Ecosystem functioning" is defined as a general functioning and primarily described in presence of and relations between ecosystem components. The food web and -transfer between ecosystem components is not mentioned as such. Given the primary production function of the vent system and the potential impacts on this primary production, it seems justified at this moment to define the ecosystem function of "Food web functioning". Later developments may urge to lump these two. Armstrong et al. (2012) argued that "Genetic diversity" is a form of "Biodiversity". Since the genetic diversity is often mentioned as one of the special, harvestable aspects of the deep sea in general and specifically vent ecosystems, it is kept as a separate criterion. In addition, the endemic potential of each vent justifies extra attention on the "Genetic diversity". Elaborating and refining on this discussion is beyond the scope of this paper.

Most structures, functions and services are assigned to the deep-sea components (orange blocks in Table 5), which seems logical when analysing deep sea literature. The two functions that play a role for all ecosystem layers are typically food web functioning and ecosystem functioning, demonstrating the importance of vent systems as food source for the pelagic system above (red frames in Table 5), Armstrong et al., 2012, Levin et al., 2016, Turner et al., 2019).

Ortega (2014) and CNS (2008) mentioned ample structures, functions and services in the general system descriptions but evaluated less of these in the chapter of the "Impact evaluations". E.g. CNS (2008) did not denominate the abstract levels of structure, functions and services, but evaluated according to our interpretation: "Habitat", "Recovery and resilience", "Endangered species" (a cultural service variant of "Biodiversity" but not integrated in Table 5 since it was on animals like marine mammals etc.), bioaccumulation (a form of "Food web functioning" and "Ecosystem functioning"), "Ecosystem functioning" and "Genetic diversity".

General discussion and conclusions

In the paper a methodology is applied to derive a generalised linkage framework of EIA criteria to evaluate the impacts and risks of SMS deposit mining. One could argue that every case is different. We think an extended, complete linkage framework should serve as a starting point for generating this case-specific linkage framework. The fact that Ortega (2014), CNS (2008) and MFE (2011) agreed to a large extent on the activities that are executed during mining operations, demonstrates that a solid basis is present for a generalised linkage framework.

Next to agreement we observed also important differences for especially "Pressure: Ecosystem component" linkages (Table 4) and other linkage combinations as well (other Tables). These important differences urge to a generalised approach because in essence the vent systems share a common ecosystem structure (ISA, 2010, Armstrong et al., 2012Boschen et al., 2016, van Dover, 2014, Levin et al., 2016, Turner et al., 2019).

The aspect "Activities" is all dependent on the degree of detail in which different studies distinguish sub-activities within the mining activity as a whole. Having an agreed-upon list of well-defined activities in SMS mining as starting point could be helpful to gain confidence from stakeholders.

The ODEMM approach with its fundaments in the MSFD functioned well as starting point, given the fact that 14 of the final 17 pressures were derived from White et al. (2013). Within these 14 pressures, 9 out of 17 pressure were defined in the MSFD (**Table 4**). Only three pressures remained from specialised SMS deposit literature. In the mostly used sources in our analysis, the actual EIA for Solwara (CNS, 2008) was the most elaborate in its approach, followed by the reports and publications on EIA methodology and then the scientific publications. The latter intend to highlight certain aspects rather than that they try to be complete. Van Dover (2014) highlights the changes in substrate qualities due to mining in respect to settlement and recovery whereas Boschen et al. (2016) highlight connectivity between vent systems. More literature will extend the linkage framework. From **Table 2** it becomes clear that for the Pressures, the overview is almost complete. Towards the higher numbers, less authors mention that particular pressure, signifying both general and the more "exotic" pressures have been found. Anyhow it seems that most important Pressures are integrated in **Table 2** given the patterns in **Table 4**.

The ecosystem components are usually site-specific on species level and community level. A generalised list could start with defining the functional groups as relevant for all vent systems and their surroundings like "Primary producers", "Suspension eaters" etc. A further subdivision could be based on higher taxonomic levels like e.g. Ortega (2014) is doing with "Vent bivalves" and "Non-vent bivalves", "Vent shrimps" and "Non-vent shrimps, etc. More research is needed to come to an all-encompassing overview.

In the EIA and reports and publications on EIA methodology more attention should be focused on ecosystem structures, functions and services. The limited overview in this study demonstrates different approaches and framing, compare e.g. Armstrong et al. (2012) and Turner et al. (2019) having different terms, aspects and detailing of structures etc. It is expected that most expansion will occur in this domain when an extensive literature overview is made.

In a next paper the subsequent step of the iRBIA methodology of Knight et al. (2013, 2015) and Piet et al. (2017) will be performed; the risk estimates in conjunction with data availability assessment alike MFE (2011). To that end CNS (2008) will be compared with their criticasters Steiner (2011) and Luick (2012) and with the risk estimates in MFE (2011).

Concluding, ideally a complete generalised linkage framework for EIA should be made available by a competent authority like ISA (for each type of mining (SMS deposits, nodules, crusts, etc.). This generalised, agreed upon linkage framework of EIA criteria can be the trusted starting point for stakeholder processes to add and adjust the EIA criteria to local issues and interests. Ideally the complete iRBIA approach with its risk and data availability estimates and associated definitions is used.

Keywords: seafloor massive (polymetallic) sulphides (SMS); hydrothermal vents; Environmental Impact Assessment (EIA); exploitation; mining; evaluation criteria, risk

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Tables

Table 1 Activities encountered in three selected references for the stages "Activities of the Seafloor Mining Tool" (SMT) and "SWOE Release".

Stage	SMT									SWOE release				Omitted	
Activity / Reference	Moving the tool	Cutting of soil	Suction of material	Depositing or loss of (waste) material (in piles)	Seafloor visualisation	Seafloor installations	Positioning tool by sonar	Raising/lowering machine to vessel	Umbilicals (and hydraulic lines, power cables, anchor lines, mooring lines)	SWOE release	Jet stream hitting bottom floor	**Mentioned of total**	**Percentage of total**	Pre-stripping of unconsolidated surface sediment	Use of slurry pipes
Ortega 2014	1	1	1	0	1	0	1	0	0	1	0	**6**	**55**	0	0
CNS 2008	1	1	1	1	0	1	1	1	1	1	1	**10**	**91**	1	0
MFE 2011	1	1	1	1	1	0	1	1	1	1	0	**9**	**82**	1	1

Table 2 Overview of the pressures encountered by several authors. Starting point were the ODEMM pressures (White et al., 2013). Pressures No 1-17; ODEMM, Listed in MSFD; Pressures 18-24: ODEMM, NOT listed in MSFD. Pressures 25-37: Added based on literature. The initials in the column Origin represent the different authors: Marine Strategy Framework Directive: MSFD White et al., (2014): W Ortega (2014): O; Coffey Natural Systems (2008): C; Steiner (2011): S; Luick (2012): L; MFE (2011) (M); van Dover (2014): vD; ISA (2011): I; Narita et al. (2015). The final selection of pressures is given in bald

No	**Pressure**	**Pressure Definition**	**Origin**	**1st selection**	**Remarks**	**2nd selection**	**Remarks**

1	**Smothering**	Cover habitat surface with materials falling to the seafloor from activities in the water column (e.g. waste substances from aquaculture cages), on land (e.g. in runoff or effluent), or around activities (e.g. around trawling gear), or from disposal of materials onto the seafloor (e.g. disposal of materials from dredging). Smothering may lead to reduced functioning (e.g. feeding) or mortality of benthic animals living on, or in the seafloor.	MSFD, W, O, C, S, L, M, vD, I, N	1	Acknowledged in relevant publications	1	
2	Sealing	Physical loss of habitat from sealing by permanent construction (e.g. Coastal defences, wind turbines)	MSFD	0	Not relevant, Ortega call this substrate loss which is essentially extraction	0	
3	**Changes in siltation (sediment concentration)**	Change in the concentration and/or distribution of suspended sediments in the water column from runoff, dredging etc.	MSFD, W, O, C, S, L, M, vD, I, N	1	Acknowledged in relevant publications	1	
4	**Abrasion**	Physical interaction of human activities with the seafloor and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring)	MSFD, W, O, C, M, vD	1	Acknowledged in relevant publications	1	
5	**Selective extraction of non-living resources**	Includes sand and gravel (aggregates) extraction, removal of surface substrates for exploitation of seabed and subsoil, or removal of seawater for e.g. cooling industrial plants or for desalination	MSFD, W, O, C, S, M, vD, I, N	1	Acknowledged in relevant publications	1	
6	**Underwater sound**	Underwater noise created from shipping, acoustic surveys, etc.	MSFD, W, O, C, S, M, vD, I, N	1	Acknowledged in relevant publications	1	
7	Marine litter	Litter originating from numerous sources but entering the marine environment and consisting of different materials including: plastics, metal, glass, rubber, wood and cloth	MSFD, W, O, C, N	0	Acknowledged in relevant publications	0	
8	**Thermal regime change**	Change in temperature of the water (average, range or variability) e.g. due to outfalls from industrial plants	MSFD, W, O, C, S, L, vD, N	1	Acknowledged in relevant publications	1	
9	Salinity regime change	Change in salinity (average, range or variability), e.g. due to outfalls from industrial plants or alterations in coastal structures affecting mixing	MSFD, W, O, C, S, vD	1	Acknowledged in relevant publications	0	Appeared not relevant in the finale evaluation
10	**Introduction of synthetic compounds**	Introduction of manmade compounds such as pesticides, antifoulants and pharmaceuticals into marine waters	MSFD, W, O, C, S, M,	1	Acknowledged in relevant publications	1	
11	**Introduction of non-synthetic compounds**	Introduction of heavy metals and hydrocarbons into marine waters	MSFD, W, O, C, S, L, M, N	1	Acknowledged in relevant publications	1	

12	Introduction of radionuclides	Introduction of radionuclides into marine waters	MSFD, W, O	0	Hardly mentioned and Ortega 2014 estimated no impacts	0	
13	Nitrogen and Phosphorus enrichment	Input of fertilisers, and other Nitrogen and Phosphorous rich substances, including any subsequent associated deoxygenation	MSFD, W, O, C, L	1	Acknowledged in relevant publications	0	Only mentioned once and no impacts envisioned
14	Input of organic matter	Organic enrichment and any subsequent deoxygenation, e.g. from industrial and sewage effluent into rivers and coastal areas, or from the waste from aquaculture or from fishing discards	MSFD, W, O, C	0	Hardly mentioned and Ortega 2014 estimated no impacts	0	
15	Introduction of microbial pathogens	Introduction of microbial pathogens into marine waters	MSFD, W, O, C	0	Hardly mentioned and Ortega 2014 estimated no impacts	0	
16	Introduction of non-indigenous species and translocations	Introduction of non-indigenous species and translocations by the activities of a particular sector (e.g. through exchange of ballast waters by shipping or from release of individuals from aquaculture)	MSFD, W, O, C, S, M, vD	0	Not to be considered, surface impact	0	
17	**Selective extraction of species**	Extraction (and subsequent mortality) of any marine fauna (vertebrate or invertebrate) from their natural habitat, including incidental non-target catch (e.g. by commercial fishing, recreational angling and collecting/harvesting).	MSFD, W, O, C, S, M, vD, I, N	1	Acknowledged in relevant publications	1	
18	Death or injury by collision	Death or injury of marine fauna due to impact with moving parts of a human activity, e.g. marine mammals with ships/jet skis, seabirds with wind turbines etc.	W, O, C, M	1	Acknowledged in relevant publications	0	Not valid for benthos, plankton or fish
19	**Barrier to species movement**	Preventing the natural movement of motile marine fauna along a key route of travel (e.g. a migration route) due to barrages, causeways, wind turbines, and other man-made structures.	W, O, C, vD	1	Acknowledged in relevant publications	1	
20	**Emergence regime change**	Changes to natural sea level regime (average, range or variability) due to barrages or other manmade structures such as coastal defences	W, O, C, S, L, vD	1	Acknowledged in relevant publications	1	
21	**Water flow rate changes**	Changes in currents (speed, direction or variability) due to barrages or other manmade structures such as coastal defences	W, O, C, M, vD	1	Acknowledged in relevant publications	1	
22	**PH changes**	Changes in pH (average, range or variability) e.g. due to run off from land-based industry	W, O, C, S, vD	1	Acknowledged in relevant publications	1	

23	**Electromagnetic changes**	Change in the amount and/or distribution and/or periodicity of electromagnetic energy emitted in a marine area (e.g. from electrical sources such as underwater cables)	W, O, C, S	1	Acknowledged in relevant publications	1	
24	Change in wave exposure	Change in the size, number, distribution, and/or periodicity of waves along a coast due to installation of coastal structures	W, O, C	0	Not to be considered, surface impact	0	
25	Waste generation	Waste consisting of different materials including oils and fats, plastics, metal, glass, rubber, wood, etc. Arising from general operations	O, C, S	0	Added by Ortega but is alike Marine litter	0	
26	Substrate loss	Surface seafloor area removed by means of excavation. Change in substrate type due to loss of key characteristic features (physical and/ or biological). Natural substrate is lost and replaced by a different kind of substrate (different soil characteristics)	O, C, S, M, vD	0	Added by Ortega but is alike Selective extraction of non living resources	0	
27	Introduction of other substances	Introduction of solids, liquids or gases not covered by other introduction types	O, C, S, vD	0	Sufficiently covered by other pressures	0	
28	Visual disturbance	Change in normal behaviour of species (e.g., avoidance of an area by birds) due to presence of humans; vessels or machinery	O, C	0	Not to be considered, surface impact	0	
29	**Underwater light**	Introduction of light for visualisation of SMT operations in deep waters.	O, C, S, M, vD, I	1	Acknowledged in relevant publications	1	
30	**Vibration**	Vibration waves induced by excavation, vertical transport and processing on board	O, C, vD, N	1	Acknowledged in relevant publications	1	
31	Emissions of NOx, SO2	Atmospheric emissions product of combustion processes (e.g., vessel engine)	O, C	0	Not to be considered, surface impact	0	
32	Emissions of particulate matter to atmosphere	Atmospheric emissions product of combustion process (e.g., vessel engine)	O, C, M, N	0	Not to be considered, surface impact	0	
33	Atmospheric noise	Atmospheric sound generated by vessel operations, on board processing and general operations and transferred to the atmosphere	O, C, M, N	0	Not to be considered, surface impact	0	
34	Entanglement	Entanglement of megafauna (cetacean, turtles etc.), in subsurface equipment including umbilicals, anchor lines, mooring lines, marker buoy lines, power cabling or hydraulic lines is a possibility	C, M	1	Acknowledged in relevant publications	0	Not valid for benthos, plankton or fish
35	Surface light	Introduction of light for visualisation of vessel operations at the surface.	C, S, M	0	Not to be considered, surface impact	0	
36	**Oxygen regime change**	changes in dissolved oxygen contents may occur by releasing the excess water with increased levels	N	1	Overlooked by most, seems important	1	

37	Gushing out the methane and CO2 in the sediment	gushing out the methane in the sediment and CO2 stored in liquid and hydrate state by activities (e.g. pressures) ranging into the atmosphere	N	0	Not to be considered, surface impact	0	

Table 3 Activities linked to pressures. White at al. (2013) was used as a starting point for the pressures. Ortega (2014) (O), Coffey Natural Systems (2008) (C) and MFE (2011) (M) were analysed. Orange cells: pressure defined in the MSFD. Blue cells: pressures defined in White et al. (2013). Mauve cells: pressures encountered in other sources. When a pressure was mentioned for a activity the first initial is given. When a high enough impact was estimated by any author, the cell is coloured red. Not coloured cells mean no impact envisioned by those authors. Completely empty cells: pressure : activity linkage not encountered.

Activity / **Pressure**	Moving the tool	Cutting of soil	Suction of material	Depositing or loss of (waste) material (in piles)	Seafloor visualisation	Seafloor installations	Positioning tool by sonar	Raising/lowering machine to vessel	Umbilicals (and hydraulic lines, power cables, anchor lines, mooring lines)	Tailings release	Jet stream hitting bottom floor
Smothering	O, C	O, C, M	O, C, M	C, M	O	C	O	C		O, C, M	C
Changes in siltation (sediment concentration)	O, C	O, C, M	O, C, M	C, M	O		O	C		O, C, M	C
Abrasion	O, C	O	O		O	C	O	C		O	
Selective extraction of non living resources	O, C, M	O, C, M	O, M		O		O			O	
Underwater sound	O, M	O, C, M	O, M		O, M		O, M			O	
Thermal regime change	O, C	O, C	O		O		O			O, C	
Salinity regime change	O	O	O		O		O			O, C, M	
Introduction of synthetic compounds	O, C	O, C	O		O		O			O, C, M	
Introduction of non-synthetic compounds	O, C	O, C, M	O	C, M	O		O			O, C, M	C
Nitrogen and Phosphorus enrichment	O	O	O		O		O			O	

Selective extraction of species	O, C	O, C, M	O, C		O, C		O			O	
Death or injury by collision	O	O	O		O		O			O	
Barrier to species movement	O	O, C	O		O		O			O	
Emergence regime change	O	O, C	O		O		O			O	
Water flow rate changes	O	O, C	O		O		O			O	
PH changes	O	O, C	O		O		O			O	
Electromagnetic changes	O	O	O		O		O		C	O	
Underwater light	O, C, M	O, C, M	O, C, M		O, M		O			O	
Vibration	O	O, C	O		O		O			O	
Entanglement								M	C, M		
Oxygen regime change	C			C						C	

Table 4 Pressures linked to ecological components. Since White at al. (2013) was not designed for SMS deposits, Ortega (2014) was used as a starting point for the pressures. Ortega (2014) (O), Coffey Natural Systems (2008) (C) and MFE (2011) (M) were analysed. When a pressure was linked to ecological components the first initial is given. When an impact was estimated to be substantial enough the initial is coloured red. Black initials mean no impact envisioned by those authors. Empty cells or missing initials mean that no link between pressure and ecological component given.

Ecological components / Pressure	Vent benthos	Non-vent Benthos	Stony corals and octocorals	Substrate	Bathypelagic zooplankton	Deep sea fish	Deep sea zone commercial fish	Mesopelagic zooplankton	Mesopelagic fish	Epipelagic zooplankton	Epipelagic fish	Epipelagic commercial fish
Smothering	O, C, M	C, M	O	O, C	O	O, M	O,	O	O, M	O	M	O , M

Changes in siltation (sediment concentration)	O, C, M	C, M	O	O, C, M	O, M	O, M	O	O, C, M	O, C, M	C, M	C, M	O, M
Abrasion	O, C	C	O, C	O, C		M	O		M		M	O, M
Selective extraction of non-living resources	O, C, M	C, M	O, C, M	O, C, M		O	O					O
Underwater sound	O, C, M	C, M	O	O, C, M	O, C, M	O, C, M	O					O
Thermal regime change	O	C	O, C	C		O	O					O
Introduction of synthetic compounds	O, C, M	C	O	C	O, C, M	O, C, M	O	C, M	C, M	O, C, M	C, M	O, M
Introduction of non-synthetic compounds	O, C, M	C, M	O, C, M	C, M	O, C, M	O, C, M	O, M	O, C, M	O, C, M	O, C, M	C, M	O, C, M
Selective extraction of species	O, C, M	C, M	O, C, M	O, C, M	C	O, C	O					O, M
Barrier to species movement	O		O	O	O	O	O					O
Emergence regime change	C	C	C	C								
Water flow rate changes	C	C	C	C								
PH changes	O, C	C	O, C	O, C	O	O	O					O
Electromagnetic changes	C	C	C	C	C	C		C	C	C	C	
Underwater light	O, M	M	O, M	M	O, C	O, C	O					O
Vibration	O		O	O	O							

Oxygen regime change	O, C	C	O, C	C	O	O						

Table 5 Ecosystem components linked to ecosystem functions and services. Letters are initials indicating the literature in which the function or services was encountered. MFE (2011) (M) was used as a starting point for the functions and services. Other authors: Armstrong et al. (2012): A; Kaikkonen et al. (2018): K; Turner et al., (2019): T; Ortega (2014): O; Coffey Natural Systems (2008): C.

	Ecosystem structure			**Functions or supporting services**						**Provisioning service**		**Cultural service**
	Habitat	**Biodiversity**	**Key species**	**Nutrient recycling**	**chemosynthetic primary production**	**Food web functioning**	**Ecosystem functioning**	**Breeding & nursery grounds**	**Recovery & resilience**	**Genetic diversity**	**Harvestable biomass**	**Protected species**
Vent benthos	M, A, K, T	A, K, T, O, C	M, O, C	A, K, O, C,	A, K, T, O, C	A, K, T, O, C	M, A, K, T, O	T	M, A, K, T, O	A, T, O, C	A, C, T	
Non-vent benthos	M, A, K, T, O	A, K, T, C	M, O, C	A, K, T, C	T, C	A, K, T, O, C	M, A, K, T, O	T	M, A, K, O	A, T, C	C	M
Stony corals and octocorals	M, A, K, T, O	A, K, C	M, O, C	A, K, C	A	A, K, T, O, C	M, A, K, T, O	T	M, A, K, O	A, C		M
Substrate	M, A, K, T, O	A, K		A, K, C	A, K, T	A, K	M, A, K	A, K, T	M, A, K, O, C		A, K	
Bathypelagic zooplankton	M, A	A	M	C	T	A, T, O, C	M, A, K, T, O, C		M, A, O			M
Deep sea fish	M, A, K, O	A	M	C	T	A, K, T, O, C	M, K, T, O, C	A, K, O	M, A, K	A	O	M
Deep sea zone commercial fish	M, A, K, O	A, K	M	C	T	K, T, O, C	M, K, T, O, C	O	M, A, K, O	A	M, A, K, T, O	M
Mesopelagic zooplankton	M		M	C	T	T, O, C	M, T, O, C		M, O			M
Mesopelagic fish	M	K	M	C	T	K, T, C	M, T, C	O	M, O		O	M

Epipelagic zooplankton	M	C	M	C	T	T, O, C	M, T, O, C		M, O			M
Epipelagic fish	M	K, C	M	C	T	K, T, C	M, T, C	O	M, O			M
Epipelagic commercial fish	M	K, C	M	C	T	K, T, C	M, T, C	O	M, O	M		M, A, T, O

Field Testing: improving environmental performance of polymetallic nodule harvesting

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Summary

Technical and environmental performance of Apollo II, a scaled polymetallic nodule mining vehicle prototype developed by IHC Mining in the framework of the Blue Nodules project, were tested in a relevant marine environment in summer 2018. The focus of this abstract is on the first 2018 field test of the Blue Nodules consortium and the lessons learned as the 2019 field test will just have finished when UMC 2019 takes place. Hopefully the implementation of the lessons learned and the design iterations for Apollo II will have resulted in an improved environmental and technical performance.

1. Introduction

To secure a sustainable access to raw materials, including critical raw materials for high-tech applications, major industrialized countries around the globe are investigating the extraction of mineral resources from the deep sea floor as a potential supplement to conventional mining on land and recycling of materials. Whilst a legislative framework regulating deep-sea mining in the context of the United Nations Convention on the Law of the Sea (UNCLOS) is under construction by the International Seabed Authority (ISA), major technological challenges still exist with regards to the extraction of minerals at industrial scale from extreme water depths and avoiding irreversible damage to deep-sea ecosystems. Focusing on polymetallic nodules, abundant especially in the eastern Central Pacific Ocean at depths between 4000 and 6000 m, the EU-funded Blue Nodules project (H2020, 2016-2020) aims at developing and proving concept and feasibility of the technology up to TRL6 for an environmentally sustainable and industrially viable mining system. Among different components of the polymetallic nodule value chain addressed in this project, in particular the nodule collector system, propulsion system and umbilical are being developed to a level that they can be tested in a realistic marine environment. A very important engineering and design aspect of the equipment is minimizing the environmental effects arising from the deployment of these systems in the marine environment with iterations for continuous improvement. After initial design and laboratory testing of various system components in 2016 and 2017, the developed systems were integrated in 2018 in Apollo II, a scaled mining vehicle prototype assembled for the purpose of testing the systems in a relevant marine environment. Two field tests were initially scheduled for early and late 2017, but were eventually postponed to summer 2018 and 2019.

2. Field Test Aims

The aim of the Blue Nodules field test was to assess the technical and environmental performance of the nodule collector system, propulsion system and umbilical, integrated in the Apollo II scaled mining vehicle prototype, in a relevant marine environment. The Apollo II vehicle, with dimensions of 5.6 m x 2.5 m x 2.3 m, weighing 3800 kg in air and 850 kg in water, and connected to the ship via an umbilical cable for hoisting, power supply and data exchange, was to that end lowered on weakly sloping muddy seabed in about 300 m water depth to carry out a series of technical tests regarding in particular:

- Tractive effort of tracks, velocity, performance and power
- Turning accuracy, performance and power
- Slip of track wheels
- Accuracy of measuring positioning

- Accuracy of measuring forward velocity
- Sinking in seabed sediment
- Amount of sediment taken up by hydraulic collector
- Seafloor following system collector
- Obstacle rejection

Minimizing environmental impact is an important goal of the Blue Nodules project, and therefore assessment of environmental effects arising from the operation of the propulsion and collector systems was an integral part of the test program, in particular regarding:

- Deformation and compaction of the surface sediment
- Mobilization of surface sediment
- Dispersion of mobilized sediment in sediment plume
- Redeposition of mobilized sediment
- Underwater noise (2019 field test)

Planned activities during the field test, along with the performance tests of the Apollo II vehicle, included multibeam bathymetric mapping, water column profiling and water sampling with CTD-Rosette system, monitoring of water column currents with ship-borne ADCP, seabed video surveying with ROV Genesis, surface sediment sampling with video-guided boxcorer, plume monitoring with an array of moored current profilers and turbidity sensors. Recording of underwater sound with a moored acoustic recorder is foreseen for the 2019 Field Test.

3. Field Test Area criteria

Field testing of equipment and measuring the environmental effects in the CCZ is very costly and imposes a lot of extra challenges to the whole operation. Therefore an area with similar seafloor sediment conditions at reduced water depth is chosen to make operations easier and improvement iterations easier.

Figure 1:Location of the Bay of Málaga field test area on the continental margin of southern Spain.

Considerations that led to selection of the Bay of Málaga (Fig. 1) as test area were the availability of seabed and bottom water characteristics comparable to those encountered in the nodule-rich areas of the deep Pacific Ocean, yet in relatively shallow water of 200-500 m water depth, with high probability of favourable sea state. Environmental characteristics critical for the field test

include the very gently inclined seabed covered with fine-grained cohesive sediment, and weakly stratified and relatively transparent bottom water, with gentle bottom current regime. Locations along the Atlantic margins of northern and western Europe appeared generally unsuitable in view of their exposure to more dynamic tidal and wind-driven currents and higher incidence of rough sea state, resulting in relatively turbid bottom waters and often coarse grained sediments.
With the opportunity to charter the Spanish RV Sarmiento de Gamboa, the search for a test area went out to the Mediterranean continental margin of Spain, where tidal currents are significantly weaker as compared to the Atlantic margin, and where favourable sea state conditions prevail especially during the summer months. In consultation with marine geologists of the Institute of Marine Sciences (ICM-CSIC) in Barcelona the Bay of Málaga was identified as the most suitable area for the test.

4. Equipment and operation

RV Sarmiento de Gamboa

Figure 2:Research vessel Sarmiento de Gamboa. Photo Robin Houthoofdt.

The multipurpose research vessel Sarmiento de Gamboa (Fig. 2) was built in 2007 on order of the Spanish national science organization CSIC, which operates the ship through its marine technology division UTM. The ship with overall length and width of 70.5 m and 15.5 m, respectively, and gross tonnage 2754 T, has been designed for operations in all oceans except the polar regions. The 16-member crew allows operations on a 24/7 basis. Berths are available for a total of 26 scientists. Winches and A-frames allow deployment of a broad range of oceanographic equipment to full ocean depth. Hull-mounted devices include a gondola with multibeam and parametric echo sounders, and two drop keels with echo sounders, ADCP and USBL. The ship has a total of 450 m^2 of laboratory space for various purposes and a range of onboard analytical equipment.

Multibeam and sub-bottom profiler

To provide a base map for all further seabed operations, the entire 4 x 4 minute test area was surveyed with multibeam echosounder. With water depths ranging from about 200 to 400 m, six E-W oriented lines were enough to cover the entire test area.

Vessel-mounted ADCP

As a basis for designing an effective setup for monitoring sediment plume dispersion, water column profiles of current speed and direction were collected continuously throughout the survey period (8-19 August 2018) with the 75-kHz Teledyne RD Instruments (RDI) Ocean Surveyor ADCP mounted in the ship's hull, along with ancillary data of ship position, pitch and roll and heading. Ship tracks covered by vessel-mounted ADCP are shown in Fig. 3.

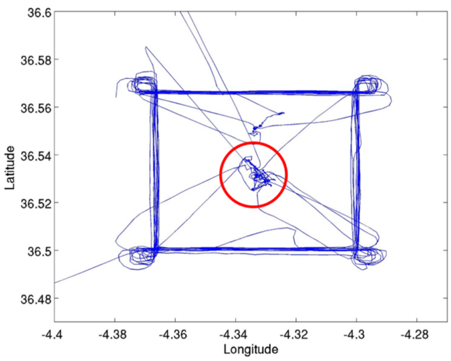

Figure 3: Ship track in Málaga Bay, outlining the perimeter of the 4 x 4 minute field test area covered by repeated vessel-mounted ADCP surveys. These surveys served to determine the spatial structure of larger-scale currents.

Tidal currents are generally weak in the Mediterranean Sea, but can be significant in the Alboran Sea close to the Strait of Gibraltar. The dominant tidal current is semi-diurnal with current speeds ranging between 2 cm s^{-1} (neap tide) to 5 cm s^{-1} (spring tide). Tidal currents are strongly aligned in the NE-SW direction largely following the elongated shape of the bathymetry in the area south of Malaga. Strongest spring tides were present between the 10^{th} and 16^{th} August 2018.

CTD and water sampling

A total of 16 casts were made with the CTD and ROSETTE system. The first cast served for acquiring a baseline profile of hydrographic parameters prior to any disturbance by the test activities, and for acquiring a sound velocity profile as input for the multibeam acquisition. Two of the JFE Advantech turbidity sensors of NIOZ were deployed with all CTD casts, one mounted at the base of the frame and one suspended from a rope below the frame. The other 8 turbidity sensors were later deployed in the mooring array for monitoring the sediment plume generated by Apollo II. Subsequent casts 2-19 were all carried out from a moving ship following Apollo II driving over the seabed. Various approaches, towyo-ing the CTD between surface and 4 mab, towing the CTD at 2 mab, towyo-ing between 2 and 5 mab or between 2 and 10 mab, were tried to acquire profiles and water samples from the sediment plume of Apollo II.

Moorings

For monitoring the sediment plume generated by Apollo II, five moorings were deployed, over which the following instruments were distributed:

- 8 JFE Advantech autonomously deployable deep-water optical backscatter sensors (OBS), which measure turbidity
- 2 Nortek Aquadopp 2 MHz current profilers, which measure current velocity
- 1 RD Instruments 75 kHz ADCP, a long-range current profiler which measures current velocity
- 2 Technicap PPS4/3 sediment traps

The moorings were launched by lowering the entire string anchor-first from the aft A-frame until touch-down on the seabed, and recovered by pulling the entire string with surface buoy first back on board.

Video boxcoring

Sediment cores for the analysis of surface sediment characteristics were collected by means of a NIOZ 'HaJa' boxcorer equipped with video camera for visual control on sampling. Video control on sampling is through a digital video recording system mounted on the corer frame. A total of 8 boxcoring casts were made in the centre of the 4 x 4 minute test area, all aimed at collecting undisturbed sediments from the site selected for the full-scale test. The collected boxcores consisted of featureless olive-brown mud, with conspicuously irregular 'pit and mound' surface topography shaped by burrowing crustaceans. In the top few cm, the sediment was very soft and watery, becoming more compacted and cohesive further downcore. Chitinous worm tubes of 2-3 mm diameter and tens of cm long were common. From each of the cores, a 6-cm diameter subcore was taken for determining sediment porosity, dry bulk density and particle size distribution. Replicate profiles of vane shear strength yielded values of undrained vane shear strength typically less than 0.05 kPa in the upper 5 cm of the cores, rapidly increasing to values around 0.2 kPa below 20 cm depth. Replicate depth profiles of bearing strength, measured at 5 cm vertical intervals with a Soiltest pocket penetrometer, yielded values of typically below 10 kPa in the upper 5 cm of the cores, increasing to values between 40 and 60 kPa below 20 cm depth.

ROV Genesis

The Remotely Operated Vehicle (ROV) Genesis is a 2000 m depth-rated CHEROKEE ROV with a Tether Management System (TMS) built by the company Sub-Atlantic. The ROV can then freely survey the seafloor connected to the TMS with a tether cable of 200 m.

11 successful dives with a total duration of a bit more than 25 h were accomplished with ROV Genesis. ROV dives served for reconnaissance of the test areas, inspection of Apollo

II on the seabed and layout of the umbilical, probing of the vertical and lateral extent of the plume generated by Apollo II, and collecting video footage of the trails left by Apollo II on the seabed.

Apollo II

Figure 4: Apollo II on deck

Apollo II is a scaled mining vehicle prototype specifically developed for operation in the harsh deep sea environment (Fig. 4). The propulsion system design focusses on a minimum of disturbance of the seabed sediment whilst maintaining a maximum of available traction. A rear track beam that can pivot around the longitudinal axis as well as (limited) rotation of the four tracks maximize contact surface between vehicle and sediment. To allow steering the rear tracks can rotate around the vertical axis by means of a steering arm.
During development of the vehicle special attention was paid to minimizing the use of hydraulic fluids (oil) on the vehicle. All motor and power consumers are electric and oil is only used for pressure compensation where absolutely needed to decrease the risk for environmental impact in case of leakages.
The nodule collector installed on the front of the vehicle is of the hydraulic (seawater) type developed and tested in Blue Nodules. The principle of the hydraulic type collector is based on the Coanda effect and makes use of a seawater flow to lift and erode the nodules out of the sea bottom. At the back of the vehicle a diffuser is mounted that is designed to minimize plume source development by reducing velocity and aiming the density flow.
Main characteristics of Apollo II:

Apollo II		Unit
Dimensions (L x W x H)	5.6 x 2.5 x 2.3	[m]
Mass in Air	3800	[kg]
Submerged mass	850	[kg]
Installed power	23	[kW]
Velocity (nominal)	0.7	[m/s]
Operational depth (max)	500	[m]

During the tests pressure sensors, a Nortek 2 MHz current profiler and JFE Advantech turbidity sensor were mounted on the Apollo II to measure the effectiveness of the collector system and the plume source parameters of tracking and the diffuser.

5. Final Test plan

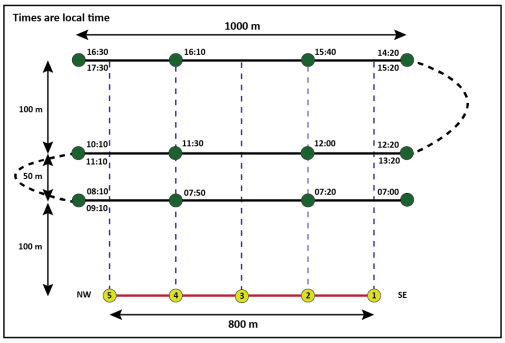

Figure 6: Apollo 2 intended test track along Moorings

During the whole cruise a lot of operational, technical and environmental data was acquired during the test runs with Apollo II and the dives with the CTD, ROV, Boxcorer and ADCP.
The final test plan was to drive Apollo II along three lines parallel to the mooring array, each line 1 km long and resp. 150 m, 200 m and 250 m distance upstream from the moorings Fig. 5 and 6). An initial attempt to drive closer to the moorings failed unfortunately.
Pausing for 1 hour at the end of each line as well as after each turn to the next line should ensure that the plume generated during each section of the track would be recorded as a separate event by the mooring sensors. Over part of the scheduled trajectory the ROV would be deployed to monitor the plume in the trail of Apollo II.

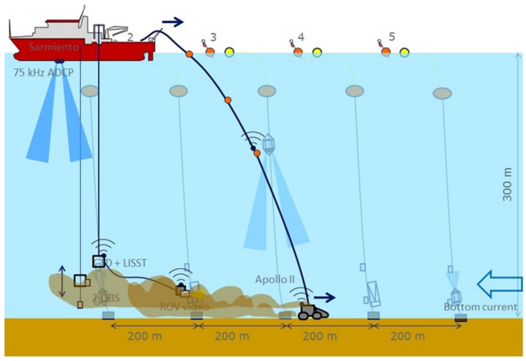

Figure 5: Overview of final test setup

After having completed the turn from the first to the second line around, ROV dive 11 was carried out to survey the freshly produced trail. Upon starting the second line, the ROV survey was resumed, now aiming at the plume rather than the trail. Diving the ROV down into the plume and back up again, and flying sideways until reaching the edges of the plume, insight was gained in the vertical and lateral dispersion of the plume. At the end of the second line the ROV was retrieved on board, and during the subsequent turn CTD casts 16-18 were carried out in a further attempt to collect water samples from the plume. Apollo II was driven along the third line with speed stepwise increasing, and with the CTD yoyo-ed at close range from the seabed. After reaching the maximum speed Apollo II lost steering control and recovered to deck. During the subsequent ROV dive 12 video footage of the trail of Apollo II was collected.

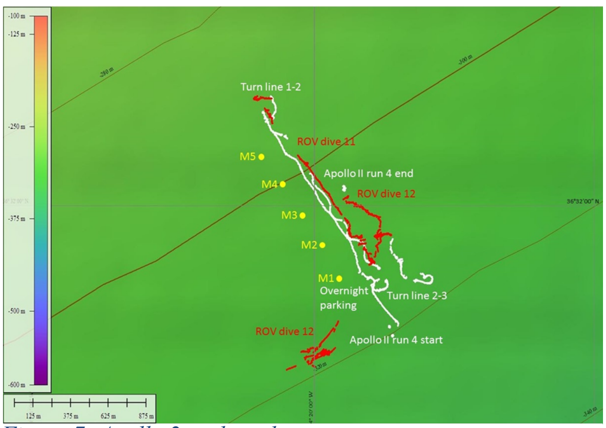

Figure 7: Apollo 2 real track

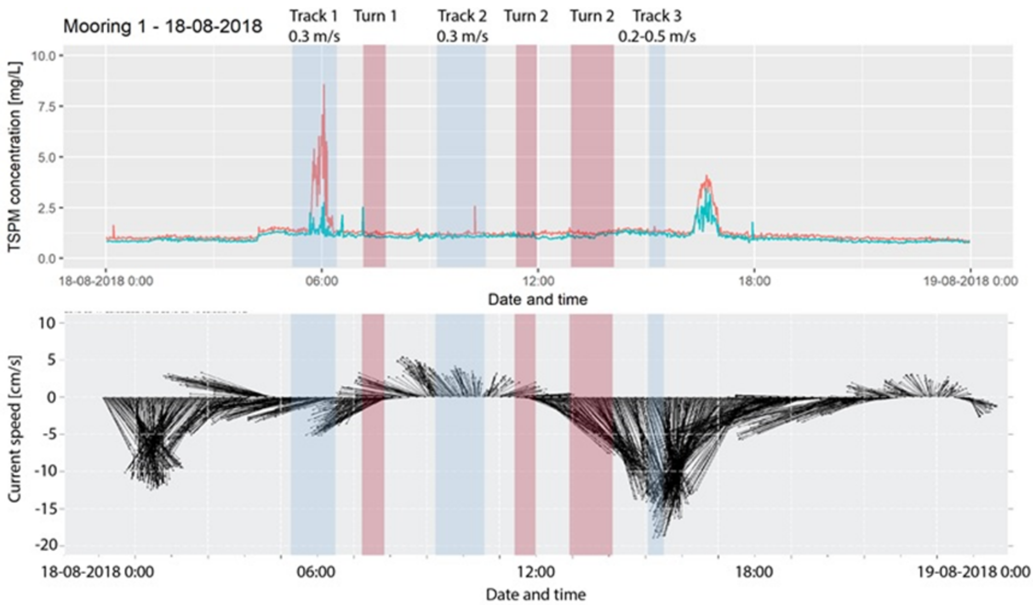

Figure 8: Upper panel: Time series record of concentration of suspended particulate matter derived from JFE Advantech turbidity sensors mounted at 1 mab (red) and 3 mab (blue) on mooring 1. Lower panel: Current variation with time. Vertical colour bars indicate different phases of Apollo II operations while it was performing test run 4 along the NE side of the mooring array.

6. Conclusions

The technical testing of Apollo II yielded valuable insights with regards to the performance of the propulsion and collector systems and umbilical, but also with regards to the launch and recovery practice and overall operation of the system. Important achievements are the following:

- The electronical control system of Apollo II remained fully functional, Cameras mounted on Apollo II provided good visual control supporting operation of the vehicle
- The independently hinged track wheels provided good traction on soft sediment, both on straight driving sections and in turns (radius 40m) and Apollo II drove more than 5km with a maximum forward speed of 0.55m s^{-1}.
- Although the collector functioned well at the start in the end it failed and the performance was hard to compare to the laboratory results given the limited submerged performance monitoring.

Points for improvement include for the 2019 Field Test:

- The heading compass didn't function well which resulted in manual drive and less control on navigation (Fig. 7).

- The hydraulic collector system and diffuser will go through a design iteration to improve performance and performance monitoring.

Taking the above into consideration, it can be observed that the field test provided valuable results with regards to environmental pressures arising from the operation of the propulsion and hydraulic collector systems:

Whilst driving performance of Apollo II was excellent, the tracks left relatively shallow impressions of about 5 cm deep in the sediment.

- At relatively close range of 100 m behind Apollo II, the plume generated by the vehicle generally extended not more than about 2 m above bottom, occasionally up to 5 m.
- Background turbidity values near the bottom were generally below 1 mg L^{-1}.
- The highest turbidity values in excess of 150 mg L^{-1} were measured at the rear end of Apollo II while the hydraulic collector was turned on.
- Sensors on the mooring array recorded short-lived peaks in turbidity up to 7.5 mg L^{-1} when Apollo II passed by at close range with the collector turned off, against background values of about 1 mg L^{-1} (Fig. 8).
- Periods of enhanced bottom water turbidity lasting several hours, as recorded by sensors on the mooring array, may be attributed to bottom trawling upstream of the moorings.

For certain aspects of environmental effects, the observations remained inconclusive:

- Due to a temporary lack of visibility near the bottom which made video-guided coring impossible, no sediment cores could be collected from the trail of Apollo II, and thus the degree of compaction of the sediment under the weight of the vehicle could not be determined.
- Due to the untimely failure of the pump motor of the hydraulic collector, no systematic sensor records were obtained of the plume generated by the hydraulic collector.

Field Test 2019:

First of all, the final test setup has proven itself as a proper setup to measure and monitor environmental aspects of deep sea mining, in combination with the CTD measurements and the aid of the ROV visual backup. With experience gained during the first field test, design iterations and operational improvements of the technical and environmental testing will be implemented during the second field test scheduled for summer 2019.

Keywords: polymetallic nodules, environmental monitoring, technology development, Blue Nodules

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Laurens de Jonge graduated in 1999 for his M.Sc in Mechanical Engineering at Delft University of Technology. After graduation he worked as R&D technician and crawler operator in offshore diamond mining for NAMCO in South Africa and Namibia. In 2002 he started working for Royal IHC as R&D project manager with specialism in subsea mining, dredging consultancy and dynamic modelling. From 2004 he managed engineering, manufacturing and service projects of offshore swivel stacks and dredging installations for the new-build dredging vessels. In 2008 his career turned back to Marine Mining when Royal IHC started a Deep Sea Mining department. Laurens was responsible for very challenging and innovative projects like the development and build of a 2km aluminium fallpipe and design and feasibility studies for the mining of subsea resources.

The development of Deep Sea Mining was boosted by two EU funded innovation projects: Blue Mining (2014-2018) and Blue Nodules (2016-2020). Laurens was responsible for submission and is now Project and Technical Coordinator of these projects. In his capacity as Manager Marine Mining, Laurens is responsible for the development of the Marine and Deep Sea Mining market for Royal IHC. This does not only involve the direct technical development and business relations, but includes involvement in the whole Mining Value Chain, legislation as well as the Social License to operate.

Geochemical and microbial characteristics of ferro-manganese crusts at depths ranging from 1100m to 5500m on the seamount in the northwestern Pacific

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Introduction

Ferro-manganese (Fe-Mn) crusts are a kind of deep-sea precipitate dominantly composed of Fe and Mn oxy-hydroxides with small amounts of clastic sediments. Thickness of these crusts range from a few to over 100 mm. They ubiquitously exist on the surface of the slopes of the seamounts at depths from 900 to 5500 meters below sea level (mbsl) (e.g., Usui et al., 2017). The Fe-Mn crusts contain extremely high concentrations of economically valuable minor metals such as Co, Ni, Te, REEs, and thus are expected as submarine mineral resources. Also, Fe-Mn crusts record the change of the ocean environments during last several tens million years, which allow us to obtain clues to clarify the paleoenvironmental conditions at the time of its deposition. We have made several research cruises to the Takuyo-Daigo and the Takuyo-Daisan Seamounts in the northwestern Pacific (Fig. 1) for last 10 years and collected the samples from several sites at a depth ranging from 1150m to 5520 m and from 1400 m to 5500 m, respectively, to clarify the geochemical and microbial features of the Fe-Mn crusts in the northwestern Pacific.

Chemical features of ferro-manganese crusts at various water depth from the Takuyo-Daisan seamount and its comparison with those from the Takuyo-Daigo Seamount

The chemical and isotopic compositions of the surface layers from the Fe-Mn crusts record the geochemical environements of adjacent seawater. The Nd isotopic compositions of the surface layer of the Fe-Mn crusts at depths ranging from 1100 m to 5500 m on the slopes of the Takuyo-Daigo Seamount agree well with those of adjacent seawater, suggesting that Nd of the crust is derived from ambiant seawater (Amakawa et al., 2017). The surfaces of the Fe-Mn crust from the Takuyo-Daisan Seamount (Fig. 1) possess wider ranges of the concentrations for most of the elements than those of the Takuyo-Daigo Seamont. For the surface layer of the crust collected from the Takuyo-Daisan Seamount, the concentration of Mn, Fe, REEs, U, Pb, Ba Sr and Be, and those of alkaline elements and Al, systematically decrease and increase with increasing depth of water, respectively. These results indicate that the chemical compositions of the deeper Fe-Mn crusts on which the Takuyo-Daisan Seamount is located much closer to the coast than the Takuyo-Daigo (Fig. 1) have been significantly affected by deep-ocean floor sediment provided by an upwelling of the deep-ocean current.

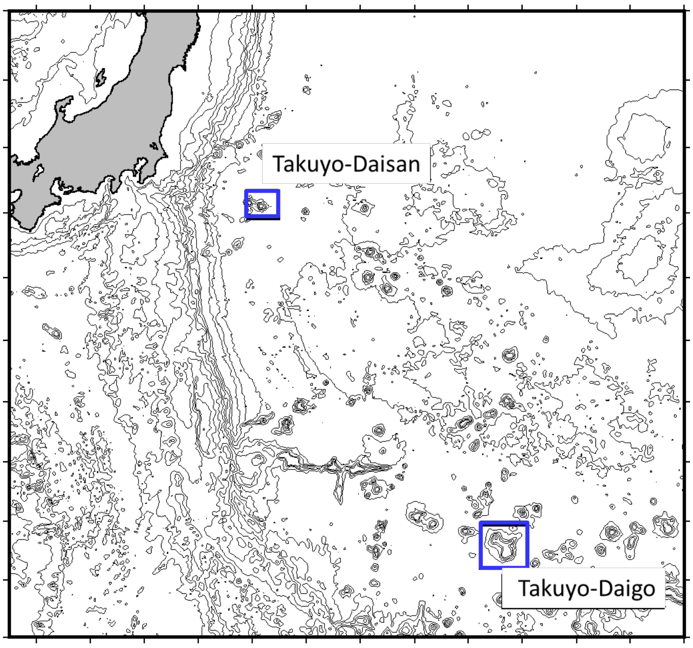

Fig. 1 Location of Takuyo-Daigo and Daisan seamounts

Microbial features of ferro-manganese crusts at various water depth from the Takuyo-Daigo Seamount

Considering wide distribution of the crusts, microbial communities on these crusts potentially play a significant role in biogeochemical cycling between oceans and seamounts. However, little is known about phylogenetic diversity, abundance and function of the crust communities. Quantitative PCR analysis showed that microbial cells were abundant (10^6–10^8 cells/g) on the crust surface through the depth. Metagenomic analysis indicated the presence of microbes involved in dissolution and precipitation of Fe and Mn, nitrification, sulfur oxidation, carbon fixation, and decomposition of organics (Kato et al., 2019). Based on our series of microbial investigation, the microbial communities likely play a role in the biogeochemical cycling of Fe and Mn, in addition to C, S and N, on the crusts and may contribute to extremely slow growth of the crusts (Kato et al., 2019).

T*his research was supported by the Next-generation Technology for Ocean Resources Exploration in the Cross-ministerial Strategic Innovation Promotion Program.*

Keywords: ferro-manganese crust, chemical composition, microbial community, deep-ocean, Takuyo-Daigo seamount, Takuyo-Daisan seamount

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Geological characterization of cobalt-rich ferromanganese crusts using deep-sea drill cores from NW Pacific seamounts

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Abstract

Hydrogenetic ferromanganese crusts have been noted as being the most abundant and having the highest cobalt-grade in Northwestern Pacific seamounts based on earlier reconnaissance regional on-site observations and sampling in the 1980s and 1990s. However, the patterns of compositional variation on a small-scale and in a range of water depths are not yet well documented. We focused on a microstratigraphic characterization of drill cores of ferromanganese crusts taken at 4-5 km intervals over the seamounts since the areal and internal variation patterns are basically controlled by their growth history and geological environment. The camera-monitored drill machine (BMS) was operated at rock outcrops, after full coverage of multi-narrow beam topographic mapping over the seamounts in the mid-Pacific seamount area, which started to grow since the subsidence of volcanic edifice and carbonate reef. The topographic mapping and BMS sampling have clearly shown a small-scale variation in thickness of crusts (up to 120 mm) basically controlled by their age, lapse time of growth, and a correlated growth history within the crusts. Our geological model indicates that the crusts have accumulated with temporal variations in mineralogy and chemistry as integrated layers of hydrogenetic precipitates over millions of years. The substrate petrology and topography, which are closely related with the geological evolution and non-tectonic movement of the seabed. A fine-scale (in millimeter) compositional and structural variations are also described and correlated among several nice drill cores. Thus, geochemical and mineralogical descriptions of full drill cores of the crusts is most important for characterizing their patterns of compositional variations within the crusts and their regional variability.

Keywords: ferromanganese crust, deep-sea drill, geological model, north Pacific, seamount

Akira Usui

Dr. Akira Usui is a geology professor at Kochi University, Japan. He worked at the Geological Survey of Japan since 1980, mainly in the field of geology, geochemistry, and mineralogy of marine ferromanganese deposits. He has published many scientific papers and maps jointly with domestic and international colleagues, based on shipboard investigations with R/V *Hakurei-maru, Hakuho-maru, Sonne, Farnella, Moana-Wave, Natsusima, Kaiyo*, *Yokosuka*, and submersibles *Shinkai* 2K, 6K. He is on the editorial board of Marine Geology and is on the editorial board of Marine Georesources and Geotechonology. He spent one year at the Scripps Institution of Oceanography, supervised by Prof. Gustaf Arrhenius. He served as the President of the International Marine Mineral Society for 2007-2008, and now is an Executive Board Member. He has been an invited principal scientist of JAMSTEC since 2011, and a member of technical advisory committee for JOGMEC committee for marine mineral exploration since 2010. His recent focus is to establish a geological growth model for hydrogenetic ferromanganese crusts in the NW Pacific seamounts based on exploration by ROVs and submersibles.

The sea trials of the second generation of the cobalt mining device

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Abstract

Changes of the second generation of cobalt mining device is provided in this report, including the electric system, hydraulic system, and collection methods. The system was design for the hard sea bottom, and first sea trails was finished on April 27 in the South China Sea, and recovered some sea rocks from the seamounts. The walking and collection functions had been working well, except some issues did occur. It also provided us some useful information about the next sea trails and the new design of the commercial mining system.

There are much research on cobalt-rich crust mining technology, for example, Yoshio (1991), Eric (2007), and LIU (2002) used CLB mining system to collect crusts; an adopted crushing head to crush crusts, and given theoretical calculation methods of mechanical excavation techniques, ZHOU (2010) used crushing head and water jet to cutting, whereas YUAN (2005) used a crushing head and vibration. The most mature technology is mechanical excavation techniques, one of the commonly used methods is the spiral drum cutting which have been widely used in land coal mines.

The first generation mining device included a hydraulic system, electric control system, tracks, cutter head, and collection and storage device. The device used a mechanical collector to cope with the power limitation which was limited by the arm cable on the ship, only 30kW power to use. We set a metal pad to avoid the dead point when the arm of the cutter head arrives at the seabed, it also ensured the arm of the cutter head to impact smoothly. Meanwhile, in order to ensure that the trailer could be smoothly placed on the ground, the upper part of the trailer was added with the middle part of the movable arm by stainless steel chains to limit the swing angle.

Keywords: Mining device; Cobalt crust; Hydraulic collection; Sea trails.

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Mechanical engineer conducting research on the technology of underwater robots and underwater equipment. Now working in Department of Deep-sea Technology and Engineering, Institute of Deep-sea Science and Engineering.

Overview of a Pilot Study for Seabed Cobalt Mining

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Abstract

Studies to develop a conceptual system for deepsea mining are conducted in China Merchant Offshore Technology Research Center (CM-OTRC), aiming at recovering the cobalt-rich ferromanganese deposits found in the Magellan seamount clusters of West Pacific Ocean. The presentation herein first reviews the market trends for cobalt, and presents the Health, Safety and Environment commitment of the organization, followed with an overview of the pilot study plan.

Under a postulated scenario of collaboration with other business partners, the studies will develop a prototype design for the mining system, a pilot testing plan, and perform an integrated test for the pilot system at a chosen location in a target mining site. The studies will be executed focusing on 1) System Architecture & Integration; 2) Seafloor Production Tools (including Seafloor Integrated Control System); 3) Riser and Lifting System; and 4) Production Support Vessel. Research tasks are elaborated for each functional component for the concept and its frontend engineering design.

Keywords: Cobalt, Deepsea Mining, Seabed Mining, Pilot System, Risers, Slurry Lifting Pump, Seabed Production Tools, Production Support Vessel, System Integration, Control System

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Dr. Xu has more than 30 years of experience in fields of marine/offshore and mechanical engineering, experienced in shipbuilding, deepwater floater projects, as well as subsea and well systems. He also has extensive engineering and delivery experience on a variety of risers including top tensioned risers (TTRs) and steel catenary risers (SCRs), flexibles, etc. He has published numerous technical papers as an author or co-author.

An Unfinished Work: The Emerging Chinese Legal Regime and Management System of International Deep Seabed Mining

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Abstract

As prescribed by the 1982 United Nations Convention on the Law of the Sea (the "LOS Convention"), the international seabed area (the "Area") and its resources are the common heritage of mankind, and activities in the Area shall be carried out as prescribed in the LOS Convention. Accordingly, in respect of the Area activities, making domestic legislations in accord with international law is particularly necessary. As a State Party to the LOS Convention, and also in order to protect the national interests as well as the common benefit of mankind, the Deep Seabed Area Resource Exploration and Exploitation Law of the People's Republic of China (the "Deep Seabed Law") was promulgated on 26th February 2016, which marked a significant step forward at both domestic and international level, and will bring effects that cannot be ignored. In order to fully understand the value and shortcomings of the Deep Seabed Law, and also to make recommendations for further improvement where necessary, this paper will examine the provisions of the Deep Seabed Law under the context of both international law and the China legal system. Specific issues under the legislation pertaining to the personal jurisdiction and applicable activities, exploration and exploitation of the Area resources, environmental protection, scientific research and resource survey, and supervision mechanism as well as the liability and penalty rules will be critically analyzed, and suggestions on how to improve this new legislation will also be presented.

Zhang Guobin

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Since 2015, Dr. Zhang has been researching the deep seabed law. He has participated as a key member in numerous research projects concerning Chinese deep seabed legislation. He is the also a member of the Legal Working Group (LWG) designated by the Department of Treaty Law, Ministry of Foreign Affairs and the Ocean Affairs Administration of China. The LWG aims to support China's diplomatic negotiations for the Regulations on Exploitation of Mineral Resources in the Area.

Dr. Zhang has published numerous articles in the field of law of the sea. His recent publications include A new step forward: Review of China's 2016 legislation on international seabed area (2016), published by Marine Policy (SSCI), and a Chinese monograph The Research on the Right of Innocent Passage (2018) published by Shanghai Jiao Tong University Press.

Research on Collecting Nodules During Deep-sea Mining: an Efficient and Environmentally Friendly Technology in Hydraulic Collecting

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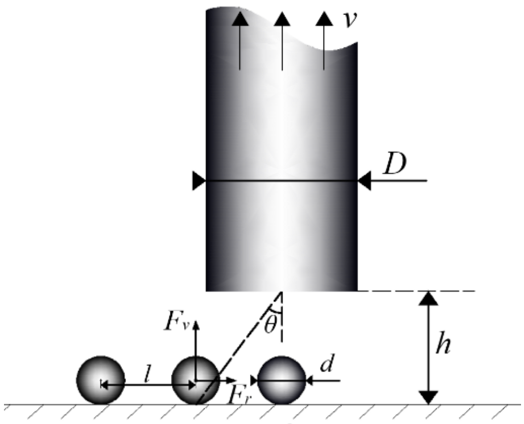
Introduction

Enormous mineral resources are distributed on the seafloor, among which ocean polymetallic nodules have been attracting more and more attentions for their promising economic value, huge reserves, and high grades compared with land-based resources. With increasing demand for various mineral resources in emerging industry (such as electric cars, smartphones and green energy generation) and gradual exhaustion of land mineral resources, deep-sea mining is thought to be a key approach for the sustainable development of increasing population requirements. Therefore, research and development of seafloor mineral resources has become increasingly urgent.

Deep-sea mining activities are expected to commence in the next decade (2020~2030). The International Seafloor Authority (ISA) has already issued 17 exploration licenses for mining polymetallic nodules in the Clarion-Clipperton Fracture Zone and Central Indian Ocean Basin. The ISA is seeking to approve of the exploitation regulations for polymetallic nodules around the year 2021, but there still remain significant research and knowledge gaps that have to be covered. The hydraulic colleting technique near the seafloor is one of the most pressing problems as it directly determines collecting efficiency as well as disturbance of seafloor sediments.

Hydrodynamic characteristics of spherical particles in a suction flow field is considered as the basis of the design of nodule collectors, but there seem to be few investigations on it. Therefore in this Seminar Report, experimental and numerical studies are carried out to investigate the characteristics of flow field and forces acting on spherical particles in hydraulic collecting. Two types of nodule collector models are designed to produce spiral and non-spiral flow, respectively. For numerical simulation, a Detached Eddy Simulation (DES) method is applied and is verified to be feasible to predict the forces acting on the spherical particles.



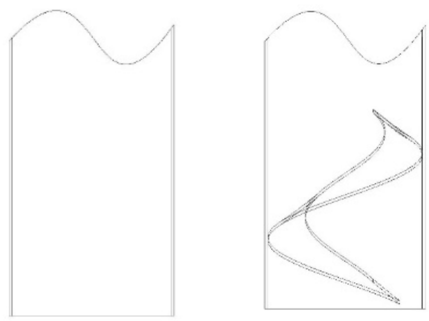


Figure 1. A hydraulic collecting model and two different nodules collector models with different structures

The vertical and radial coefficients of the spheres are defined as empirical equations using dimensionless quantities. The impacts of main collecting parameters on vertical and radial force coefficients of the particles, as shown in Figure 1, are investigated. The parameters consist of the Reynolds number (*Re*), the ratio of bottom clearance to diameter of the particle (*h/d*), and the angle between the collector inlet and the particle (*θ*). An insight into understanding the characteristics of flow field in hydraulic collecting for deep-ocean mining is provided by comprehensive analysis on the regular pattern of dynamic change of wake vortex structures and pressure distribution. It is found that the spiral flow helps strengthen the suction force. In addition, the characteristics of suction flow field are obtained by flow visualization tests, which are applied to explaining the force characteristics of particles in the suction flow field. This study is expected to be useful for understanding the mechanism of hydraulic collecting and refinement of the collecting process.

Experimental and Numerical Method

3.1 Test setup

The whole test system consists of three parts: suction, movement and measurement as shown in Figure 2. The suction part is mainly composed of glass flume and pump circulation device. The size of glass flume is 2.5m*1.5m*1.0m. The water in the flume is connected to the pump through a pipe, in which the rated power is 22 kW and the maximum flow rate is 100 t/*h*. The LDG-SIN-DN100 electromagnetic flow meter is installed at the outlet of the pump to measure the flow rate through the pump. Considering the fact that the flow rate at the inlet of the pipe is almost the same as the measured one, the average flow velocity is calculated and defined as flow velocity in pipe. In addition, a 0.7-meter baffle is installed and two parallel honeycomb plates are placed to weaken the impact of water wave on force measurement. The movement part is composed of an ER50-C10 six-degree-of-freedom robot, whose lower arm is fixed to the inlet of the pipe. By adjusting the motion of the mechanical arm to change the position of the pipe entrance, the precision can reach 0.01 mm and 0.01°. The measurement part adopts three-component force sensor. The top of the sensor is rigidly connected with the measured particle, and its bottom is rigidly connected to the stainless-steel plate placed on the bottom of the flume. In addition, an acrylic plate is installed under the particle, so that the acrylic plate can be considered as a boundary, and the force sensor has no effect on the flow field above the plate. In the experiment, the vertical distance between the inlet and the particle is measured as the vertical distance between the bottom of pipe and the acrylic plate, and it is defined as the bottom clearance h.

The force sensor is connected with the data acquisition system, and it can measure the data of the vertical suction force of the particles within a period of time. To ensure the accuracy of the measurement results, the layout structure of force sensor in the experiment has been improved many times, and the system tolerance is successfully maintained within 1%. In addition, in previous tests, it was found that if the measured particle is too heavy or too light, it will cause an oscillation of the measured value. Therefore, the particles used in the vertical force tests are designed to balance their buoyancy with the proper gravity, so that the measurement results can be more accurate.

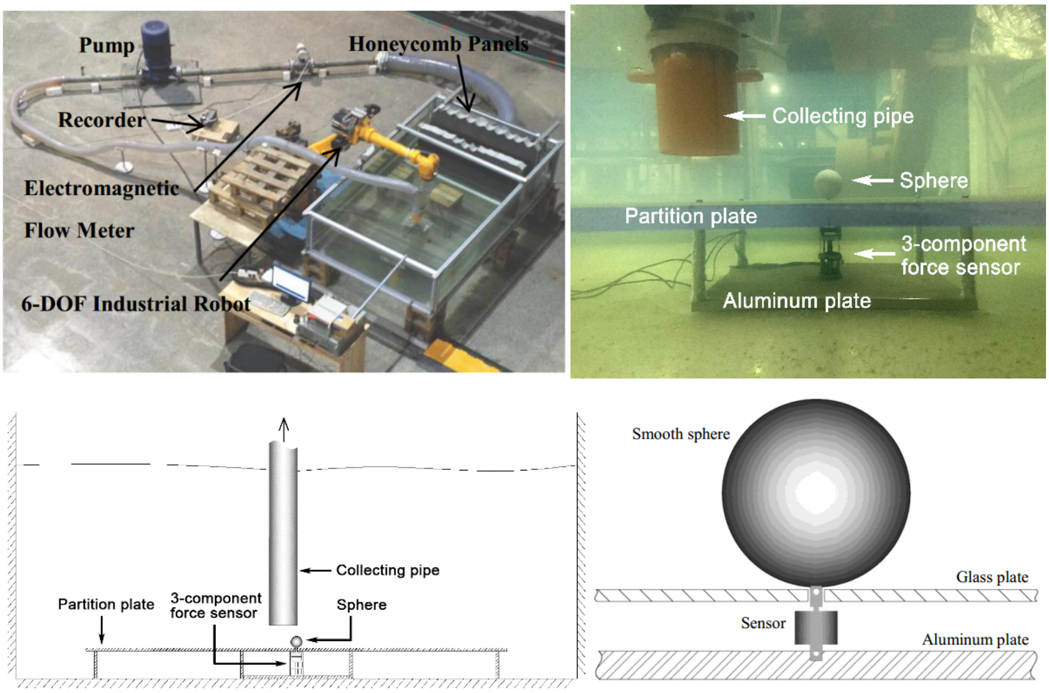


Figure 2. The test system in detail

3.2 Numerical method

Constantinescu and Squires (2003) applied Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) to predict and investigate the flow around a sphere at a Reynolds number of 10,000 in the subcritical regime. Comparison of the computed results with experimental data showed that LES and DES were able to simulate the flow around a sphere. In this study, a DES method based on Shear Stress Transport (SST) model (SST-DES) is used in STAR-CCM+ to study the characteristics of flow field and forces acting on particles in hydraulic collecting.

DES is a hybrid RANS/LES model which employs Reynolds-Averaged Navies-Stokes (RANS) in the regions near boundary layers and Large-Eddy Simulation (LES) in the separated region. SST turbulence model combines the k-omega turbulence model and K-epsilon turbulence model such that the k-omega is used in the inner region of the boundary layer and switches to the k-epsilon in the free shear flow.

The SST-DES model is selected in this research for high computational efficiency and good precision. When the flow field is simulated by DES, better simulation accuracy can be obtained with less mesh number. The SST model with an accurate and robust near wall treatment and a zonal DES formulation is qualified for accurate prediction of flows with strong adverse pressure gradients and separation (Menter et al., 2003).

The two equations of Shear-Stress Transport-model (SST model) can be presented as:

$$\frac{\partial(\rho_w k)}{\partial t}+u_i\frac{\partial(\rho_w k)}{\partial x_i}=P_k-\frac{\rho_w k^{\frac{3}{2}}}{l_{k-\omega}}+\frac{\partial}{\partial x_i}\left[\left(\mu_l+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] \quad (1)$$

$$\frac{\partial(\rho_w \omega)}{\partial t}+u_i\frac{\partial(\rho_w \omega)}{\partial x_i}=C_\omega P_\omega-\beta_\omega\rho_w\omega^2+\frac{\partial}{\partial x_i}\left[\left(\mu_l+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]$$
$$+2\rho_w\left(1-F_1\right)\frac{1}{\sigma_{\omega_2}}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (2)$$

and the eddy viscosity is given by

$$\mu_t=\min\left[\frac{\rho_w k}{\omega},\frac{a_1\rho_w k}{\Omega F_2}\right] \quad (3)$$

where P_k and P_ω are induced by turbulence and are constant in model equations according to the results in Menter (1993).

In the dissipation term of k equation of SST model, the parameter of turbulence scale $l_{k-\omega}$ can be obtained by

$$l_{k-\omega}=k^{1/2}/\beta_k\omega \quad (4)$$

The parameter $l_{k-\omega}$ is replaced by $\min\left(l_{k-\omega},C_{DES}\Delta\right)$ in DES method, where $\Delta=\max\left(\Delta x,\Delta y,\Delta z\right)$ is the longest side length of the mesh and C_{DES} is equal to 0.65. In the regions near boundary layers, where $l_{k-\omega}$ is less than or equal to Δ, the DES model can be viewed as SST model. In the separated region, where $l_{k-\omega}$ becomes greater than C_{DES}, the DES model can be considered as LES model.

Results and Conclusions

4.1 Optimization of design parameters of spiral deflectors by numerical simulation

Two main design parameters of spiral deflectors are the helical angle α and the length *L*, as shown in Table 1. Case groups are classified in terms of various combinations of the two design parameters and working parameters, including sphere diameter *d*, pipe diameter *D*, bottom clearance *h*, and flow velocity *v*.

Table 1. Case groups in terms of various combinations of design parameters and working parameters

Case Group	*d*(m)	*D*(m)	*h*(m)	*v*(m/s)	*L*(m)	α (°)
for *L*	0.036	0.1	0.055	1.4	0.0150,0.0175, 0.0200,0.0225, 0.0250,0.0275, 0.0300,0.0325, 0.0350	30
for α	0.036	0.1	0.055	1.4	0.03	10,15,20, 25,30,35, 40,45,50

The effect of length *L* on *Fv* of the particle is shown in Figure 3, with the helical angle α at 30°. It is clear that *Fv* reaches its maximum when *L*=30mm, with the relative increment peaking at 8.46%.

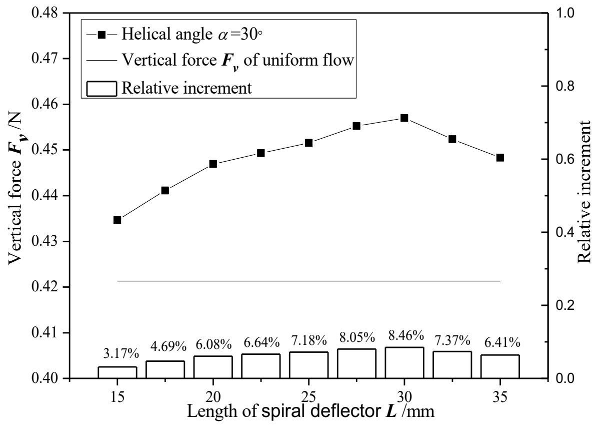


Figure 3. Relations between length of spiral deflector *L* and vertical force *Fv*

The effect of helical angle α on *Fv* of the particle is presented in Figure 4, with the selected spiral deflector length *L*=30mm. *Fv* climbs slightly when α<15°. A remarkable decline can be observed when α>30°. And at α=30° it shows a relative increment of 8.46%, which is selected to be the proper parameter of the spiral deflector.

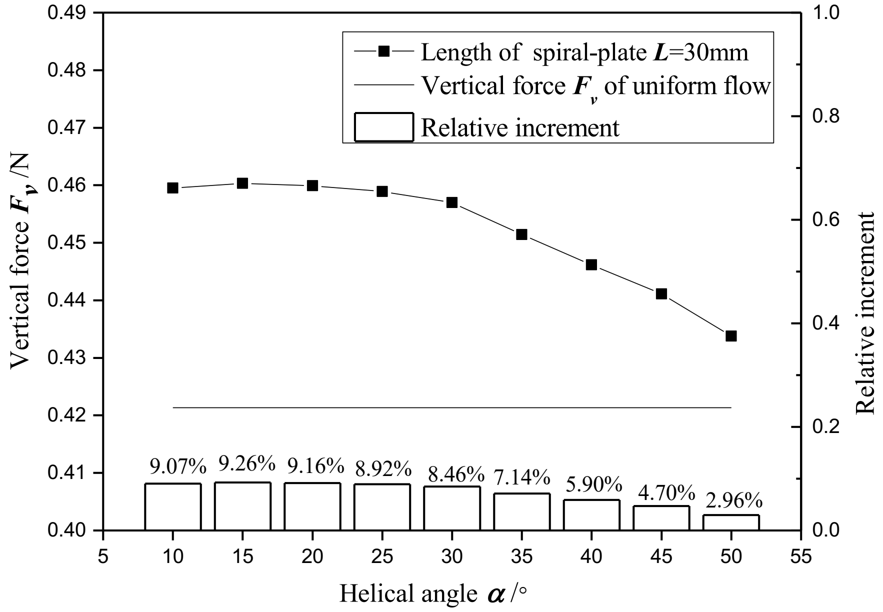


Figure 4. Relations between helical angle *α* and vertical force *Fv*

4.2 Test results of cases with/without spiral deflectors

Test results reveal differences in values of vertical force *Fv* acting on the particle under different bottom clearance *h* and flow velocity *v* between spiral and non-spiral flow cases. *Fv* of spiral flow tend to be greater than that of the corresponding non-spiral cases, which is more significant when the collecting pipe is drown closer to the sphere. For example, the force value of spiral flow is 0.3675N compared to 0.2952N of non-spiral flow, showing an increase up to 24.5% when the bottom clearance *h* is 50mm and the flow velocity *v* is 1.0m/s. As *h* increases, *Fv* produced by spiral flow declines more significantly and the gap between the results of spiral and non-spiral cases becomes less noticeable.

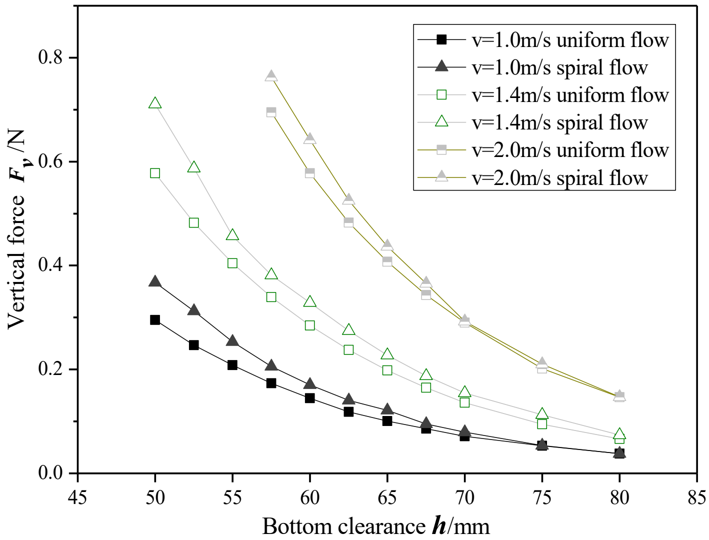


Figure 5. Relations between suction force and bottom clearance and flow velocity in spiral/non-spiral flow collecting

4.3 Influence of *h/d* on *Cv*

Figure 6 presents a comparison between spiral and non-spiral cases in terms of the relationship between vertical force coefficient *Cv* and ratio of bottom clearance to sphere diameter *h/d.* Here each point of *Cv* represents the average value of *Cv* obtained from multiple cases with the same *h*/d. This is acceptable because for a group of cases with a certain value of *h/d*, the value of *Cv* tend to be very close to each other despite the different flow velocity *v*, showing good agreement with the conclusion drawn earlier (independent of *Re*). The logarithms of *Cv* are calculated and are found to have a linear relationship with *h/d* as shown in Figure 7.

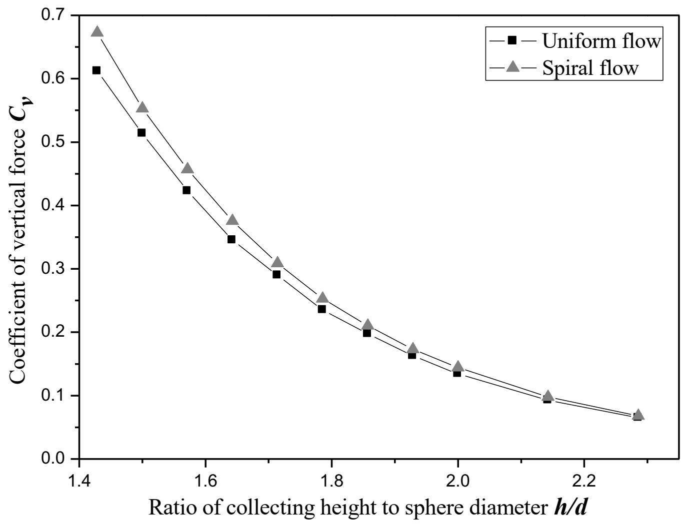


Figure 6. Relations between C_v and *h/d*

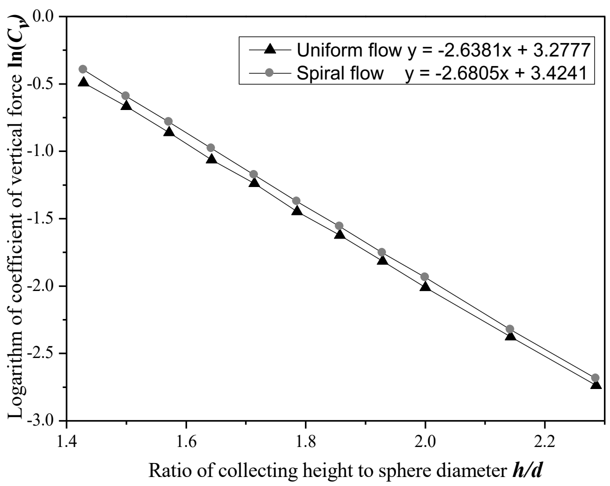


Figure 7. Relations between ln(C_v) and *h/d*

4.4 Comparison between experimental and numerical results

Results obtained by numerical simulation show good credibility as shown in Figure 8. Tolerances between measured values of vertical force *Fv* and simulated ones are controlled within ±10%. The comparison validates the feasibility and high accuracy of the numerical method for forecasting the forces on particles. The arrangement of the sensor may be the cause of the tolerance between the experimental and numerical results, by disturbing the flow field and the small gap between the bottom of the sphere and the ground.

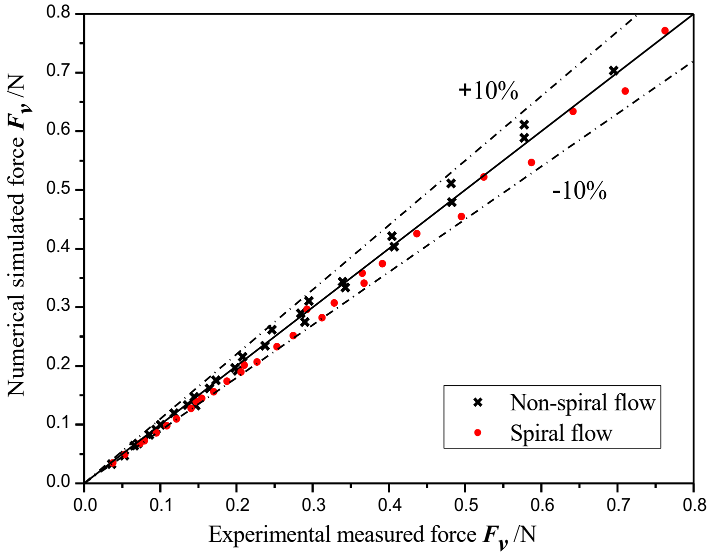


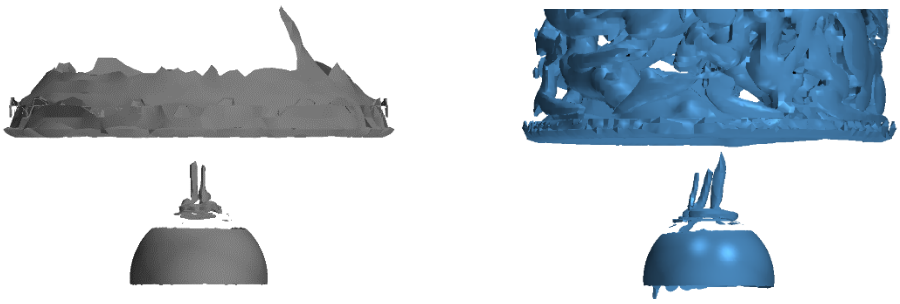
Figure 8. Comparison between values of measured and calculated vertical force

4.5 Three-dimensional vortex structures in the flow field

It can be concluded that spiral flow exerts stronger suction force on the sphere as the value of vertical force in the collecting tube with spiral deflectors is clearly greater. One reason for that is the spiral flow brings about an increase of the scale of the vortex structure as shown in Figure 9. As to the recognition of the vortex structure, Q criteria was applied, where Q is defined as

$$Q = -\frac{1}{2}\left(\|\mathbf{S}\|^2 - \|\mathbf{\Omega}\|^2\right) \tag{5}$$

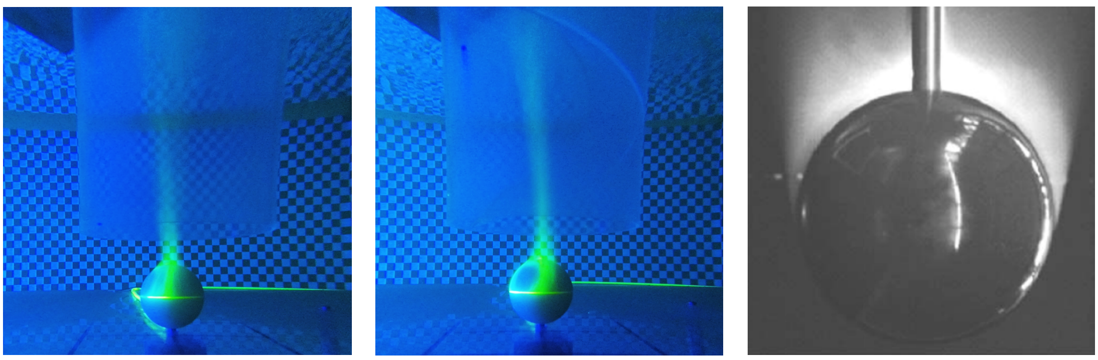
S, Ω represent strain tensor and rotation tensor respectively. In this case, Q is chosen as equal to 5000. Figure 9 indicates that under this condition the scale of vortex structures in spiral flow is significantly larger than that of the case without a spiral deflector. Therefore, the suction force induced by spiral flow is supposed to be stronger.



(a) without spiral deflector (CFD) (b) with spiral deflector (CFD)

Figure 9. Comparison of the scale of vortex structures

Furthermore, flow visualization test results indicate that the wake vortex separation point in a suction flow is much nearer the top of the particle than that in a uniform flow, as shown in Figure 10. A closer separation point of the wake vortex near the top of the particle may result in a smaller area on the particle that is influenced by the wake vortex, leading to smaller vertical suction force coefficient. This may explain the results that the vertical suction force coefficients of spheres in spiral flow are greater than those in non-spiral cases, as presented in Figure 6.



(a) without spiral deflector (Test) (b) with spiral deflector (Test) (c) flow around a sphere in a uniform flow

Figure 10. Flow visualization results for flow around a sphere in spiral and non-spiral cases

4.6 Conclusions

1. The value of vertical suction force on spherical particles in spiral flow is greater than that of non-spiral flow at equal flow velocity (v) and bottom clearance (h). One possible reason for that is the spiral flow increases the scale of the wake vortex structure of particles. As a consequence, using spiral flow could be a proper method of collecting nodules efficiently with lower energy consumption.

2. The vertical suction force coefficient (*Cv*) decreases exponentially with the ratio of bottom clearance to diameter of the particle (*h/d*, ranging from 1.52 to 2.22) and is nearly independent of Reynolds number (*Re*, ranging from 36000 to 72000) for both spiral and non-spiral flow.

3. The vertical force prediction for single ore particle in collecting condition based on numerical simulation with DES-SST model is feasible and sufficiently precise. Therefore, it is a promising method to design new collectors by numerical simulation.

Keywords: Deep sea mining; Hydraulic collecting; Spherical particles; Force characteristics; Suction flow field; Spiral flow

Zhao Guocheng, Xiao Longfei, Zhao Weijie, Yue Ziyu, Hu Jingchao

Longfei XIAO (left), Guocheng ZHAO (right) and their

Deep-sea mining prototype collector

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Zhao Guocheng, Ph.D. candidate, president of student science association in Shanghai Jiao Tong University. His major is Naval Architecture and Ocean Engineering, focusing on research of nodule lifting in deep sea mining near the seabed for 4 years, specifically in developing environmentally friendly ocean mining technology and assessing the impact of the nodule lifting on the environment from the view of fluid mechanics by both experimental method and numerical simulation. He was awarded "Outstanding Top Ten Student of China" award nomination and "Outstanding Top Ten Student of Shanghai Jiao Tong University" award.

Field Planning & Seafloor Production Tool Concept Review

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Abstract

At China Merchants Offshore Technology Research Center (CM-OTRC), we have been conducting some conceptual studies aiming at recovering cobalt-rich ferromanganese deposits found in the Magellan seamount clusters of West Pacific Ocean. In the presentation, we focus on the subject of field planning for seabed mining and review of the seafloor production tool concepts.

Field Planning for Seabed Cobalt Mining

The field planning is defined as the short-term spatial mine planning (SMP), which is a process of analyzing and allocating the spatial and temporal distribution of human activities on the seafloor related to a mining project. The research subjects for field planning as presented pertain to route planning and operation efficiency. The factors considered in the field planning include seafloor terrain constraints and feasible mining concepts, also known as field development architectures. The seafloor terrain survey may be obtained with a resolution up to a few meters at relatively affordable financial terms. Some specific field planning items covered in the presentation include licensed areas, route planning for strip mining, etc.

Seafloor Production Tool (SPT) Concepts

The mining of a cobalt-rich crust deposit calls for a crawler type Seafloor Production Tool (SPT), aka Seafloor Mining Tool (SMT). Different types of cobalt deposit harvesting mechanisms are discussed. For higher operational efficiency, a combination of multiple crawlers, each with single or a few functions, may be considered in lieu of a single crawler with all-in-one functions. Additionally, mining from complex and highly sloped surface may require a more advanced chassis for the crawler as opposed to mining from a relatively flat seafloor.

Keywords: Cobalt, Crust, Nodules, SMP, field planning, route planning, SPT, SMT, Seabed Mining, crawler, drum cutter, chassis

Presenters: Zheng Wilson, Xu Lixin, Zhang Fan, Sun Mingyuan

Main Author – Zheng Wilson

Zheng Wilson works as a naval architect with CM-OTRC, with over nineteen years of hands-on industrial experience in offshore floating systems.

Responsible for global performance, mooring and/or global structural design loads, Mr. Zheng has had substantial involvements in the following deployed projects: Stampede, Malikai, Shenzi, Oveng/Okume, Marco Polo, West Seno and Prince TLPs; Medusa, Devil's Tower, and Front Runner Spars; Stones FPSO, West Seno FPU, and Sakhalin-1 Arkutun Field Development Transportation Barge. At Sea Engineering (now part of INTEC-Sea), he deployed motions simulation software WINPOST as a production tool, which precedes the market acceptance of HARP, the commercial version of WINPOST. He also engineered the TLP-TAD mooring and hawser systems for Oven/Okume TLPs and West Seno TLP, the latter being the industry first, implemented with his proprietary multi-body time domain algorithm based on WINPOST.

Mr. Zheng received his Master's degree in Ocean Engineering from Texas A&M University, College Station, TX, and Bachelor's degree in Naval Architecture from Shanghai Jiao Tong University.

Surface Support System Selection for Deep-sea Mining

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Abstract

Riser vertical lifting system with surface support platform is the main production mean in deep-sea mining. The function of the system is to transfer the ore slurry from sea floor to the surface platform by a rigid riser or a flexible riser with a pump system.

This presentation report here is in focus on the surface support system type selection, including the positioning system selection and the platform type selection. The main driver for the positioning system selection and for the surface platform type selection have been introduced. Three types of positioning system, including (1) DP system; (2) Drag anchor mooring system and (3) Temporary tugboat mooring system, have been discussed. Three types of production platforms have been investigated, including (1) Integrated full function new-build platform/vessel; (2) Tender assisted production unit – it consists of a motion-friendly production platform and a service vessel with storage capacity; and (3) Converted platform/vessel from used drilling semi-submersible (SEMI) or a large service vessel. A summary of pros and cons for the positioning system and for platform type selection have been presented for helping the decision making of the surface support system selection.

Keywords: Deep-sea Mining, Production Platform, Coupling Motion, Vessel Selection, Mooring System.

Joe Zhou

- Joe Zhou, PhD, PE, Senior Principal Engineer;
- Thirty-Two (32) years of experience in offshore engineering and naval architecture. Project experience includes design, analysis and model testing of TLP, SEMI, FPSO, Spar oil platforms and other floating production systems;
- From April 2018 to present, work at China Merchants Offshore Technology Research Center. From 2004 to 2018, worked at Technip USA, Inc., Houston.

The advances of project of investigation and study on the rare Earth resources in deep-sea sediments in the Pacific Ocean

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Abstract

A newly discovered potential REE resource occurs in sediments deposited on the deep-ocean floor. The investigation of these deposits is funded by the China Geological Survey, and the investigation work at sea was undertaken by the research vessel "Haiyang liu Hao" of the Guangzhou Marine geological Survey. From 2013 to 2017, the survey area was focused on the central basins of Pacific and the northwestern Pacific basin, and the southeastern Pacific basin was preliminarily surveyed. A total of five survey cruises with about a total of 220 days were completed, and about 120 large gravity and piston coring stations were completed with an average sampling length of 7.6 meters, about 5,700 sediment samples for chemical analysis of major, trace and rare earth elements have been completed in the laboratory on land. After five years of deep-sea rare earth investigation and study, a breakthrough in geological prospecting of deep-sea rare earth resources in the Pacific Ocean has been achieved and remarkable achievements have been made, mainly including the following five aspects:

(1) The central basins of the Pacific and the northwestern Pacific basin have been determined to be the metallogenic prospective area of deep-sea rare earth resource, and more than one million square kilometers area have been delineated as the metallogenic prospective area in the Pacific Ocean with the content of ΣREY 700 ppm as the cut-off grade. The ΣREY 700 ppm is the minimum industrial grade of ionic type rare-earth ore in southern China, which is reasonable for outlining the prospective area. The amount of rare

earth resources from the REY-rich deep-sea sediments have been estimated in the prospective area. It is shown that there is a huge amount of rare earth resources in the prospective area. The highest rare earth content of ΣREY up to 5983 ppm was found at three meters below the seafloor at survey station XTGC057 in the northwestern Pacific basin.

(2) The characteristics of rare earth deposits in deep-sea sediments in the Pacific Ocean have been basically determined. The rare earth deposits in the deep-sea sediments of the Pacific Ocean belong to the strata-bound type ore deposits. The pelagic clay sediments with high P and phillipsite content are the most favorable REY-rich pelagic sediments. The REY-rich sediment layers are mainly shallow and surface dark brown deep-sea clay layers rich in zeolites from Cenozoic, the thickness of REY-rich sediments ranging from a few meters to more than 30 meters can be delineated by shallow profiling with a characteristic chert layer at the bottom of the REY-rich sediment layers. The structure of the REY-rich sediment layer in the survey area is similar to that of the Japanese EEZ area around Minamitorishima in the northwestern Pacific Ocean.

(3) The rare earth deposits in deep-sea sediment are a new type of rare earth deposit with a high correlation with phosphate, which is different from the ion-adsorbed rare earth ore in south China, The distribution pattern of REY-rich deep-sea sediments in the Pacific Ocean is mainly affected by the high REY content of fish tooth bone fragments (apatite) mixed in deep-sea sediments, showing clear negative Ce anomaly and positive Y anomaly. Rare earth elements in the deep-sea sediments mainly occur in phosphate minerals (the remains of fish bones), while the ion-adsorbed rare earth ore in south China, whose distribution pattern of rare earth is mainly influenced by the parent rock granite with a obvious negative Eu anomaly, has no rare earth carrier minerals. According to the statistics of a large number of measured samples, the average content of rare earth in the REY-rich sediments of the north northwest Pacific Ocean, the central Pacific Ocean and the southeast Pacific Ocean is 812.01ppm, 870.59 ppm and 1033.49 ppm respectively, and the proportion of medium and heavy rare earth elements in the REY-rich deep-sea sediments is 1.7 ~ 2 times that of the ion- adsorbed rare earth ore in south China, and the proportion of Y in the REY-rich deep-sea sediments is 1.9 ~ 2.5 times that of the ion-absorbed rare earth ore in

south China. REY-rich deep-sea sediments in the Pacific can be named as a phosphate type rare earth potential ore of REY-rich deep-sea sediments.

(4) The measurement and estimation method of rare earth content in deep-sea sediments at sea has been established using the Y content; the positive correlation between the content of Y and the total content of rare earth (ΣREY) can be used to estimate the ΣREY through measuring Y alone onboard ship.

(5) The technological process of acid leaching, mineral separation and extraction of rare earth elements in deep-sea sediments has been preliminarily established. The rare earth elements from deep-sea sediments have been recovered by mineral separation–preconcentration and acid leaching, and the total recovery rate is 62.9%. Hydrochloric acid has the best leaching effect on Y with the recovery rate of up to 94.5%. Y has been extracted from REY-rich sediments in the laboratory using an effective technological process, and the product of Y rare earth oxide has been make, the content of Y_2O_3 (purity) is up to 79.02.

Considering the large amount of rare earth resources on land at present, it is difficult for commercial mining of rare earth resources in deep-sea sediments to occur in foreseeable future, and there have great uncertainties, so in the short term, the fact that there has a large amount of rare earth resources in the deep-sea bed will not affect the price of rare earth in the international market.

Keywords: The Pacific Ocean, REY-rich deep-sea sediments, Rare earth resources; Phosphate

Zhu Kechao

Zhu Kechao is a marine geologist at Guangzhou Marine Geological Survey. He has participated in about 20 research cruises mainly on ferromanganese nodule and cobalt-rich crust survey,and major in resources assessment of ferromanganese nodules, geochemistry of cobalt-rich crust, geochemistry of REY-rich deep-sea sediments. He has undertaken the project of investigation and study on the rare earth resources in deep-sea sediments in the Pacific Ocean since 2013.

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PROGRAM AND ABSTRACTS

Abstracts for Poster Presentations by author or presenter's surname

Non-supervised classification of benthic habitats based on seafloor geomorphology in the French Exploration Contract for Polymetallic Nodules – Clarion-Clipperton Zone

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Abstract (Poster Presentation)

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. This allowed scientists to get a precise understanding of the seafloor geomorphology in these areas. We attempted to characterise benthic habitats using GIS processing of the bathymetric dataset. The first step was to create a theoretical bathymetric model based on the oceanic crust's age and its distance from the oceanic ridge modelled empirically by Hillier and Watts (2005). A differential raster was created by comparing this model to the high-resolution bathymetric dataset. Bathymetric highs (e.g. ridge crests, seamounts) have up to +900m of difference with the empirical model and bathymetric lows (e.g. troughs, large basins) up to -465m difference. By setting different bathymetric difference thresholds, we are able to distinguish these features, as well as high and low intermediate plateaus. These geomorphological features are considered as distinct faunal habitats. We extracted basic statistical data of many variables derived from both bathymetric and acoustic dataset. These variables are described by Diesing (2015) in the EMODnet-Geology Case Study. We developed a Python script to automatise the creation of the rasters of these variables, as well as their basic statistics, for each geomorphological province. Each variable has a different contribution in the definition of the habitats

characteristics. We now have a full understanding of several faunal habitats, which correspond to distinct geomorphological provinces across the eastern sectors of the French Exploration Contract, using an in-house GIS processing.

Keywords: Polymetallic Nodules, CCFZ, Non-supervised Classification, Benthic Habitats, Seafloor Geomorphology, 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.

Acquiring exploration data from polymetallic sulphides on the Mohns Ridge on the Norwegian continental shelf

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Abstract

The new legislation for mineral activity on the Norwegian continental shelf entered into force on 1st July 2019. In accordance with this legislation, the Ministry of Petroleum and Energy (MPE) has initiated its work on the initial strategic impact assessment, which is part of the prescribed process for opening areas on the continental shelf for exploration and exploitation of seabed minerals. In this respect, the Norwegian Petroleum Directorate (NPD) is given the task to provide the necessary database on seabed minerals by assembling all existing data and acquire new as needed. The existing data largely comes from two decades of research by the University of Bergen (UiB), partly in cooperation with the NPD, and supplemented by some data from the Norwegian University of Science and Technology (NTNU). In 2018, the NPD carried out its first marine acquisition cruise for seafloor massive sulphides (SMS) under an international tender using an AUV fitted with the relevant sensors including HiSAS, self-potential (SP), magnetometer (SCM), sub-bottom profiles (SBP) and geochemistry (CH_4, turbidity, pH, ORP). It proved to be an efficient way to acquire exploration data for seabed minerals. A new hydrothermal field was spotted by SP and confirmed by ROV dive. Now, in 2019, NPD is carrying out yet another acquisition cruise for sulphides; this time deploying a fleet of 3 – 4 AUVs working simultaneously and fitted with the same sensors as in 2018. At the time of writing, the cruise is still going on. However, it has so far proved a success. Efficiency in data acquisition is more than doubled and two extinct sulphide deposits have been confirmed by SP and proved by ROV dives.

The poster will present details of the operations and end results of this year's cruise, and a summary of the experience of the use of the technology applied so far.

Key words: Seafloor massive sulphides (SMS), Autonomous underwater vehicle (AUV), Mohns Ridge, continental shelf

Harald Brekke

Harald Brekke is project coordinator and senior geologist in the Norwegian Petroleum Directorate (NPD). In 1996, after more than 10 years as an exploration geologist he became the project coordinator for the technical part of establishing the outer limits of the continental shelf of Norway in accordance with the UN Convention of the Law of the Sea. He was member of the Commission on the Limits of the Continental Shelf (CLCS) from 1997 to 2012. He has given advice to many coastal states in the preparation of their submissions to the CLCS. He has been member of the Legal and Technical Commission (LTC) of the International Seabed Authority since 2013; currently holding the position as Vice-chair of the Commission. In parallel with his work in the CLCS and the LTC, he has been the NPD coordinator of international Arctic research and mapping projects in the Barents Sea and Arctic Ocean.

Chatham Rock Phosphate – an example of a sustainable development of seabed mineral resources while minimising the environmental impact and using ground breaking technology

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Abstract

A deposit of phosphate nodules is on the Chatham Rise approximately 450 kilometres to the east of New Zealand. The deposit contains sufficient rock phosphate to supply New Zealand's phosphate fertilizer needs for at least 20 years. It was first investigated commercially 50 years ago by Global Marine, followed by JBL Minerals in the early 1970's. NZ and German government research and industry groups then took it up again, with major field programs in 1978 and in the early 1980s.

Due to difficult global and local economic conditions the project ground to a halt in 1984. The project was resurrected in 2007 when Chatham Rock Phosphate applied for a prospecting licence. This was granted in 2010 and a successful subsequent mining permit approval followed in 2013. The initial application for the separately required environmental permit was declined in February 2015.

The picture has changed significantly since Chatham's initial application was declined in March 2015.

Changes have occurred in terms of, how the application will be prepared, the EPA's operating procedures, helpful changes to the governing Act, legal precedents, relevant environmental issues, particularly water quality, evolving health and safety standards, and phosphate rock ethical supply issues.

Further, Chatham now has the support of the local iwi (Maori tribe) who will be most affected by our operation. This is unprecedented in New Zealand.

These changes in combination strongly support the logic of reapplying for the environmental permit.

Keywords: Marine Mining, Boskalis, rock phosphate, carbon emissions, cadmium, reactive phosphate rock, water quality, Ngati Mutunga

Chris Castle

Chris Castle is the founder and CEO of TSX.V, NZAX and Frankfurt listed Chatham Rock Phosphate.

He is also managing director of associate company Aorere Resources Limited, whose business is the seed capital financing and subsequently listing of early stage resource projects.

He has been an independent director (since 2000) of Vietnam based and TSX.V listed Asian Mineral Resources Limited and was both a director and chairman of ASX listed King Solomon Mines based in Inner Mongolia.

He has been involved in minerals projects since 1975. His mining and mineral exploration background includes projects with Amoil NZ, Kanieri Gold Dredging, Vaaldiam Resources, and Australian Anglo-American.

Chris is a chartered accountant with 43 years' experience in investment and corporate finance.

Preparation of Bonded Super-hydrophobic Thin Film

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Abstract

By combining Polydimethylsiloxane (PDMS) and carbon fabric, a superhydrophobic film with repeated adhesion performance was fabricated by the introduction of microarray structure on the PDMS polymer surface with a template method. The results show that the contact angle and rolling angle on the microstructural surface of the thin film are 154° and 14°, respectively, having low adhesion superhydrophobicity performance. The close combination of PDMS and carbon fiber fabric can endow the superhydrophobic film with higher adhesion performance and mechanical property. The breaking strength reaches 116.96MPa. The as-prepared superhydrophobic film can be adhered on different materials. After long time adhesion of 30 days and repeated adhesion of 50 times, the as-prepared film still maintains high adhesion and superhydrophobic properties, which shows that the superhydrophobic film has good mechanical stability and durability and can meet the requirements of reusability for a long time, Superhydrophobic properties that can be applied to marine equipment engineering, and repair the large-area damaged super-hydrophobic coating quickly and efficiently, highlight the importance of the innovation process of marine resources exploitation.

Keywords: Adhesive; Superhydrophobic; Surface micro-structure; Adhesion; Repair; Marine equipment

Based on an elastic non-adhesive material, the elastic fabric with adhesive layer, the superhydrophobic film with repeatable adhesion was prepared by combining chemical synthesis with reversible adhesion of gecko. SEM was used to observe and analyze the surface morphology of the prepared films, and the results are shown in figure 1.

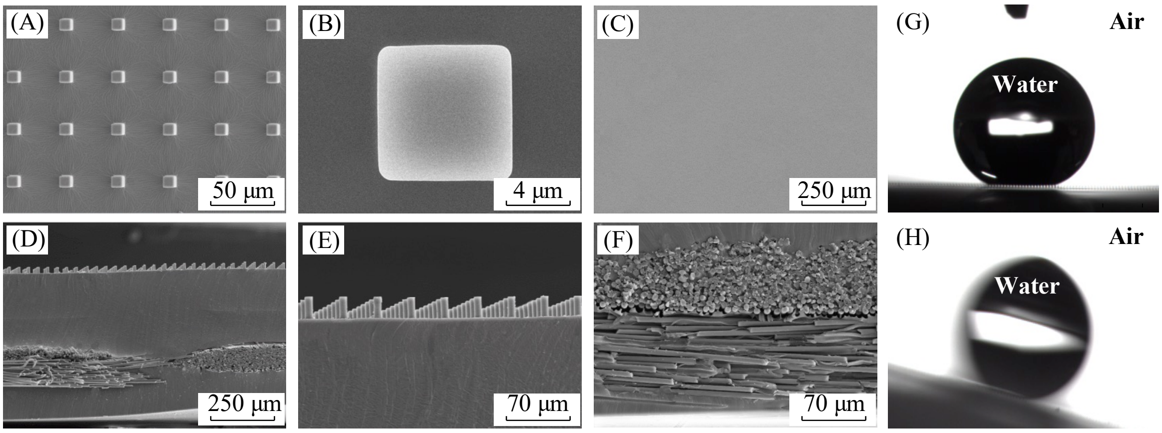

Fig.1 SEM and CA of the film
(A) The pillar structures on the upper surface of the film; (B) Magnified image of one pillar; (C) Smooth structure on the lower surface of the film; (D) Cross-sectional view of film; (E) Magnified image of pillar arrays; (F) Magnified image of the fibers; (G) and (H) Shapes of a water droplet standing and rolling on the surface, respectively.

According to SEM observation of the microstructure of the thin film material in figure 1 (A, B), it can be seen that the surface morphology constructed by the template shape is microarray columnar structure, all the columns are arranged neatly and orderly, the surface is smooth and flat, the diameter of the single column is 10μm, and the spacing between the columns is 30μm. As shown in figure 1 (C, D, E, F), the PDMS/carbon fiber thin film material is entirely composed of three parts, the surface layer is shaped by the microarray structure and the surface is flat. The inner part is carbon fiber fabric, which is made by interwoven warp and weft, with the single fiber bearing a diameter of about 6.9μm. The bottom layer is elastic adhesive layer. The surface wettability of the film-forming surface was investigated by the contact angle test method. It can be seen that the contact angle of the water droplet on the front side of the film is 154° [Fig. 1 (G)], showing the characteristics of super-hydrophobicity. When the surface is slightly tilted, the water droplet is very easy to roll and its roll angle is measured to be about 14° [Fig. 1 (H)], showing low adhesion.

The above results show that by constructing the microarray structure on the PDMS surface, we have successfully achieved the preparation of superhydrophobic film.

The addition of fiber fabric can effectively improve the mechanical properties of the material. We tested the mechanical properties of pure PDMS film and PDMS/carbon fiber film by tensile testing machine. As can be seen from Figure 2 (A), the strain of PDMS sample gradually increases with the continuous increase of the stress value during the tensile process. When the load critical value is reached, the stretching continues to cause fracture, and the breaking strength is 1.69MPa. As shown in Figure 2 (B), the same as the stress value of the increasing strain of PDMS/carbon fiber film increases gradually. When the critical value of the damage of the material is reached, the tensile deformation causes the sample to break, resulting in yielding of the film material, and the yield strength is 116.96MPa. As the strain increases, the stress does not increase but decrease, eventually leading to tensile fracture. The results show that carbon fiber as a reinforcing material provides strong firmness and stability for the adhesive materials, and the crosslinking of PDMS and carbon fiber reinforced fabric has greatly increased the mechanical strength of the superhydrophobic thin film, giving us a better practicality of the prepared superhydrophobic surface.

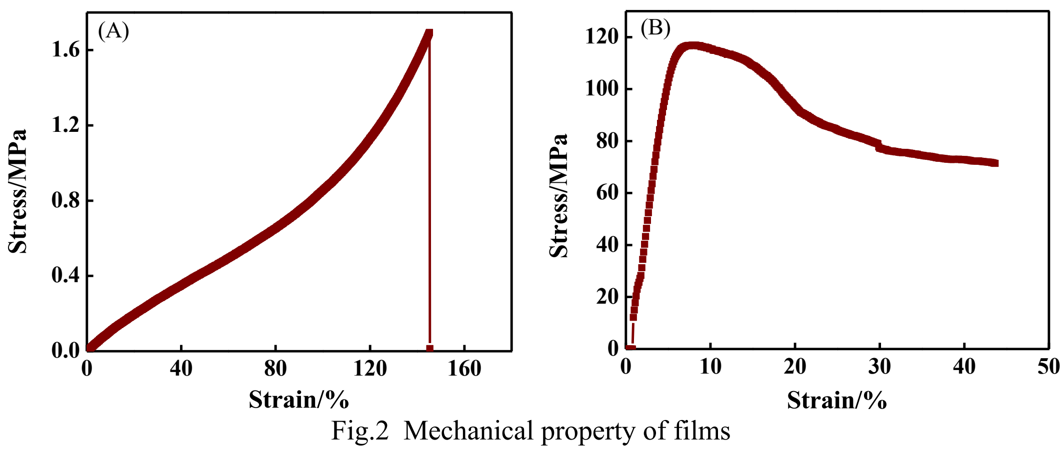

Fig.2 Mechanical property of films
(A) Stress-strain curves of pure PDMS film; (B) Stress-strain curves of PDMS/carbon fiber film.

The surface of the prepared PDMS/carbon fiber thin film material has unique adhesion properties in addition to superhydrophobic properties and good mechanical properties. The back of the film can be attached to many common substrates. We verified the adhesion of the superhydrophobic film by means of hanging weights, and the analysis of the relevant mechanical properties. Figure 3 shows the optical photograph of the superhydrophobic film adhered on glass, stone, aluminum, wood, polyimide film, and carbon fiber fabric materials, respectively. In the figure, the adhesion area of film and substrate is 3cm × 3cm, and the weight of the hanging weight is 500g. As can be seen from Figure 3, even under the action of a certain external force, our film can still firmly adhere to the surface of the substrate without desorption or damage, and always maintain a high strength and adhesion effect, indicating that there is a good adhesion between the film and different materials.

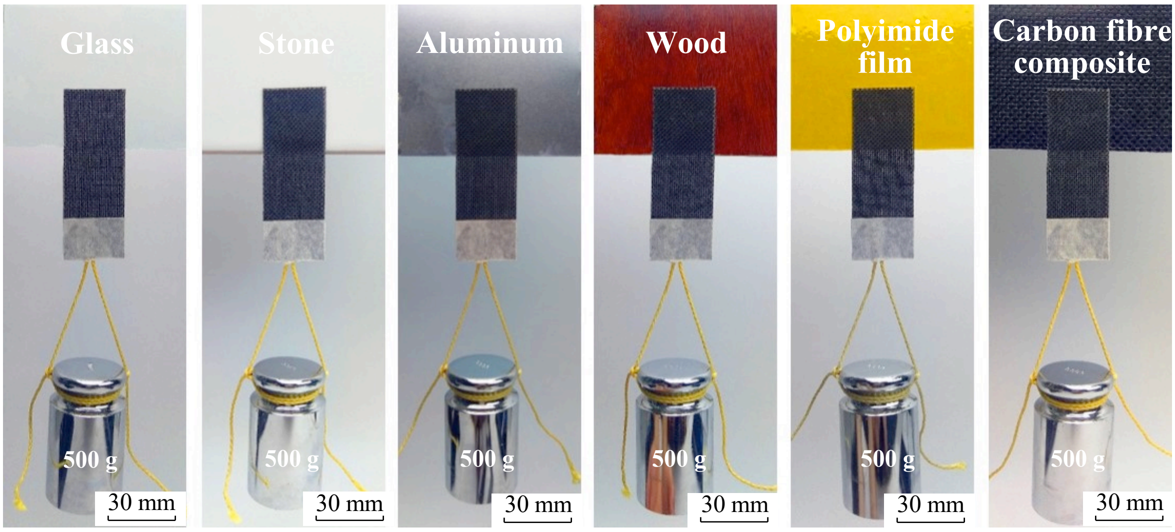

Fig.3 Optical photos of the superhydrophobic films bonded to different substrates

Using the tensile tester, we further tested the adhesion of the superhydrophobic film (the bonding area with the substrate was 3cm × 3cm) to further evaluate the adhesion properties of the film. The adhesion between glass, stone, aluminum, wood, polyimide film, carbon fiber fabric material and superhydrophobic film was tested, the results are shown in Figure 4. The superhydrophobic films prepared by us have good adhesion properties with different substrates. The above results indicate that the superhydrophobic film we prepared has excellent adhesion properties and can be applied to different substrates.

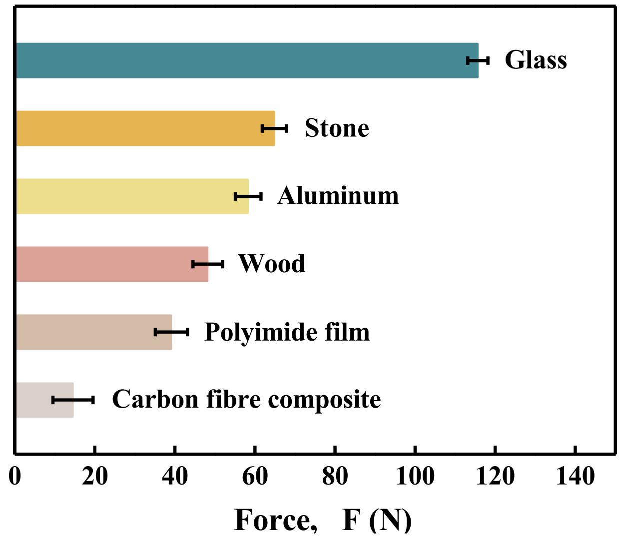

Fig.4 Adhesive forces of the film

We further verified the reusability of superhydrophobic films. It can be seen from Figure 5 (A-E) that the superhydrophobic film can be repeatedly bonded on the material (the weight of the hanging weight is 500g). When the film is re-bonded to the material, the film under a certain external force did not occur desorption phenomenon, still maintaining a high adhesion effect. In order to further analyze the re-adhesiveness of the superhydrophobic film, the adhesion between superhydrophobic film and substrate after 50 cycles of superhydrophobic film was tested by applying a tensile testing. It can be seen from figure 5 (F) that after 50 cycles of bonding, the superhydrophobic film still maintains high adhesion performance, and the film body is not damaged and can be reused continuously. The results show that the superhydrophobic film can be bonding with excellent cyclic adhesion performance.

In addition, as the storage time of the film increases, although the adhesion between the film and the glass substrate decreases slightly, it can be seen from figure 5 (G) that the adhesion between the film and the glass is still higher than 100 N even after 30 days, indicating that the film prepared by us has excellent stability. In addition to the adhesion properties, the wetting properties of the film front were also investigated in the process of the film recycling and stability. The research results are shown in the right curve of figure 5 (F) and figure 5

(G), showing that after the same number of cycles and storage time, the surface of the film prepared by us still maintains the superhydrophobic properties, which further proves the excellent stability of the film material.

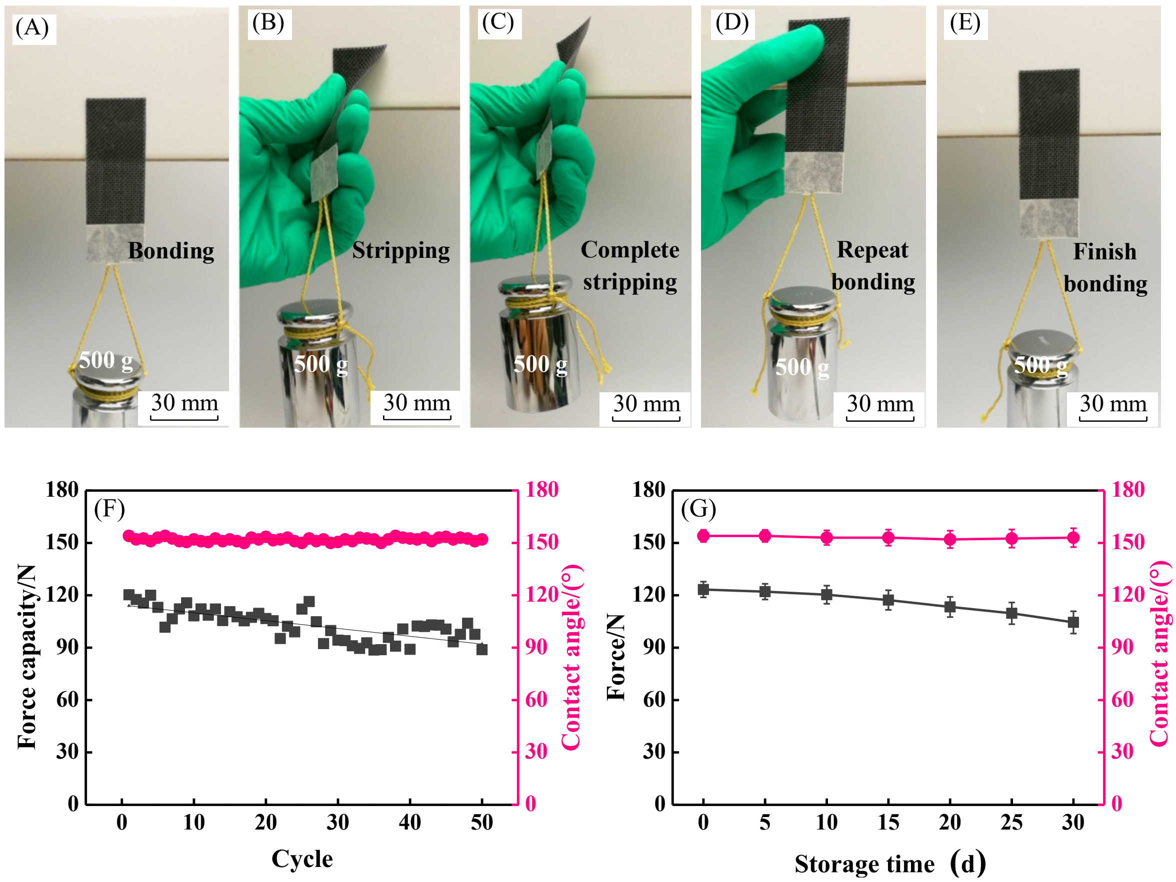

Fig.5 Stability of the film
(A-E) Optical photos of one cyclic adhesion process for the film to the stone substrate; (F) Adhesive forces (left side curve) and contact angles (right side curve) of the film after 50 cycles; (G) Adhesive forces (left side curve) and contact angles (right side curve) of the film after 30 d storage.

The reason why the bonding superhydrophobic film prepared in this paper has superhydrophobic properties is due to the rich microarray structure on the front side of the film, and the superhydrophobic characteristics of its surface can be further explained by the Cassie equation:

$$\cos\theta_c = f_1 \cos\theta_1 - f_2 \tag{1}$$

Where, θ_c——The contact angle of a rough surface;

θ_1——The contact angle of a smooth surface;

f_1 ——The fraction of the solid substrate under the droplet;

f_2 —— The fraction of air under the droplet (f1+f2=1).

It can be obtained from formula (1) that the larger f_2, the larger θ_c, that is, the larger the ratio of air, the better hydrophobicity the surface shows. It is known that the fraction of air on the surface has a great influence on the hydrophobic property of the surface. In this paper, θ_1 is 107°, θ_c is 154°, and the value of f_2 is 0.857 calculated by the formula (1). The results show that the fraction of air on the front side of the film is large enough to endue the surface with super hydrophobic characteristics. Moreover, the water droplets can only contact the top structure of the microarray due to the existence of the air layer, greatly reducing the contact area between the solid and liquid, Therefore, the surface shows low adhesion characteristics, and the water droplets can be freely scrolled above it.

In this paper, a new type of superhydrophobic thin film which can is adhesive was prepared, the microarray structure was obtained by shaping, and the elastic fabric with adhesive adhesion layer was used to realize superhydrophobicity and reversible bonding of the film material. The study found that the superhydrophobic film has a good fast adhesion. It can obtain better adhesion performance when the preloading time is 1s and the preloading force is 30N, and the superhydrophobic film can still maintain a high adhesive performance after 50 times of load cycles adhesion. The prepared film has good mechanical stability and durability at the same time, which can meet the requirements of adhesive performance that can be repeatedly bonded for a long time, and realize fast and large-area repair of the damaged superhydrophobic coatings.

Chen Ming

Deputy director of research laboratory of Deep-sea resource development, Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, senior engineer, master supervisor. He has been working since 1996, mainly engaged in the automatic control of Deep-sea equipment, mechanical and electrical integration of technical research. He has presided over 4 projects of the Pioneer A and Pioneer B of Chinese academy of sciences, 1 major plan project of Hainan province, and participated in more than 10 projects. He joined the Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences from 2014, now he is interested in underwater flexible super-hydrophobic composites and in-situ test systems.

Ma Haoxiang

He received his Ph.D. in the National Key Laboratory of Science and Technology on Advanced Composite in Special Environments of Harbin Institute of Technology in 2018. He joined the Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences from 2018, now he is interested in underwater flexible super-hydrophobic composites.

Shipboard magnetic and rock-magnetic characterization of hydrothermal activities in the North Fiji basin

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Abstract

Recently a shipboard magnetic exploration has been utilized to delineate a potential hydrothermal vent field. On the basalt basement, hydrothermal activity weathers magnetite within the basalt and results in decrease of total intensity of magnetic remanence, causing a negative magnetic anomaly. However, shipboard magnetic exploration in the North Fiji basin (KF-1, KF-2 and KF-3 areas), where hydrothermal signals were identified, revealed magnetic anomalies of dipole shapes with abrupt positive/negative intensity variations. Notably, magnetic dipoles were aligned along with the major fracture lines. To identify the cause of such anomaly pattern, magnetic properties of basement rocks, including concentration, grain-size, and mineralogy of magnetic minerals, were measured. According to the bleaching effect from the fresh black colored basalt, alteration was progressed to almost white colored one. Except for highly altered rocks, most of altered rocks showed significant enrichment of coarse-grained magnetic minerals, causing positive magnetic anomalies. Their magnetic mineral accumulations were more distinctive than fresh basalt rocks. From thermal experiments, we identified that dominant magnetic minerals varied from magnetite to pyrrhotite as alteration level increased. Considering the higher enrichment magnetic minerals in altered rocks, hydrothermal fluids circulating basements progressively accumulate pyrrhotite. At a more advanced stage, the hydrothermal fluids might decompose magnetite and remained only less magnetic pyrrhotite within the highly altered rocks causing negative magnetic anomalies.

Keywords: magnetic anomaly; magnetite; pyrrhotite; alteration; hydrothermal fluid

Sang Bum Chi

Sang Bum Chi is the senior director of the Marine Resources Research Division, KIOST (Korea Institute Ocean Sciences & Technology). He received his Ph.D. from Inha University of Korea in 2003. His dissertation is entitled, "A Study on Geotechnical Properties of Deep-sea Sediments and Manganese Nodule Occurrence in Clarion-Clipperton Fracture Zone, Northeast Equatorial Pacific". He has been working on the Development of Deep Seabed Mineral Resources Program since 1990. He also works on a deep-sea manganese nodule project as a manager since 2010. His main research interest lies on the geotechnical properties of the deep-sea minerals and their surrounding environments.

An estimation study about the amount of collection in the pick-up device for the deep-sea mining system

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Abstract

After the discovery of manganese nodules on the seafloor of oceans, many researchers have put great efforts into the development of mining technology for marine resources in the deep ocean. A self-propelled miner was developed by the Korea Research Institute of Ships and Ocean Engineering (KRISO) in Korea, to acquire manganese nodules in the deep seabed. This miner consists of several components: a tracked vehicle, a hydraulic pick-up device, a conveying device, a crusher and a disposing pump. Among these components, a hydraulic pick-up device is particularly important because it can estimate the profitability and commerciality of the total deep-sea mining system. Therefore, this research is about an estimation of how much of the manganese nodules are collected by the hydraulic pick-up device compared with total reserves, and how its economic worth. There are two main objectives of this paper. The first objective is to design the pick-up device using the real experimental data about the shape, size, and mass of manganese nodules in the deep-sea miner. The second objective is to estimate the amount of collection and its economic value from identification of the probability distributions about the shape, size, and mass of manganese nodules. A total of 175 data sets of manganese nodules for this study were obtained from the KR5 (Korea reserved) deep seabed through 47 stations by the research vessel *Onnuri* in 2009 and 2010 and by the *RV Ka'imikai-o-Kanaloa* in 2011.

Keywords: Deep-sea mining system, Hydraulic pick-up device, Manganese nodules, Probability distribution function

Su-gil Cho

Su-gil Cho is a senior engineer in Korea Research Institute of Ships & Ocean engineering (KRISO). He received his B.S. and Ph.D. degrees in automotive engineering from Hanyang University, South Korea. He has researched on machine design, multidisciplinary design optimization, probability statistics and metamodeling techniques.

Design and Implementation of Monitoring System for Deep Sea Cobalt-rich Crust Sampling Vehicle

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Abstract

A deep-sea sampling vehicle is an important tool of deep-sea mining of cobalt-rich crusts, in order to accomplish the sampling detection of deep-sea mineral resources. According to the design demand of deep-sea sampling vehicle, this paper introduces the whole architecture of sampling system, analyzes the functions of system, and designs the surface monitoring system for the sampling vehicle. In order to solve the problem of remote real-time and multiple communications equipment, large amounts of heterogeneous communication are required. Combined with the C++ language and Visual Studio development tools, which are? based on the interactive programming method of visual interface and database. The hybrid communication technology of Modbus serial port / network multi-node is adopted, and the multi-equipment heterogeneous communication is realized. Use of dual channel real-time communication technology improves the speed and stability of the whole system under a complex environment. Finally, the effectiveness of the monitoring system is verified by the simulation test and the hardware in a loop test, which provide a reference for the development of other similar monitoring systems software.

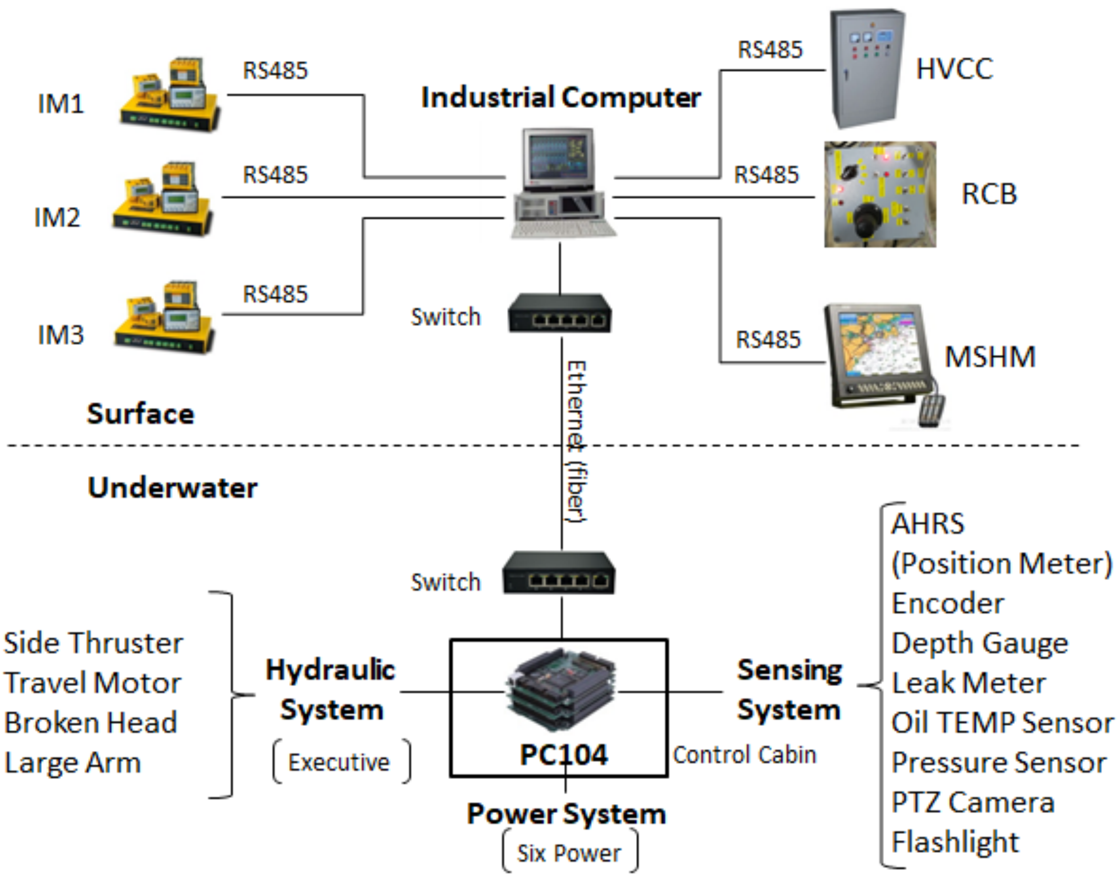

Fig. 1. System Architecture of Sampling Vehicle

Keywords: Mining Vehicle Monitoring System; Hybrid Communication; Dual Channel Communication; Test Verification; Modbus.

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Seabed Mineral Resources Extraction-ICCP

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ABSTRACT

Marine pipeline is a very critical technology for seabed mineral exploitation. The intelligent composite continuous pipeline (ICCP) developed by Shanghai FB Oil Equipment Tech Co., LTD is the best pipeline for deep-sea mineral exploitation. The flexible intelligent pipe is a kind of high-performance fiber reinforced thermoplastic composite intelligent pipe, with optical fiber, downhole pump and well fluid information can be monitored online, which are conductive to realize intelligent mineral exploitation. Excellent wear resistance and corrosion resistance to sea water. Besides, ICCP can resist long-term application dynamic fatigue when it's used in ocean environment, and the length of single piece can reach to 3000m. In addition, the tensile and compressive properties of ICCP can be designed according to the requirements. This kind of flexible intelligent pipeline will be a technological revolution in the future.

The Introduction to ICCP

See fig.1 and fig.2 for the schematic diagram and physical drawing of intelligent composite continuous pipeline structure. The product is composed of three layers: intelligent inner layer, reinforcement structure layer and Out sheath.

(1) Intelligent inner layer provides power for the pipeline. With optical fiber, downhole pump and well fluid information can be monitored online. oil and gas (corrosion resistance,

scale resistance and wax resistance) are transported by the inner pipe.

(2) Reinforcement layer is the skeleton, which is subjected to internal and external pressure. The fibers are infiltrated with thermoplastic resin to fit different purpose. Fiber reinforcement greatly improves the bending fatigue resistance of pipeline.

(3) Out sheath: Protect ICCP during transportation, installation and operation.

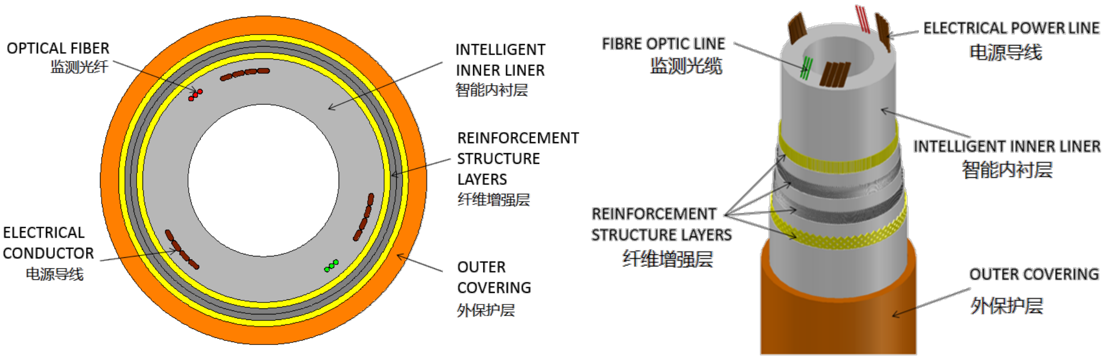

fig.1 The structure of ICCP

fig.2 The Structure of ICCP

For Seabed Mineral Resources extraction, flexible intelligent pipe has the following advantages:

(1) Intelligent. With optical fiber, downhole pump and well fluid information can be monitored online, which are conductive to realize intelligent oil fields.

(2) light weight. It can reduce the load of offshore platform equipment, reduce operation difficulty, improve operation efficiency and enhance the stability of later work when it is used in seabed mining.

(3) Excellent wear resistance. The intelligent inner layer can be designed with a special wear-resistant layer, which is not only wear-resistant but also resistant to seawater corrosion and can greatly improve the life of ICCP.

(4) High tensile strength. Its tensile strength can be designed to more than 500 tons.

(5) Excellent fatigue resistance. It can resist dynamic fatigue of seawater when it is applied in Marine environment.

(6) The length of single piece can reach to 3000m, enhancing installation efficiency.

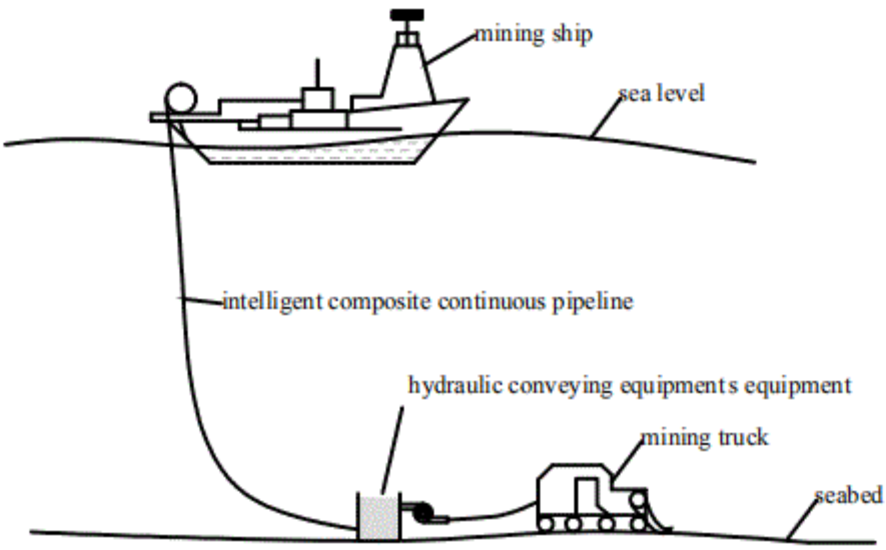

fig.3 Intelligent Tube Mining System Diagram

Intelligent tube mining system consists of mining ship, intelligent composite continuous pipeline, downhole tools, hydraulic conveying equipment, mining truck and other equipment.

Keywords: intelligent composite continuous pipeline, mineral exploitation, Intelligent, light weight, fatigue resistance.

Feng Guojing

Feng Guojing: Chief Engineer

1973.3~1977.3: Studied in middle school affiliated to China fourth academy of astronautics;

1977.4~1979.5: Responded the call of “Going to the countryside”;

1979.5~1981.5: Learned Measurement and Control Technology and Composite Material Technology in Shanxi Institute of Aerospace Technology;

1981.5~2003.6: Worked in 401 institute of China fourth academy of astronautics;

2003.6~2012.6: Engaged in R&D and integration of non-standard equipment as a freelancer;

2012.6~so far: Established Shanghai FB Oil Equipment Co.,Ltd, as chief engineer.

Experience:

In 1982, due to his outstanding contribution to the work, he solved the failure of key imported equipment in engine test, and won the title of advanced producer in that year, besides, he won the third-class merit;

In 1995, he organized and designed China's first "horizontal solid rocket engine thrust vector test stand" for the air-to-air missile research institute, making important contributions to the institute and giving personal awards;

In 1996, he organized and designed the first "horizontal aero-engine thrust vector test frame" in China, which won an important project for the institute;

In 2003, he designed the first "vertical solid rocket engine rotating test stand" in China.;

In 2004, he designed the first "swaying test and measurement device for flexible nozzle of solid rocket engine" for x   institute of aerospace;

In 2006, the first set of "fuze target supersonic intersection ground test system" was designed for the air guide institute in China. The main technical difficulty of this system is to solve the problem that the soft brake is rapidly applied after the intersection of two high-speed flying devices facing each other, and the brake acceleration is smaller than the non-damaging value of the equipment;

In 2009, he organized and designed the "production device for infiltrating the protective cover of the leader of the fiber-reinforced aerogels warhead" for x institute of aerospace;

In 2009, he cooperated with tbea luneng taishan cable factory to develop "composite cable core" and developed "closed high-pressure rubber dipping system".

In the company, as the chief engineer, when there are technical difficulties in the key nodes of the project, he will provide the project team with tough ideas and solutions, and coordinate the cooperation of various technical personnel.

Low-grade ultramafic-hosted SMS deposits: Case study of the Pobeda hydrothermal field

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Introduction

Seafloor massive sulphide (SMS) deposits associated with ultramafic rocks are widespread along the Mid-Atlantic Ridge (MAR). Compare to basalt-hosted, these deposits are enriched in Cu, Zn, Au, Co, Ni, and Au, where Cu+Zn contents vary from 20 to 40 % (Fouquet et al., 2010). The Pobeda hydrothermal cluster (17º09´N) is located on the eastern flank of the MAR rift valley and associated with lower crust and mantle rocks (gabbro-peridotities) of an oceanic core complex (Bel'tenev et al., 2015; 2016). The sulfide mineralization shows low grades of Cu, Zn, and Au with high Ni contents. The factors affecting this unusual composition of SMS from Pthe obeda site are considered.

Results

The Pobeda cluster was discovered in 2014-2015 during 37 Cruise of the R/V Professor Logatchev (Polar Marine Geological Exploration Expedition). This cluster consists of two hydrothermal fields. The age of the SMS is estimated at >177 ka (Gablina et al., 2018) and present-day hydrothermal activity is observed (Bel'tenev et al., 2015, 2016). Deposits were sampled by TV-grab (seven stations) and by dredge (two stations). The host-rocks are mainly represented by serpentinized peridotite and gabbroid. The recovered samples are represented by fragments of massive sulfide (no chimneys), mineralized rocks, hydrothermal crusts, and sulfide-bearing sediments. The detailed compositions were determined for 40 samples of massive sulfides.

The mineral composition is represented by pyrrhotite and pyrite; isocubanite, sphalerite, chalcopyrite, anhydrate, and opal are less common. The texture of alteration and replacement were recognized in most of samples.

The mean metal content was compared with SMS of the MAR related to ultramafic and mafic host-rocks. For ultramafic-hosted deposits, the SMS of Pobeda hydrothermal cluster is characterized by low contents of Cu, Zn (Cu+Zn <10%) (Fig. 1) and Au (Fig. 2). The

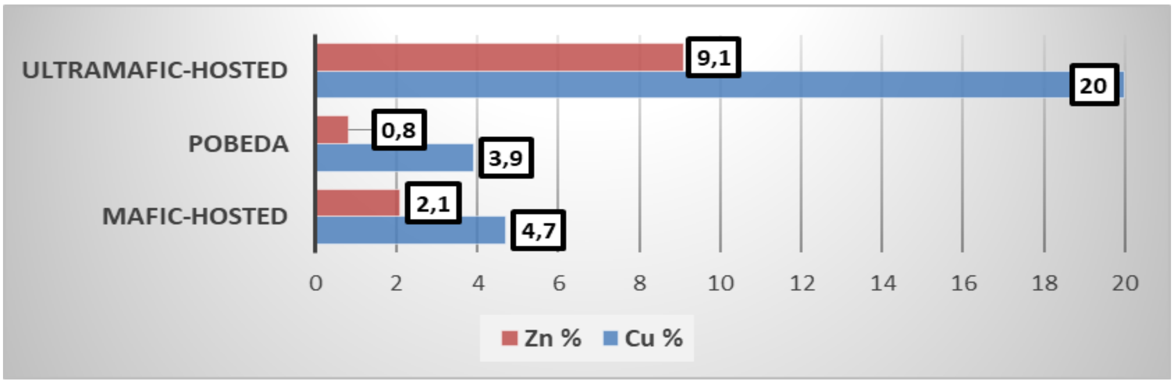

Figure 1. The mean Cu and Zn content in SMS from Pobeda and from the MAR related to ultramafic and mafic host-rocks. (Source: VNIIOkeangeologia database: ultramafic-hosted deposits – 334 samples; mafic-hosted deposits – 726 samples).

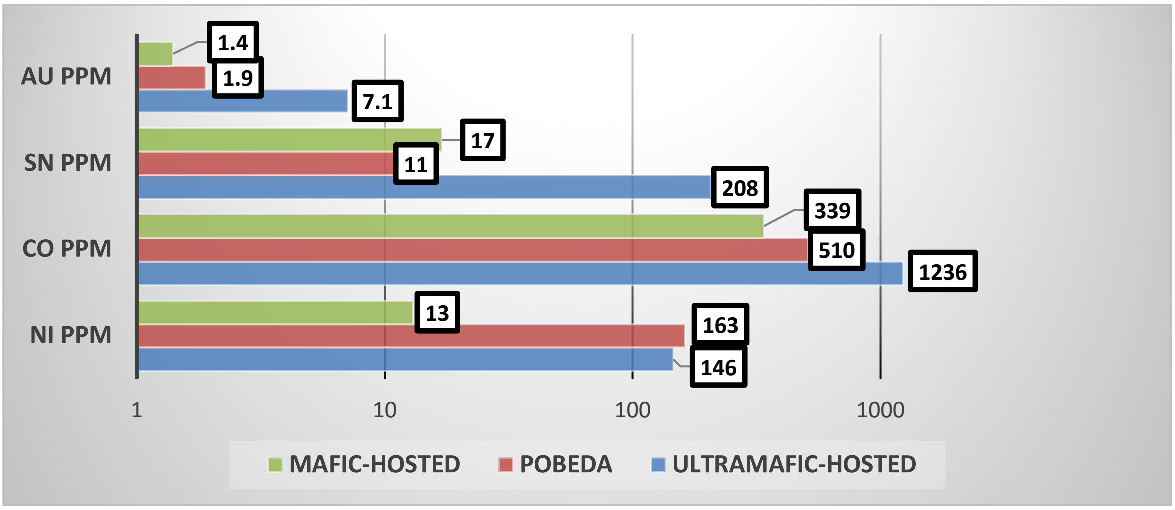

Figure 2. The mean Au, Sn, Co and Ni content of SMS from Pobeda and from the MAR (related to ultramafic and mafic host-rocks).

elevated Sn concentration is usually detected in ultramafic-hosted deposits (Fouquet, 2010) but is not typical for the Pobeda SMS deposits (Fig. 2). Despite the low major metals content, SMS are highly enriched in Ni (max = 613 ppm) (Fig. 2), which is typical for the MAR ultramafic rock-hosted deposits.

The following factors are considered to control the depletion of Cu, Zn, and Au and enrichment of Ni:

Cu, Zn, and Au depletion and Ni enrichment could be related to unrepresentative sampling of the hydrothermal mound. Video observation registered abundant chimneys, which are characterized by higher concentrations of ***Cu, Zn, and Au*** metals but were not recovered. Another reason for low grades of ***Cu, Zn, and Au*** metals in Pobeda SMS might be connected with the age and degree of alteration. Taking into account old age (and long evolution) of the samples (>177 ka) and high degree of secondary processes that resulted in wide spread textures of replacement, it is suggested that Cu and Zn were dissolved from the primary minerals and re-deposited in more enriched (younger) zones ("zone-refining" process). In addition, the presence of abundant pyrrhotite and relicts of anhydrite indicate a very high-temperature (above 350º C) environment that might not have been favorable for ***Cu, Zn, and Au*** precipitation. At the same time, these environments promoted high Ni in the SMS.

Acknowledgments

The authors would like to thank Larisa Lazareva for the provided samples. We express thanks to operators Vladimir Shylkovskyh and Natalia Vlasenko for microprobe investigations.

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Anna Firstova

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GIS - based approach to define permissive areas for SMS exploration along the slow-spreading Mid-Atlantic Ridge

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Introduction (Poster Presentation)

Seafloor massive sulfides (SMS), have gained increased attention both, by scientist but also by stakeholders in the last decade. With the shift to more sustainable green energy and technology, the demand for certain key metals has risen in the last few years and is foreseen to further increase in the near future. Furthermore, the increasing cost-intensity of land-based mining as well as political and environmental concerns have further accelerated the search for alternative sources for these materials [1]. Even though SMS deposits have been known as marine equivalent to land-based volcanogenic massive sulfide (VMS) deposits for several decades, the marine exploration for SMS deposits is still in its infancy. Hydrothermal systems and the associated deposits form along the active plate margins in almost every ocean, however, primarily along Mid-Ocean Ridges (MOR), in arc and back-arc environments [2]. To date, we know almost 600 hydrothermal vent fields of which nearly 400 are associated with SMS occurrences of varying sizes and ore grades [3, 4]. Most of these occurrences are hydrothermally active and discharge hot, metal-rich fluids. From an exploration point of view, they are relatively simple to detect due to their chemical and physical signature in the water column [5]. However, these active hydrothermal fields tend to be in an early stage of development and are therefore commonly quite small. Additionally, they host chemosynthetic faunal communities that should be protected from future deep-sea mining ventures [6]. Hence, inactive sites that have gone through a full life-cycle of metal deposition, where hydrothermal activity has ceased, and where associated high-temperature vent communities have disappeared, are seen as the more reasonable mining target. These inactive systems, however, lack the prominent water column signature and are potentially covered by volcanic material or pelagic sediments, which makes exploration for inactive systems challenging [4]. Many inactive sites are also considered to be located at some distance to the neovolcanic zone increasing the areas that needs to be explored to several million km^2. Therefore, we need new methodologies and procedures to narrow down the search areas to permissive tracts, which are likely to host large and economically interesting SMS occurrences. Few research groups work on the development of exploration models and approaches aiding the search for these undiscovered deposits. A probabilistic approach for the delineation of permissive areas on the northern Mohn's Ridge was developed by Juliani and Ellefmo (2018) [7]. Here we present our work to develop a semi-automated procedure to define exploration criteria and permissive areas based on geographic information system (GIS) analysis of ship-based multibeam data along the Mid-Atlantic Ridge (MAR).

Geological settings and hydrothermal fields

The MAR is a slow-spreading Mid-Ocean-Ridge with a full-spreading rate of less than 40 mm per year and stretches from the Arctic Ocean northeast of Greenland, for more than 16,000 km to the South Atlantic. It is dominated by a high relief which is shaped by an interplay of tectonic and magmatic processes [8]. Even though, it is largely dominated by the volcanic formation of oceanic crust and basaltic rocks, studies in the last two decades have shown that detachment faulting and the exhumation of deeper crustal and mantle rocks is more frequent than previously thought [9]. Some of the largest known sulfide deposits in the Atlantic are associated with detachment faulting or are located on oceanic core complexes (OCC) [10].

The geological setting of SMS at the slow-spreading MAR is diverse. Here, we distinguish between (i) axial basalt-hosted sites within the neovolcanic zone, (ii) off-axis occurrences that are basalt-hosted but associated with large normal faults or detachments, and (iii) hydrothermal systems related to the exposure of mantle rocks, commonly at OCCs (Figure 1). Each group has certain characteristics, which are reflected in the location and setting of the hydrothermal field. For example, Menez Gwen, a basaltic-hosted site is located on an axial volcano within a rifted, even larger volcano at the segment centre of a spreading segment. Another basaltic-hosted field, the Broken Spur field, is associated with an axial volcanic ridge (AVR). Both systems are located within the neo-volcanic zone (NVZ) and occur on rather smooth, symmetrical ridge segments. In contrast, the TAG hydrothermal field, a basalt-hosted, but detachment-related hydrothermal field, is located 3 km away from the axis, close to the intersection of the highly tectonized volcanic valley floor and the eastern ridge flank, which is exhumed by a detachment fault. The TAG segment exhibits an asymmetrical morphology and is tectonically very complex. Ultramafic-hosted sites can be grouped into two categories, fields directly associated with prominent OCCs, such as the Semyenov ore cluster and sites like Logatchev, which show no obvious OCC but have reported occurrences of exhumed gabbroic and mantle rocks in their surroundings. Most of these fields are located further off-axis, along the inner valley walls.

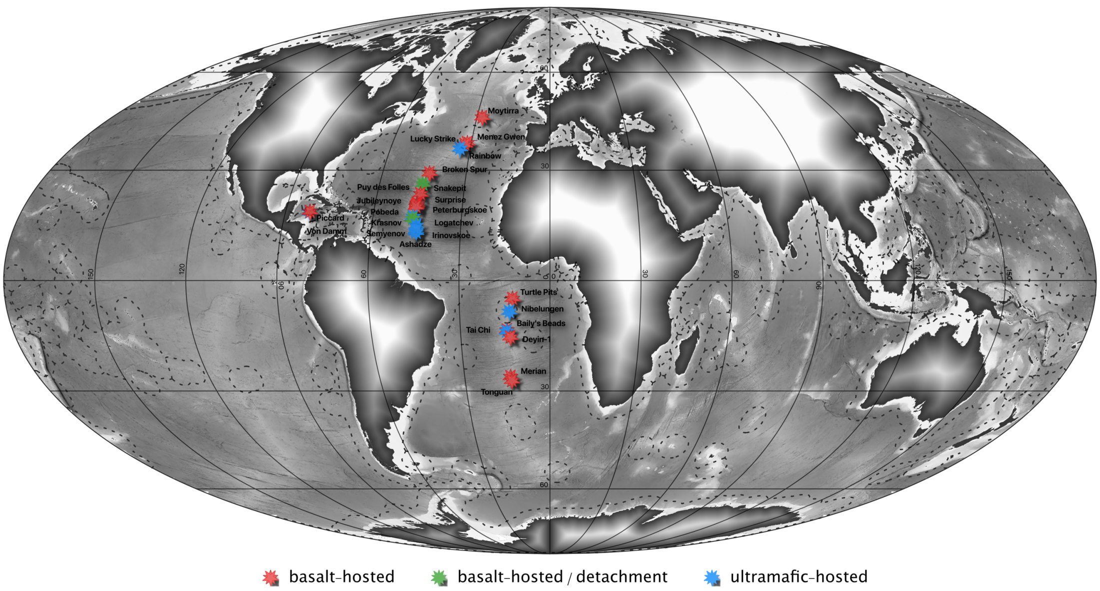

Figure 1: Shaded global relief map of the ocean (GEBCO). Positions and type of the hydrothermal fields in the Atlantic are highlights by the stars. Not all fields are displayed if they are closely spaced.

Methodology

The digital elevation models (DEMs) used in this study were derived from multibeam bathymetric surveys acquired for 42 known hydrothermal fields along the Mid-Atlantic Ridge between the Moytirra hydrothermal field at 45°N and the Tonguan hydrothermal field at 27°S. Two hydrothermal fields in the Cayman Trough were sampled for comparison. We analysed the morphological characteristics in the vicinity of the hydrothermal fields. Derivatives of the DEMs, such as slope, aspect, bTPI (large-scale topographic position index [11]), TRI (terrain ruggedness index [12]) were sampled, compared and combined in a second step with two geological criteria (vicinity to major faults and association with large axial volcanoes), which are major factors for the presence of large massive sulfide occurrences. The spatial criteria were derived from analysis in the statistics software package "R" and combined with the geological criteria in a classification scheme (Figure 2) using the model builder in QGIS (v.3.4.).

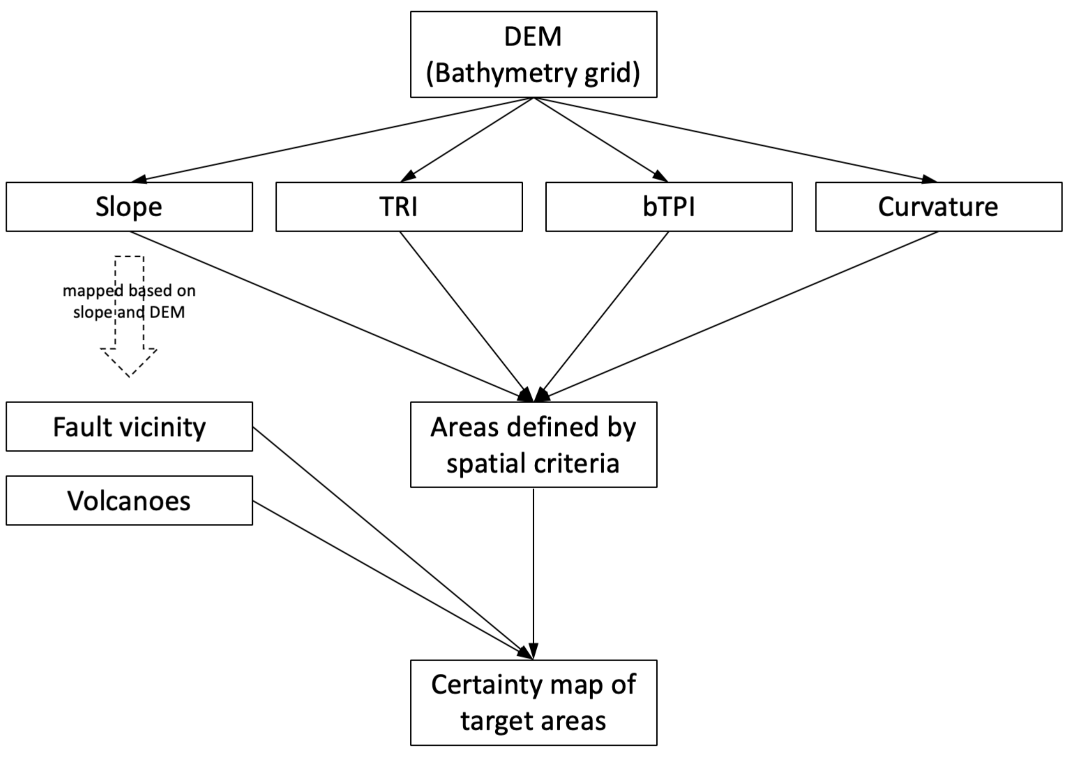

Figure 2:Schematic sketch of the classification scheme applied in QGIS.

Results

The application of the spatial criteria derived from the vent site catalogue and the combination with the two geological criteria results in a “certainty” map, highlighting the areas where we expect additional sulfide deposits, based on the analysis of the other known vent sites. An example for each type of hydrothermal field is given in Figure 3. The highest values reflect the areas that achieve the highest “score” in our classification scheme and relate to the areas with the highest certainty based on the analysis. For comparison, we choose study areas of approximately 100-150 km^2. The delineation of permissive tracts reduces the search areas significantly. Only considering the highest scores for each example, the search area is reduced by 70-80 %. Even though we know from several of these areas that there are no additional hydrothermal plumes in the water column, we cannot exclude that there are unknown inactive massive sulfide deposits.

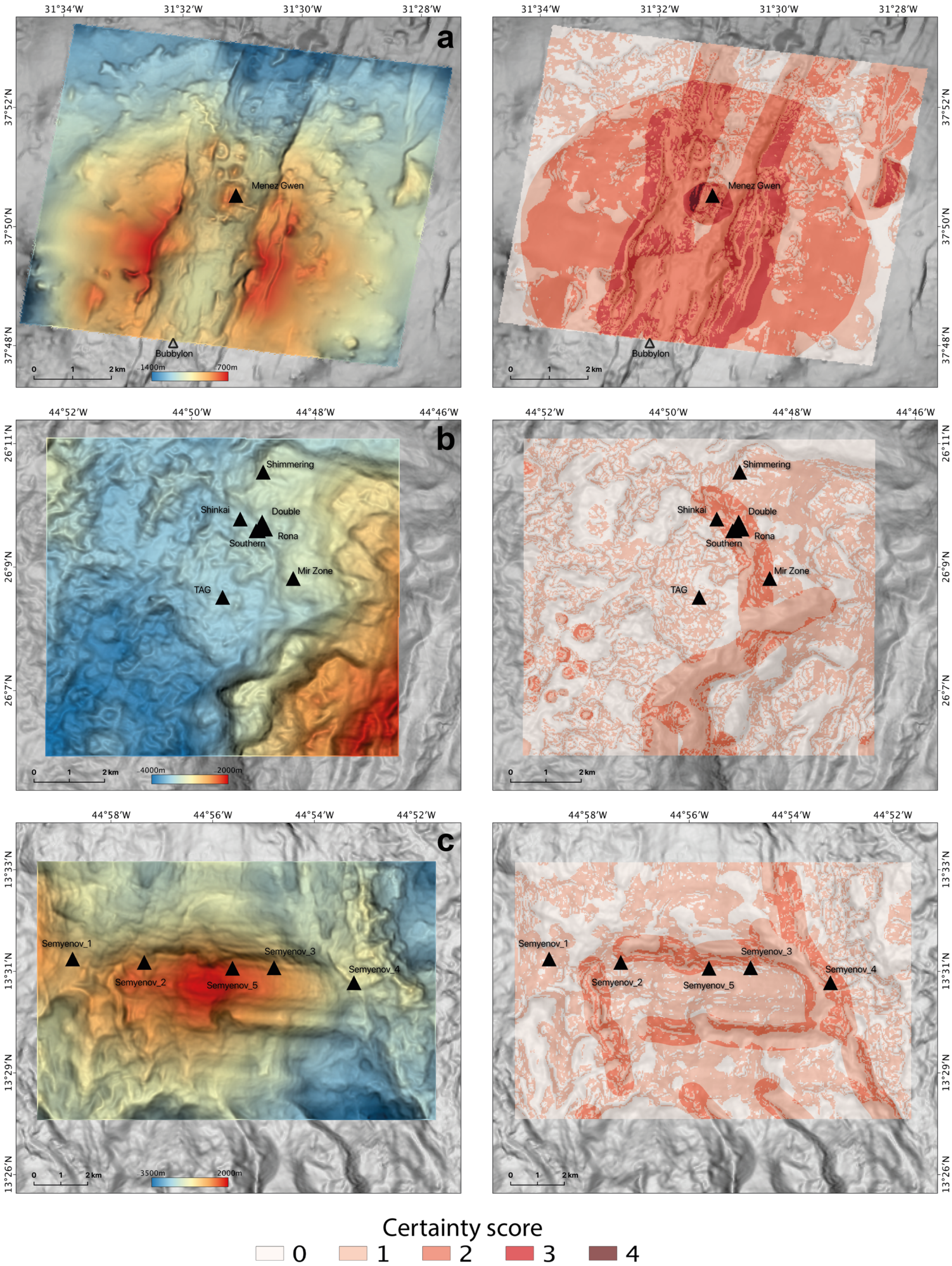

Figure 3: High certainty areas defined by the spatial and geological criteria. a) Basalt-hosted site Menez Gwen, b) Basalt-hosted but detachment-associated hydrothermal field TAG, c) Ultramafic (OCC)-hosted ore cluster Semeynov.

Outlook

To verify the validity of the classification scheme we have to investigate areas with the highest scores. However, the classification scheme is based on the current bathymetric data sets from the 44 known hydrothermal fields. Thus, the delineation of permissive areas is based on the available knowledge and might not reflect all existing SMS deposits. The consideration of ship-based gravity and magnetic data might complement the bathymetric data in the future. In general, the more hydrothermal fields and SMS deposit we find, the more data we collect, the better can we improve the model.

Another step will be the implementation of a fuzzy classification scheme rather than a binary, which might result in a higher number but also more reliable certainty classes. In addition to improving the delineation procedure of the permissive areas, we have to develop the methodologies and tools to identify and locate buried SMS deposits in the highlighted areas. Only this technology will enable us to reliable assess the resource potential of SMS deposits along the slow-spreading ridges, and also in other geological settings, if we start to look for these deposits away from the spreading axis in the older and more sediment ocean crust.

Keywords: seafloor massive sulfides, Mid-Atlantic Ridge, exploration criteria, GIS, permissive areas

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Sebastian Graber

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A 3D method to dynamically model the cutting of submerged rocks with evaluation of pore pressure effects

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Introduction

There are many challenges in seabed mining that will benefit from an efficient and effective rock cutting tool. The knowledge about the rock cutting process is mainly based on experiments and experience. As a result, most of the dredging companies use form of analytical or semi-empirical rock cutting models as a basis for the use and design of the excavation equipment. For such an application these models are beneficial. However, if one wants to investigate how to improve the rock cutting process itself, these models will not be detailed enough.

In the current situation, the best option would be to perform experiments, but this can be very expensive and time consuming. And still the detail that can be gained from experiments is rather limited. Therefore it is desirable to have an alternative to those expensive and time consuming experiments. This paper discusses the development of a numerical model that, in the end, will allow us to simulate the rock cutting process and to analyze it in detail. The developed methodology is already tested and validated in 2D, (Helmons et al. 2016, Helmons 2017), but an extension to 3D is desired to be able to analyze aspects that are simply not possible in 2D. Although experiments will always be needed to validate the developed ideas, the number of experiments needed can be greatly reduced.

Rock cutting process

In general, rock cutting processes are dominated by fracturing and fragmentation of the rock, caused by a mechanical action from the cutting tool In a single cut, it is possible that all rock failure mechanisms occur simultaneously. The phenomenological model of van Kesteren (1995), see figure 1, gives an overview of a generic rock cutting process. In this model, rock can either fail due to cataclasis (compaction, crushing), shearing and tension. These failures are initiated first by indention of the tool, which will create a crushed zone (due to cataclasis) near the tip of the tool. With further indention, the crushed zone increases in size, up to the limit where the surrounding rock cannot withhold the crushed zone anymore, allowing shear cracks to occur. Getting closer to the free surface of the rock, shear cracks will bifurcate towards tensile cracks, which can grow unstably to the surface of the rock. This results in chips that can break out. The phenomenological model is based on sharp tools, which is an assumption that is unfortunately not valid for most of the time while operating.

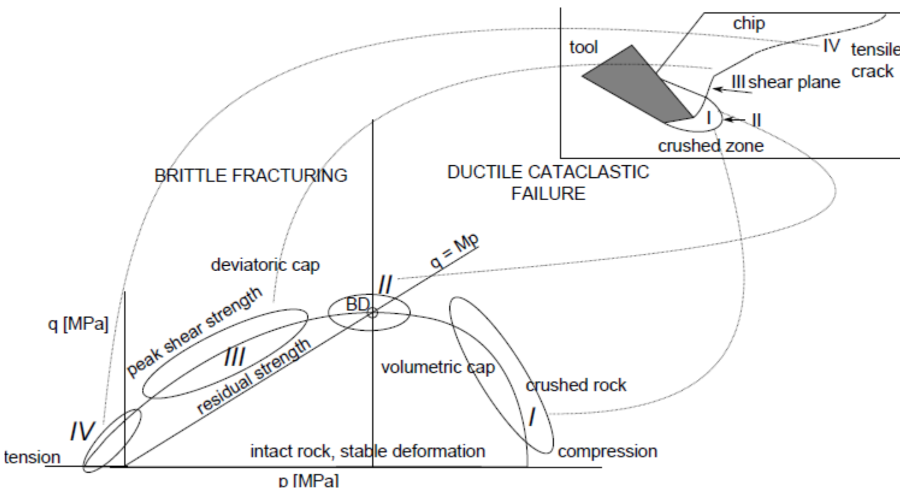

Figure 1. Phenomenological rock cutting model, based on van Kesteren (1995).

To what extent the various phenomena of the phenomenological model occur depends on many different parameters, e.g. the rake angle, the depth of cut, water depth, cutting velocity, rock properties.

The water in and surrounding the rock cannot be simply assumed to be negligible, as it can be of major influence on the cutting process. First of all, water can influence the mechanical response of a generic rock through physico-chemical effects and through drainage related effects (hydro-mechanical coupling). The effect of the physico-chemical interactions depends on parameters like the mineralogical composition, porosity, grain constituents. It is complicated to deduct through experiments how the mechanical response of the rock is affected by the physico-chemical interactions. Therefore it is necessary to perform all material tests in wet (saturated) conditions.

The significance of the hydro-mechanical coupling in rock deformation processes basically depends on the deformation rate w.r.t. the permeability of the rock (van Kesteren 1995), and the relative hydrostatic pressure w.r.t. the strength of the rock, Helmons et al (2016). The significance of the deformation rate (i.e. cutting velocity), can be determined through the pore Peclet number, given as

$$\zeta_{Pe} = \frac{v_c t_c}{D} = \frac{v_c t_c \mu\left(C_f - \alpha C_s + n(C_p - C_s)\right)}{\kappa}. \qquad (1)$$

With pore Peclet numberζ_{Pe}, cutting velocityv_c, cutting depth t_c, diffusion coefficient$D$, dynamic fluid viscosity μ , effective stress coefficient α, compressibility of the rock fabric, solid grains and pore fluid, respectively given by C_f, C_s and C_p, porosity n and intrinsic permeability κ.

Drained behavior is expected for the cases where $\zeta_{Pe} < 1$ and undrained behavior is expected for the cases where $\zeta_{Pe} > 10$. In the case of undrained behavior, two mechanisms can occur, depending on the local loading conditions and the rock properties, van Kesteren (1995), i.e. dilative strengthening and compactant weakening. Dilative strengthening is likely to occur in the regions where cracks (are about to) occur. Its significance is related to the hydrostatic pressure, as during dilation the local (pore) volume increase can be that fast that the pressure drop will to the vapor pressure and thus cavitation occurs, i.e. the maximum pressure decrease is approximately the same as the hydrostatic pressure. As a result of this local pressure drop, the crack resistance of the rock increases.

On the other hand, compactive weakening is likely to occur in the region of the crushed zone, where the rock is compressed, resulting in a decrease in volume. This results in a pore pressure increase, which effectively lowers the local apparent strength of the rock. This can also be of effect on the size of the crushed zone, as is shown in cone indention tests on St. Lieu limestone with varying indention velocities (van Kesteren, 1995). Furthermore it needs to be noted that the size of the crushed zone is also affected by the type of rock that is cut, i.e. limestone will likely have a crushed zone that is larger than in a sandstone with similar strengths, permeability and porosity. This effect is caused by the hardness of the grains of the rock (Verhoef, 1997).

Rock cutting models

Various researchers have attempted to develop a model to calculate the cutting forces in rock cutting. However, there are significant distinctions between various models, as each of them assumes a dominant failure mechanism. Table 1 gives an overview of the most common rock cutting models, along with which failure mechanism is assumed to dominate the cutting process and what type of tools are used to derive the analytical model or that were used to perform the experiments. Furthermore, an overview is given of which rock properties are used to calculate the cutting forces. The symbols that are used for the rock parameters are tensile strengthσ_t, compressive strength σ_c, shear strength/cohesion c, external friction angle δ, internal friction angle ϕ, hydrostatic pressure p_h and intrinsic permeability κ. Thus far, the model of Miedema (2014) is the only analytical model (that is also publicly available) that also considers the effect of hydrostatic pressure and the dilative strengthening effect.

These or similar models can be used to determine the cutting forces, given the tool geometry, rake angle and the depth of cut. Based on these conditions, these models can be suitable for the design of equipment. However, in the case that one is interested in a more detailed analysis of the cutting process, these models will not suffice. First of all, these models all assume an ideal rock geometry. Secondly, the cutting motion is parallel to the free surface, effectively assuming that the tool enters the rock at sufficient penetration.

Table 1. Semi-empirical and analytical rock cutting models

Source	**Tool type**	**Dominant mechanism**	**Analytical / empirical**	**Rock parameters used**
Evans (1965)	Wedge	Tensile	Analytical	σ_t, δ
Nishimatsu (1972)	Wedge	Brittle shear	Analytical	σ_c, δ, ϕ
Miedema (2014)	Wedge / chisel	Tensile / brittle shear / cataclasis	Analytical	$\sigma_c, \sigma_t, \phi, \delta, p_h, \kappa,$
Li et al (2018)	Conical pick	Crushing / brittle shear	Analytical	$\sigma_t, \sigma_c,$

Helmons (2017) developed a 2D simulation method for rock cutting processes under water. This model is validated with strain rate dependent tri-axial tests, 2D tile cutting experiments, drilling and hyperbaric rock cutting experiments of Alvarez Grima et al (2015). Unfortunately, the rock cutting process is a fully 3D process, and thus many aspects cannot be properly simulated in 2D, e.g.break out pattern, shape of the groove, optimal tool spacing.

Therefore the 2D model of Helmons (2017) will be extended to 3D, resulting in a tool that can be used to further investigate the rock cutting process while avoiding the necessity of numerous experiments. Furthermore, the numerical model can support the analysis by modeling effects that cannot be measured in experiments, e.g. local pore pressure while cutting.

Methodology

The most essential components of the numerical modeling framework are explained in this paper, or a more detailed explanation see Helmons (2017). The methodology is based on the combination of Discrete Element Method (DEM) and the Smoothed Particle approach

(SP). The DEM is used to represent the behavior of the rock. The coupling of pore-fluid pressure and the rock is modeled as a pore pressure diffusion process, which is solved with SP. Both DEM and SP are particle-based methods that use a similar algorithm, which makes it convenient to combine both methods.

In DEM, rock is represented as an assembly of rigid spherical particles (discrete elements) that have mutual interactions in normal and tangential directions. The translational and rotational motion of a particle is governed by Newtons second law.

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

$$\vec{F} = \overrightarrow{F_n} + \overrightarrow{F_t} = F_n\vec{n} + F_s\vec{t} \qquad (2)$$

Where $\vec{F}$ is force vector, $\vec{n}$ is unit normal vector to the particle surface at the point of interaction, $\vec{t}$ is the tangential unit vector and the subscripts $_n$ and $_s$ are respectively normal and shear.

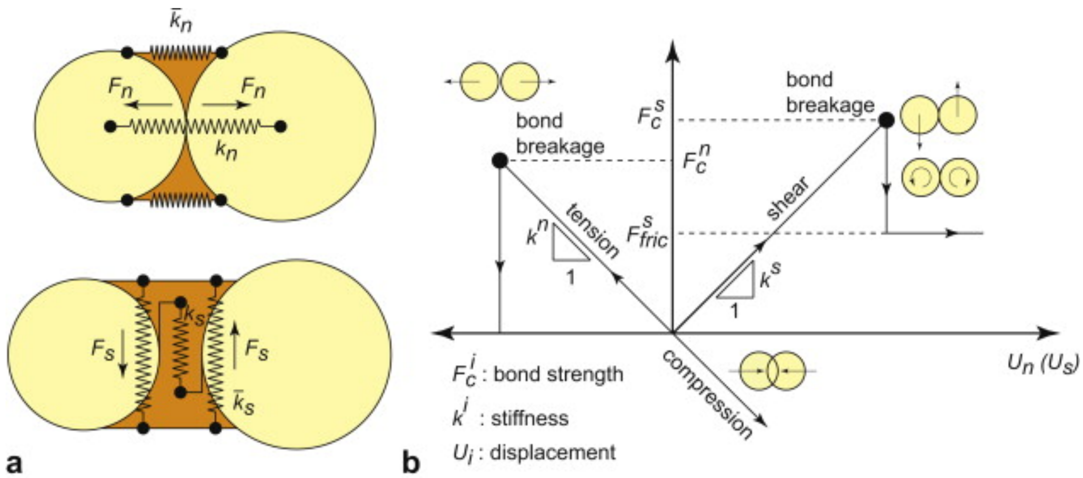

Figure 2. Parallel bonding model, both for normal and shear interactions. Based on Potyondy and Cundall (2004).

The interactions are modeled with a constitutive model. Here, the parallel bond model is used (Potyondy and Cundall, 2004), see fig 2 . This constitutive model not only affects normal (tension/compression) and shear interactions between two particles, but it also restricts bending and twisting of two particles, effectively coupling the interaction of two particles in 6 DOFs. The interaction in the bond itself is a linear elastic perfect brittle model. The interaction between two particles is modeled as a collision when either their bond is broken or when never a bond has existed between those contacting particles. For collisions, a linear elastic model is used in both shear an normal direction. Coulomb friction is used to allow for sliding frictive behavior between particles.

Because the bulk modulus of water is in the same order of magnitude as that of the rock, water has to be considered as a compressible fluid. The low permeability of the rock and the high deformation rate that is applied make it that the fluid flow can be modeled as a pore pressure diffusion process. The pore pressure diffusion equation consists of the combination of the mass conservation law, Darcy flow and a constitutive model for the compressibility of the fluid. This combination leads to the pore pressure diffusion equation given by

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

With pressure p, time t, bulk modulus of the fluid M, intrinsic permeability κ , dynamic viscosity of the fluid μ, effective stress coefficient α and volumetric strain ϵ_V. Note that this equation is similar to heat conduction.

As DEM is based on a discontuum approach, it is required to ‘convert’ the discontinuous data of the DEM towards a continuum field. This is achieved by a smoothed particle interpolation technique. A beneficial effect of the smoothed particle approach is that is can also be used to directly solve the pore pressure diffusion equation (3).

Preliminary results

Here it is opted to mimic the rock properties of the limestone, and the rock cutting setup as used in the experiments of Alvarez Grima et al (2015). This means that the rock sample is calibrated for a UCS of 10 MPa, in a specimen of 0.2x0.2x0.4 m. The chisel is positioned at a rake angle of 68 degrees with the horizontal axis, and the depth and width of the cut is both 0.02m.

Although the methodology is already validated in 2D in Helmons (2017), it is not yet validated for the 3D case. More simulations have to be performed to be able to properly validate the 3D model. Therefore these results are still preliminary. Figure 3 shows the results of the rock specimen at the instance of macro-failure, being damage, local pressure drop (under pressure) due to dilation and the resultant pressure gradient. The color scale shows the amount of damage, which is defined as the ratio of the number of broken bonds of a particle over the total initial bonds of the same particle. Note that in the case of failure of saturated rock, pressure gradients can get to extreme ranges, i.e. in the order of GPa/m. Preliminary results of the rock cutting simulation are shown in figure 4, respectively showing damage and pressure gradient distribution at the same instance in the cutting process.

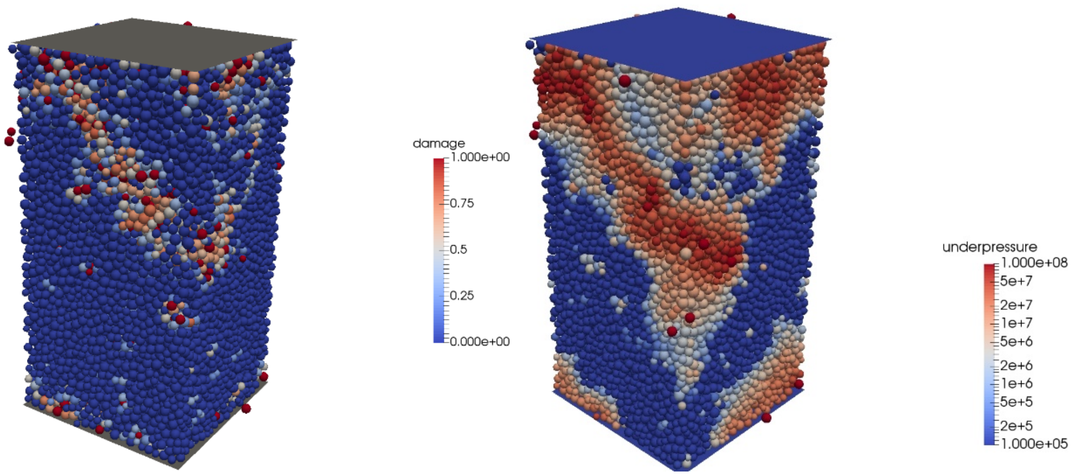

Figure 3. Various parameters at moment of failure. Left top shows damage per particle, blue is completely intact, red is fully disintegrated. Top right is the amount of underpressure that would have been generated as a result of dilation in the cracks.

More detailed simulations with a larger amount of particles will be necessary to properly evaluate the rock cutting process. However, at the current status, emphasis first has to be put on properly validating the 3D model approach itself, to ensure that the 3D rock cutting simulations predict the correct type of behavior.

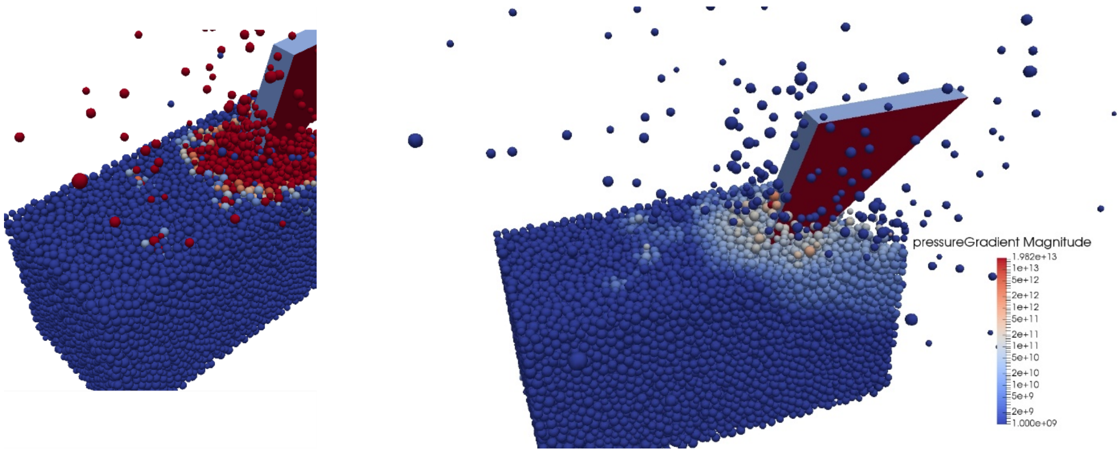

Figure 4. left: Linear cutting experiment, left shows damage, right show pressure gradient distribution

Conclusions

The rock cutting process is a complex process in which various kinds of failure mechanisms can occur simultaneously. A 2D model for the cutting of saturated rock has already been tested and validated. Extension of this model to 3D will be able to support research related to the cutting process itself, enabling us to investigate improvements of the cutting tool while being less dependent on experiments. Preliminary results show that the 3D model works, but the results still need to be validated through comparison with experiments. The development and validation of the 3D model is still in development. Results of the validation steps will be published soon.

Acknowledgments

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Keywords: Discrete Element Method, Rock Cutting, Pore Pressure

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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. In 2012, Rudy started his PhD research in the Dredging Engineering group of the Delft University of Technology. 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. Currently, Rudy is employed there as Assistant Professor for Subsea Engineering and Deep-Sea Mining. He is also the project coordinator of the EIT Raw Materials Upscaling project 'Blue Harvesting'. His main research interests are related to seabed interactions, e.g. excavation processes for sand, clay and rock, and the dispersion of turbidity plumes.

Design of Oval Plane Mirror Component in Marine Remote Sensing Satellite for Mineral Resources

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Abstract (Poster Presentation)

The exploration and monitoring of marine minerals is of great help to our society. Observing oceans from space is a good idea. Marine remote sensing satellite play an important role in this process. The paper makes design of oval plane mirror component in a marine remote sensing satellite and makes thermal test to verify its feasibility. Result shows that the design scheme is reliable.

The lightweight mirror structure of spatial optical instruments has evolved with the development of space technologies. For optical instruments such as space telescopes and remote sensors, the lightweight and support technologies of their mirrors have become relatively mature. Usually, a spatial optical instrument sits on the top of a satellite. The lightweight design of its mirror will bring down the complete instrument weight, thus dramatically reducing the weight of a whole satellite, cutting the satellite launch cost and prolonging the instrument life. Therefore, lightweight mirror technology is of self-evident significance to spatial optical instruments.

This paper designs in detail a spatial oval plane mirror module from three aspects, namely the selection of optical and support material, the lightweight design and the support structure design. The finite element method is used to static, dynamic and thermal properties of the designed mirror module. Meanwhile, a set of mirror product has been developed to carry out a comprehensive environment test. The FEA result and the environment test result show

that, with enough static rigidity, dynamic rigidity and thermal stability, the designed mirror module can meet the technical requirements of its spatial optical instrument.

In the spatial environment, the mirror module will experience not only extreme heat but also the crucible of dynamics during launch. Thus it is required that material selection, lightweight design and support structure design be taken into comprehensive consideration during the design of mirror module. The common material parameters are in the table below.

Table 1. common material

Material	P(g/mm^3)	E(GPa)	A($/10^{-6}\cdot K$)	μ
SiC	3.2	310	2.4	0.21
Zerodur	2.53	91	0.05	0.24
ULE	2.21	67	0.03	0.17
K9	2.51	88	7.1	0.22

The mirror mentioned in this paper is an oval plane mirror with a 210 mm major axis and a 150mm minor axis. By introducing the theoretical research findings of available mirror lightweight designs, the design thickness of this mirror is defined as 30 mm. For lightweight purpose, a grinding head made of high-hardness alloy steel is used to remove some material from the mirror back into an open structure consisting of a center hole, 8 combined radial symmetric ribs and a rib-free periphery to facilitate the adjustment of mirror back without compromising the mirror shape accuracy. The mirror lightweight rate obtained is about 50%. Considering the severe hot environment the mirror experiences, a key part of mirror module design is to choose a flexible support structure. A flexible link can not only absorb the energy arising from the mismatch of thermal properties caused by temperature variation, but also insulate vibration and relieve part of the assembly stress. While increasing the flexibility of the flexible link, its strength must be ensured to avoid its damage in a mechanical environment. To improve the overall rigidity of the mirror module involved in this paper, multi-flexible support bars arranged in a certain way shall be adopted. The flexible support structure and the mirror module structure is shown in the Figure 1.

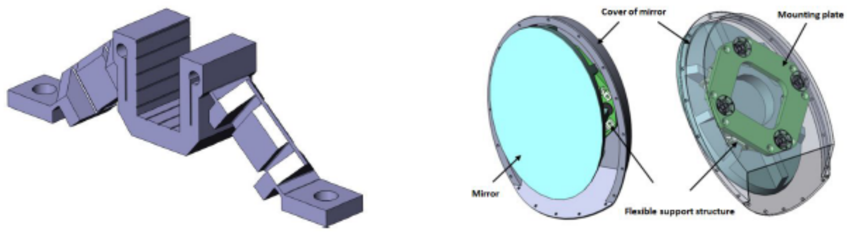

Figure 1. Oval plane mirror component

According to the design of actual mirror module, a finite-element simulated analysis model is built to analyze its environment adaptation mainly involving three parameters: the mirror shape values in three orthogonal directions in a gravitational assembly environment where the mirror module is at room temperature (20℃), the mirror shape values at the required ultimate temperature, and the mechanical dynamic stiffness of mirror module. When the mirror module is under a gravity inertia load and the temperature loads, its shape value will vary, as shown in Table 2.

Table 2. The result of simulation analysis

Load	PV/λ	RMS/λ	Displacement (μm)	Inclination （″）
Gravity in the X direction	1/67	1/351	（0.4、0、0）	（0、1.7、0）
Gravity in the Y direction	1/67	1/421	（0、0.6、0）	（1.7、0、0）
Gravity in the Z direction	1/26	1/115	（0、0.1、0）	（0、0.2、0）
-10℃	1/16	1/72	（0、0、0）	（0、0.6、0）
45℃	1/25	1/115	（0、0、0）	（0、0.5、0）

What's more, some experiments should be conducted to verify the feasibility of the design scheme. According to the requirements of design indicators, the mirror module shall work normally under thermal loads (at the extreme temperatures -10°C and 45°C) in outer space and vacuum, the mirror shape accuracy PV is better than λ/3, and the RMS is better than λ/30. To verify the module's thermal adaptability, a thermal-optical vacuum experiment is conducted to check the shape accuracy of this product at the extreme temperatures -10°C and 45°C. This experiment is shown in the Figure 2, and its results in the Figure 3 ~ Figure 4.

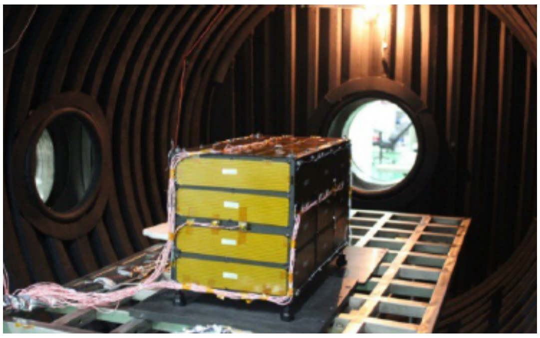

Figure 2. Thermal experiment site

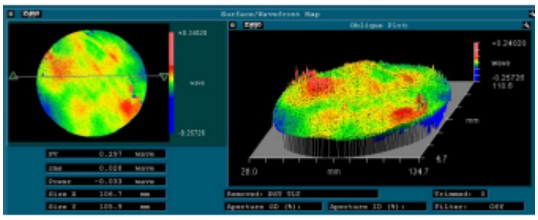

Figure 3. surface shape test at the -10°C

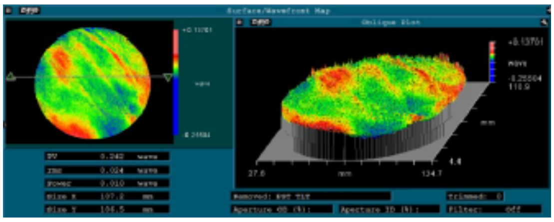

Figure 4. surface shape test at the 45°C

It can be observed from the inspection results that, the mirror module meets the design requirement that in the vacuum environment where the mirror module is under thermal loads (at the extreme temperatures -10oC and 45oC), the mirror shape accuracy PV will be better than λ/3, and the RMS will be better than λ/30 (λ=632.8nm).

As the key component of a spatial optical instrument, the oval plane mirror needs to stand the test of a harsh dynamic environment during the launch. To simulate the mechanical environment at the launch stage, a dynamic experiment is done to check if the mirror module exposed to vibration will suffer plastic deformation and damage. The vibration experiment includes checking the sinusoidal and random vibration in three directions and scanning the characteristic frequency before and after the vibration in every direction. The results of mechanical vibration experiment are shown in the Figure 5-7.

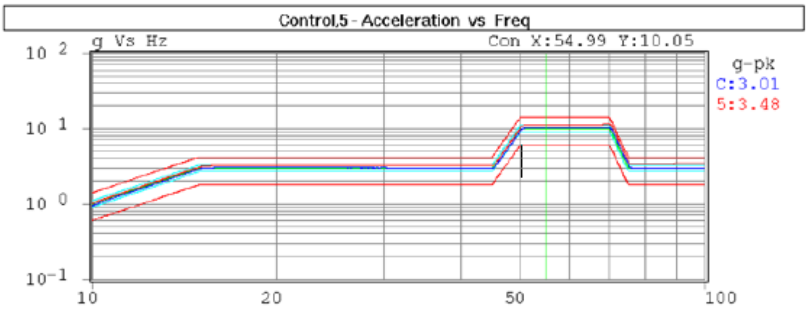

Figure 5. Experiment of sine vibration in the X direction

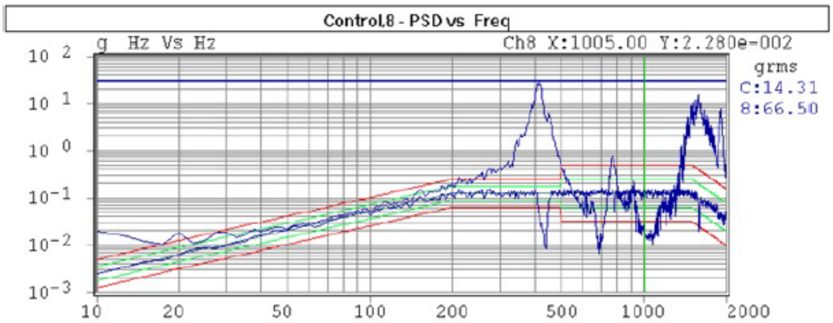

Figure 6. Experiment of random vibration in the X direction

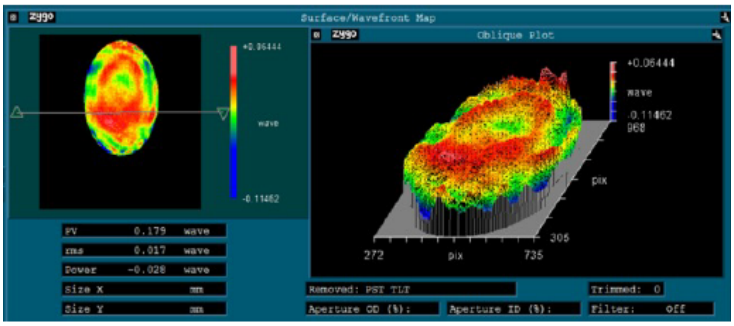

Figure 7. Shape accuracy of the tested module in the X direction after the mechanical experiment (PV=λ/6, RMS=λ/58)

The mechanical experiment results show that, under the preset mechanical vibration, the strength of this mirror module hasn't been damaged. The optical performance testing after the experiment indicates that, the PV of the module is better than λ/5 and the RMS is better than λ/50. This demonstrates that the structure is free from deformation and the module meets the design requirements of such a mechanical environment.

The paper makes design oval plane mirror component in marine remote sensing satellite for mineral resources. It is believed that marine remote sensing satellite would be widely used in the flied of exploration and development of marine mineral resources.

Keywords: Marine Remote Sensing Satellite, Oval Plane Mirror Component, structure design, simulation and experiment

Hu Yongming

Hu Yongmin was born in 1971. He is working in Xi'an Institute of Optics and Precision Mechanics of Chinese Academy of Sciences. His current research field is structure design and analysis of space optical instruments.

Mineral associations in the crusts from Mendeleev Ridge based on SEM-EDS and microprobe analyses

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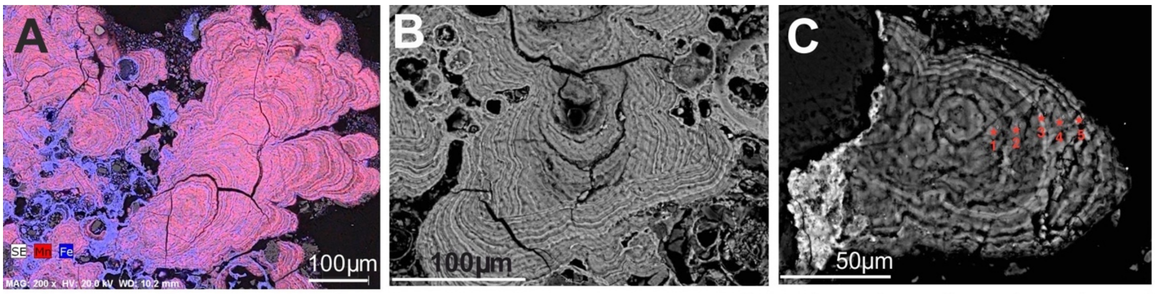
Abstract (Poster Presentation)

Ferromanganese crusts and nodules from the western Arctic Ocean are characterized by a unique composition compared to crusts formed elsewhere in the global ocean (Konstantinova et. al., 2017; Hein et. al., 2017). Here we studied mineral associations of three crusts from southern Mendeleev Ridge using SEM (Hitachi S-3400 N) with an energy dispersive X-ray spectrometer (EDS) (Oxford X-Max 20; Geomodel Center, St. Petersburg State University, operator Vladimir Shilovskich), and four samples were analyzed by variable pressure SEM coupled with a X-ray spectrometer (VP-SEM-EDS HITACHI 3700N with X-ray spectrometer BRUKER Xflash 5010SDD; Hercules Laboratory, Evora University; operator Luis Dias). The Pearson correlation coefficient was used to calculate coefficient matrices for spot-analyzed chemical data, which is a measure of the strength of linear dependence between two variables. Statistical significance will be specified at either a 99% or a 95% confidence level (CL).

SEM-EDS and microprobe results define three mineral associations in the crusts from Mendeleev Ridge, differing in chemical composition and morphology: FeMn mineral association, Fe mineral association, and detrital mineral association.

The FeMn mineral association is the typical matrix for hydrogenetic crusts, consisting of manganese oxide and iron oxyhydroxide laminae (Anikeeva et al., 2002; Hein and Koschinsky, 2014). This mineral association is characterized by columnar and colloform structures (Fig. 1). The average Fe/Mn ratio is 1.01, which is typical for hydrogenetic crusts from the Pacific Ocean (Hein et al., 2000). On the scale of laminae, Fe/Mn ratios vary over a small range, from 0.75 to 1.27, reflecting the ratio of manganese- to iron-rich laminae (Fig. 1C).



	1	2	3	4	5
Fe/Mn	0.79	0.75	1.27	1.25	0.86

Fig. 1. A. Columnar and branching columnar structures, and B. Colloform structures of ferromanganese minerals consisting of manganese and iron laminae. C. Red dots show locations of spot chemical results of Fe and Mn contents (inset table as ratios).

The FeMn mineral association consists of intergrowths of Mn oxide and Fe oxyhydroxide. Mn shows positive correlations with Ni, Ca, Mg, S, and Na; Fe correlates with P, Cl, and Si. The correlation coefficient for Mn and Fe in spot samples is -0.75, which reflects for the most part the redox favored temporal accumulation of either Mn or Fe oxides. The Fe-Mn correlation coefficient for all bulk samples is +0.54, which integrates data for all Fe- and Mn-rich laminae and detrital material.

The iron mineral association was identified based on SEM images that exhibited a predominantly Fe composition. Generally, it occurs as rims around grains and therefore borders pore space and cracks, including voids created by the dissolution of plankton tests, usually foraminifers (Fig. 2). This iron oxide contains small amounts of Al, Si, Mn, Mg, Na, and P.

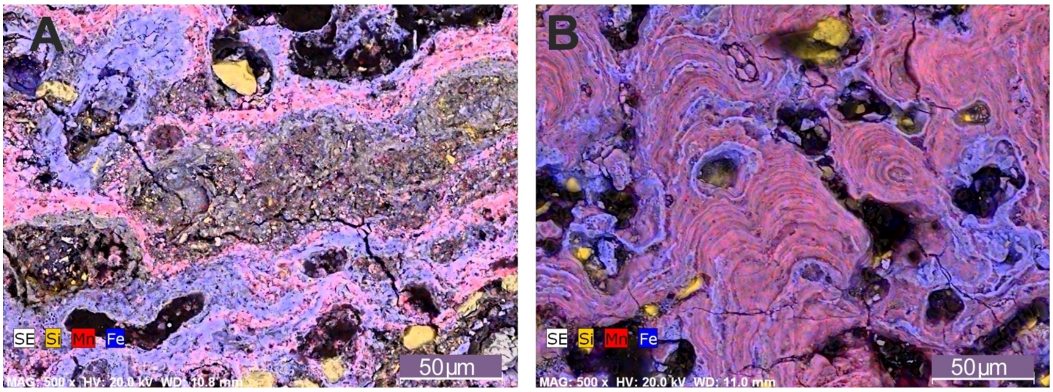


Fig. 2. SEM photos with EDS element mapping of the iron mineral association.

The correlation matrix analysis for the iron mineral association shows Fe has a significant positive correlation only with vanadium and significant negative correlations with Mg, Al, and Mn at the 95% CL.

The *detrital mineral association* consists of sand-sized to micrometer-sized particles differing in roundness and composition that are genetically associated with various rock types (Hein et al., 2017; Konstantinova et al., 2017). The predominant detrital minerals in the crusts, characterized by different grain sizes, are quartz, feldspar, and apatite (up to 2 mm), and barite, ilmenite, zircon, monazite, rutile, baddeleyite, and chromite up to 0.1 mm. As a rule, the grains are angular; well-rounded minerals are not common.

Keywords: Mineral associations, ferromanganese crust, Mendeleev Ridge.

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Natalia worked at the I.S. Gramberg Institute for Geology and Mineral Resources of the Ocean since 2013. She gained the experience in geological and oceanographic research at the USGS for nine months as a Fulbright Fellow with James R. Hein in 2016-2017, and again for 6 weeks in 2018. In 2018 Natalia received a Ph.D. in Geology from the Saint Petersburg State University. Natalia is currently studying ferromanganese crusts from the Arctic Ocean to better understand the nature and origin of these deposits.

Characteristics of the Polish contract area in the Mid-Atlantic Ridge

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Introduction

The Polish exploration area is located along the Mid-Atlantic Ridge (MAR), encompassed by the Hayes, Atlantis, and Kane transforms fracture zones (26°09'-32°50' N) that split the research area into two large segments. The total length of the area is 876 km, and it is a part of the international seabed area beyond the limits of national jurisdiction of any State and claimed continental shelf. From the north, it borders with the Portuguese extended continental shelf and from the south with the IFREMER (France) exploration area.

The Mid-Atlantic Ridge is one of the most promising areas for the occurrence of seafloor massive sulfides (SMS), but the key challenge is to depict the location of the most significant deposits with a mining value, considering the technical and legal framework. In turn, this requires understanding the conditions of their formation. Based on the available data set, a map of the Polish exploration area highlights the most prospective areas of the occurrence of massive sulfides (Fig. 1).

Morphostructural analysis of Polish contract area

The aforementioned segments of MAR (separated by the major transform faults) are also subdivided into smaller features by a non-transform offset which can be assigned to different structural type: magmatic with predominant volcanic processes or tectonic where magmatism is reduced (German et al., 2016). It is assumed that half of the SMS deposits in the Polish exploration area are associated with basalts (magmatic

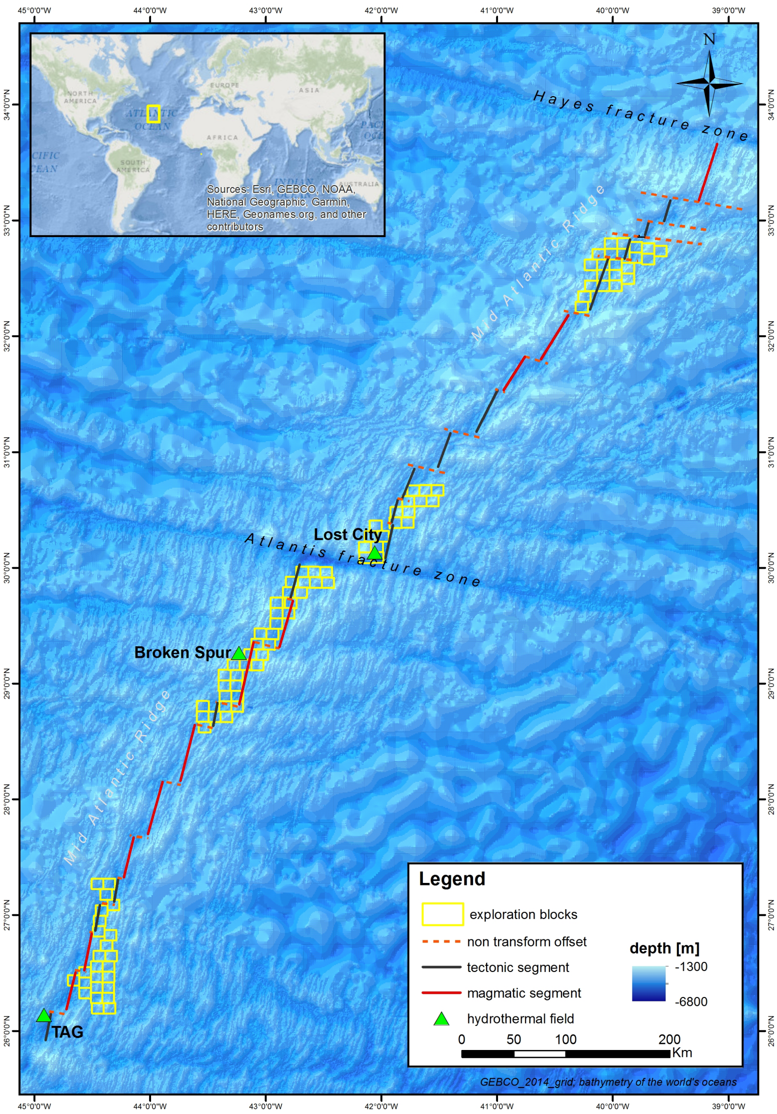

Figure 1. Map showing the detailed location of the polish exploration area with distinguished tectonic and magmatic segments and hydrothermal fields.

segments) and the other half (tectonic segments) with uplifted lower crust and mantle rocks (oceanic core complex – OCC).

The magmatic segments are mainly characterized by generally higher bathymetric level, at the average (about 1000 m) relative depth of the rift valley, and lack of major longitudinal tectonic steps, as well as significant intersegment dislocation intersects, and lack of uplifted plutonic gabbro-peridotite rocks. Magmatic activity is low, and seafloor spreading might be accommodated by tectonic extension along faults [Escartin et al., 2008; Humphris et al., 2015].

The tectonic segments are characterized by relatively small length or expressed intersegment fragmentation, mosaic, and contrast of the flank structure, and extensive development of the major differently oriented tectonic dislocations. As a consequence, outcrops of plutonic rocks occur on one or both flanks of the rift valley [Cannat et al., 1995; Escartin and Cannat, 1999; Ciazela et al., 2015]. Based on available data, the SMS deposits associated with an asymmetrical mode of accretion and gabbro-peridotite rocks (tectonic segments) are considered as promising for large high-grade SMS deposits.

Nature Value

Several biophysical processes are imposed on the hydrogeological processes described above, causing different segments of the mid-ocean ridge (separated by faults) to form separate biogeographic units with ambiguously defined boundaries. Exploration polygons concentrated in five separate clusters (A-E) should be considered as diverse and different from each other, both geologically and biologically, despite their location within one geological feature (MAR). This will be taken into account when planning and preparing for the first research cruise for the Polish concession area in the MAR. The most significant attention of the international community is concentrated in the area of the Atlantis Massif (29°56' N), partly located in the Polish reserved zone (cluster C). Within this area, at a depth of 750 to 900 m is located the famous field of alkaline (non-metallic) hydrothermal vents with a height of up to 60 m called "Lost City." These white chimneys are characterized by significant activity and low-temperature hydrothermal fluids. They constitute a record of at least 30,000 years of changes in their functioning (Blackmann et al., 2002; Früh-Green et al., 2003; Kelly et al., 2005). Marine fauna living on their surface characterize valuable forms of adaptation to these extreme conditions (e.g., chemosynthesis) (Van Dover, 2000; 2011). The Atlantis Massif is the subject of intense and comprehensive international research conducted since 2000. Based on results obtained, with the consistent efforts of the international scientific community, efforts are made to approach this area with strict protections.

Next Steps

The basic (environmental) research planned as part of the cruise for the contract area aims for observation of the ocean floor, as well as physicochemical measurements of the water column and the collection of oceanographic, biological data, and geological samples. An important aspect is the observation and estimation of the size (occurrence and bulk) of polymetallic sulfide deposits. The research will comprise also active hydrothermal vents, which are rare and extreme habitats with extremely individual conditions. They are often places for the development of unique adaptations of living organisms and the concentration of mineral deposits. Planned research should provide helpful hints in response to several crucial questions related to hydrothermal areas. However, the main research potential will be directed to expired hydrothermal areas as well as inactive hydrothermal vents, which are also a potential source of polymetallic resources.

Keywords:
Mid-Atlantic Ridge, morphostructural analysis, hydrothermal fields, massive sulfides.

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Agata Kozłowska-Roman: geologist at the Polish Geological Institute - National Research Institute. She graduated at the University of Warsaw with an MSc degree in Geology (tectonics and cartography specialization). The main interests are the use of GIS methods in geology and structural geology.

Michał Tomczak: senior marine geologists at the Polish Geological Institute in Szczecin. Obtained Ph.D. title in the Oceanology (water chemistry) from University of Szczecin. The main interest is the application of biomarkers in deciphering of the environmental changes.

Artur Skowronek: the head of the Pomeranian Branch in Szczecin, Polish Geological Institute - National Research Institute. Obtained Ph.D. title in Geology and he is specialized in environmental geochemistry, particularly contamination of bottom sediments. His interests include carbonate petrography as well as legal aspects of water management.

SEAFLOOR INVESTIGATIONS
Ocean Exploration Specialists

Assessment of polymetallic nodule resources using high-resolution AUV based geophysical imagery, near-bottom photographs and seabed boxcore sampling.

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Abstract:

In the quest to assess and obtain Measured Resource status of deep-ocean polymetallic nodule deposits it is critical to acquire and cross-correlate multiple geophysical datasets and geologic samples. Seafloor Investigations LLC has organized and overseen three cruises to the Clarion-Clipperton Zone (CCZ) and been directly involved in at-sea operations for several more. We have optimized the geophysical instrument specifications and methodology used in survey acquisition and processing to produce high-resolution co-registered datasets in 5,000-meter water depths. The establishment of robust analytical methods and workflows for correlating geophysical data, geologic properties and physical samples allows for an increased confidence in the assessment of seabed nodule deposits. Such an assessment can be used to report a 'Measured Mineral Resource' that meets international reporting standards (i.e. JORC, NI 43-101). Additionally, the geophysical products and geologic interpretations used in the assessment allow for the fine-scale characterization of seafloor terrain and morphology for engineering purposes.

Keywords: polymetallic nodules, resource assessment, AUV survey, high-resolution geophysical data, sidescan data, boxcore samples, near-bottom imagery, deep-ocean surveys, resource assessment.

Mr. Gregory J Kurras

Gregory J. Kurras
Principal & Owner of Seafloor Investigations

Mr Kurras is a Marine Geologist Geophysicist with over 25 years of combined industry and academic experience in the offshore survey industry working in deep-ocean regions around the globe. He has extensive technical expertise working in all depths but a focus on deep-ocean environments using a variety of geophysical and hydrographic systems and processing packages. He has expertise in AUV operations, advance positioning techniques, geologic interpretation, marine habitat classification, and geospatial data management for deep-ocean exploration. His technical expertise combined with extensive project management and logistics experience produce field programs that result in high-quality results, typically exceed goals and insure satisfied clients.

SEAFLOOR INVESTIGATIONS

In situ Biomarker Discovery in Deep-sea Amphipods for Deep-sea Mining activities using TMT-based Comparative Proteomics

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Abstract

With the discovery of massive mineral resources at the seafloor, rich in copper and other metals, the economic interest in deep-sea mining increased. Aside from the economic benefits, however, the deep-sea mining process also brings along environmental concerns. The establishment of optimal biomarkers of deep-sea mining activities in deep-sea species will thus provide important ecological information for environmental impact assessment of deep-sea mining. Most of ecotoxicological assessments of these activities were conducted under laboratory conditions and using shallow-water species, in which the results may diverge from that of the actual field conditions. In this study, we present the first evidence of *in situ* copper exposure experiments performed on deep-sea amphipods. The successful rate of the *in situ* exposure experiment set-up in deep-sea environment was also analysed based on the copper concentration integrated by the amphipods samples. The collected samples were treated by a Tandem Mass Tag(TMT)-based coupled with 2-dimentional

(Liquid chromatography–mass spectrometry/mass spectrometry) LC-MS/MS to identify the proteins and quantify their expression level change after 48-hour copper exposure. The successfully exposed amphipods samples by this experimental approach was 64.3% and *Abyssorchomene distinctus* was selected as the target species of this study. A total of 2937 proteins were identified and annotated. Difference in protein expression and the specific interactions between the proteins and copper were acquired to propose a candidate biomarker for deep-sea mining activities. 110 proteins were significantly up-/down-regulated, and they were found to be involved in molting cycle, oxidative defences, metal binding or cellular transportation. Among the differential expressed proteins, Na+/K+ ATPase showed unique interaction with copper and had high sensitivity to indicate the copper level. Therefore, this protein might act as a potential biomarker for deep-sea mining activities. This is a key stepping stone in the development of guidelines for environmental impact assessment of deep-sea mining activities that should integrate data on ecotoxicological effects in deep-sea species.

Keywords: Amphipods, Biomarker, Deep-sea mining, Environmental Impact Assessment (EIA), Proteomics

Kwan Yick Hang

Yick Hang is a first-year master student from Department of Ocean Science, the Hong Kong University of Science and Technology. He obtained his bachelor's degree in environmental science from the same university in 2018, and he developed genuine interest and passion in marine biology and ecology throughout his study.

Being inspired by the project he did in his final year of college, Yick Hang decided to devote himself into the exploration of the balance between marine environmental conservation and the related economic developments. His current research focuses on analyzing the potential environmental impact of deep-sea mining on the corresponding benthic organisms with proteomics approaches, in which aiming to purpose a more environmental-friendly mining method where the bottom ocean ecosystem undergoes minimum disturbance.

A Non-Metallic Riser Concept for the Ultra-Deep Seabed Mining Vertical Transport System

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Abstract

The most daunting challenge for the ultra-deep seabed mining vertical transport system is the sheer weight of a conventional steel riser string in some 5000m water depth. Practices adopted from the oil and gas industry for offshore exploration and production point to the use of steel pipes connected by special couplings to form the long riser string hanging from the floating host mining vessel. Indeed, most mining risers built or designed so far are based on rigid steel pipes because the manufacturing technology and installation methods are field proven and have unparallel track records. Steel pipe risers typically require a substantial derrick on the mining vessel for deploying and recovering the riser string, and allocation of a large deck space for storing the riser joints. These result in a large vessel demanding a high capital cost.

Flexible risers are easier to deploy and less deck space is required for the reels. However, they suffer from the lack of tensile strength from the steel or synthetic fibre armouring to sustain the riser's own weight and the pump a free hanging riser has to carry. The riser's protective outer sheath is also susceptible to mechanical damage upon multiple deployments that can potentially lead to the loss of integrity.

The author is proposing in this work a novel twin line non-metallic riser configuration that will have minimal submerged weight in water and yet have sufficient strength to carry the pump, and even the seabed miner in tandem during deployment. The slurry transporting

pipe string is made entirely of polymer and synthetic fibre materials with limited tensile strength as it is required only to carry its own relatively light weight in water. A research programme is being initiated to develop a prototype pipe for this purpose. Preliminary dynamic behaviour analysis results will be presented to demonstrate the feasibility of this concept.

Keywords: Riser, Non-Metallic, Deepwater, Mining, Vertical Transport

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.

Research on Shipborne Dewatering Process Technology in Deep-sea Sulfide Mine

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Abstract

Based on our research on the dehydration characteristics of the deep-sea sulfide ore model and the correlation between the dehydration efficiency of the dewatering equipment and the non-steady state conditions, this paper generates an integrated dehydration process of the deep-sea sulfide ore shipborne dewatering system and designs the system configuration by simulating the dehydration condition tests and the whole process test of the ore sample. The integrated dehydration process consists of the main operation that includes a section of screening, a section of centrifugation and a section of pressure filtration and the two-stage cyclone concentration auxiliary operation. When the amount of slurry that needs to be treated is 4000m^3/h (the total amount of the dry ore: 400t/h), we can obtain three solid mineral granule products with yield of 63.36%, 18.38%, and 15.89% respectively (the total amount is 390.52t/h) and with water content of 5.74%, 9.41% and 15.25% respectively, and wastewater with a flow rate of 3,869.70 m3/h and with a solid content of 0.24%.

Keywords: Deep-sea sulfide ore dewatering, sieve dehydration, centrifugal dewatering, filter press dewatering, cyclone concentration

Liu Shimei

Liu Shimei received the Master's degree from Central South University in 2011. He is currently the Senior engineer in Changsha Research Institute of Mining & Metallurgy. His areas of expertise are: magnetic separation technology and equipment, non-metallic ores (garnet, feldspar, quartz, kaolinite) further processing technology, comprehensive utilization of beach placer, ore dressing of seabed mineral resources, recycle use of resources, and waste water treatment.

Zhou Yueyuan

Zhou Yueyuan received the bachelor's degree from Central South University in 1981. He worked as a researcher (JICA) in the Research Institute of Tohoku University Japan during 1984~1985. He is currently the Chief Engineer in Changsha Research Institute of Mining & Metallurgy. He is an expert obtaining the special allowance of State council. His areas of expertise are: magnetic separation technology and equipment, electrical separation technology and equipment, iron and manganese process technology, non-metallic ores (garnet, feldspar, quartz, kaolinite) further processing technology, comprehensive utilization of beach placer, ore dressing of seabed mineral resources, recycle use of resources, and waste water treatment.

Deep-sea mining equipment research at the Marine Equipment and Technology Institute of Jiangsu University of Science and Technology

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Introduction of Marine Equipment and Technology Institute of Jiangsu University of Science and Technology

Marine Equipment and Technology Institute of Jiangsu University of Science and Technology, a scientific research department of Jiangsu University of Science and Technology, is a Collaborative Innovation Centre of Jiangsu province's university, which specialized in the research, design and development of marine equipment. Based on the national strategy of marine and the local development requirement of marine equipment industry, the institute devotes core and generic technology research, key system and equipment production development, scientific and technological achievement, and industrialization transfer in five major fields: marine transportation equipment, marine development equipment, marine safety equipment, marine scientific research equipment, and marine equipment manufacturing technology. And the institute promotes the integration, industrialization and internationalization of marine equipment scientific and technological achievements by development a new government-industry-university cooperation and joint innovation mechanism.

The institute has the china-Ukraine Technology transfer center, the Jiangsu Marine Equipment Military-civilian Integration R&D Center, the China Ship and Ocean Engineering Industry Intellectual Property Alliance Secretariat, the Jiangsu Shipbuilding Industry Association Secretariat, and a Marine equipment additive manufacturing (3D printing) R&D center, which is the biggest in the domestic shipbuilding and Marine Engineering fields, with the most advanced equipment and the complete technical services in East China.

The institute has 8 high-level scientific research and innovation talent teams to research in the field of marine structure design technology, advanced manufacturing technology and equipment, ship and Marine Equipment, novel Navigation device design, special material technology, and applications for ocean, green energy technology and equipment. In the past three years, the institute has undertaken a number of national and provincial major scientific research projects, including the National Science and Technology Ministry's 973, 863 projects, the Ministry of Industry and Information Technology project, the State Oceanic Administration's Innovation and Development Demonstration Project, and the Jiangsu Provincial Key Research and Development project. Through research, the institute not only produces a series of products and achievements including observational and operational underwater robots, multi-function surface unmanned boats, LNG vaporizer, ship welding electromagnetic induction processing system, solar hydrogen-metal hydrogen storage-fuel cell power supply integrated system, seawater desalination integrated device, and ketone fire extinguishing agent.

1. Introduction of Deep-Sea Mining Equipment

Deep sea mining equipment includes submarine mining equipment, lifting equipment and surface support systems. As the main part of deep sea mining equipment, mining and lifting devices is the core equipment.

In recent years, offshore oil and gas exploration device can be used at 3000 m water depth. With development of deep sea power transmission and communication technology, deep sea motor and hydraulic technology, components pipeline transportation technology, deep sea investigation and marine robot technology, all these technology can meet the deep sea mining equipment manufacture and the deep sea mining equipment manufacture is feasible.

Marine Equipment and Technology Institute of Jiangsu University of Science and Technology research the deep mining equipment since 2017. By joint co-operation with domestic and abroad enterprises and institutions, the institute’s research focused on some key technologies in the core equipment field. The institute has established a cooperation agreement with the first deep sea vessels ship designer SeaTech and manufacture Mawei shipbuilding LTD to jointly develop the core equipment for mining vessels and deep sea mining key technologies and equipment. In 2018, deep-sea mining project team is built to research below three main key technologies on mining equipment, lifting equipment and water surface support systems.

1) Deep-sea heavy-duty unmanned vehicle technology: Overall design of deep-sea mining vehicles, deep-sea mining vehicle hydraulic power system, deep-sea mining vehicle drive system, deep-sea mining vehicle remote and unmanned autonomous control system, and other key equipment, devices and specialty materials for deep-sea mining vehicles.

2) Modular mining and mining collection device technology: Modular deep-sea crust ore mining equipment for underwater mining vehicle, deep-sea crust mine crushing device, and fine-grained mineral collection and Primary selection device, integrated control and

reliability research of mining equipment, mining equipment materials and lightweight technology.

3) Mineral collection and lifting technology: Fine crushing mineral fluid lifting and transportation, special fluid pump and mineral lifting pipeline, mineral collection and flexible conveying pipeline.

2. Deep-sea Mining Lifting System Research

The lifting process lifts the ore from the concentrator to the surface mining vessel. Research mainly includes fine-grained mineral fluid lifting and transportation, special pumps and mineral lifting pipelines, the development of mineral collection, flexible transmission pipelines, and the positioning of lifting equipment, simulation analysis of solid-liquid two-phase fluid in the pipeline.

Deep sea mine lifting system is designed, the crushed ore is transported to the surface of the mining vessel through a special lifting pump on the seabed, and the separated wastewater is returned to the seabed through a high-pressure pump to drive the special ore lifting pump work on the seabed. The advantages of this lifting system are:

(1) Avoiding the wastewater directly be discharged to the sea surface and polluting the environment;

(2) The special lifting pump is volumetric pump which has the advantages of high efficiency, long service life and convenient maintenance;

(3) The power of the lifting system is installed on the mining ship, avoiding the restrictions of deep-water motors and power transmission. The specific principle is shown in Fig.1

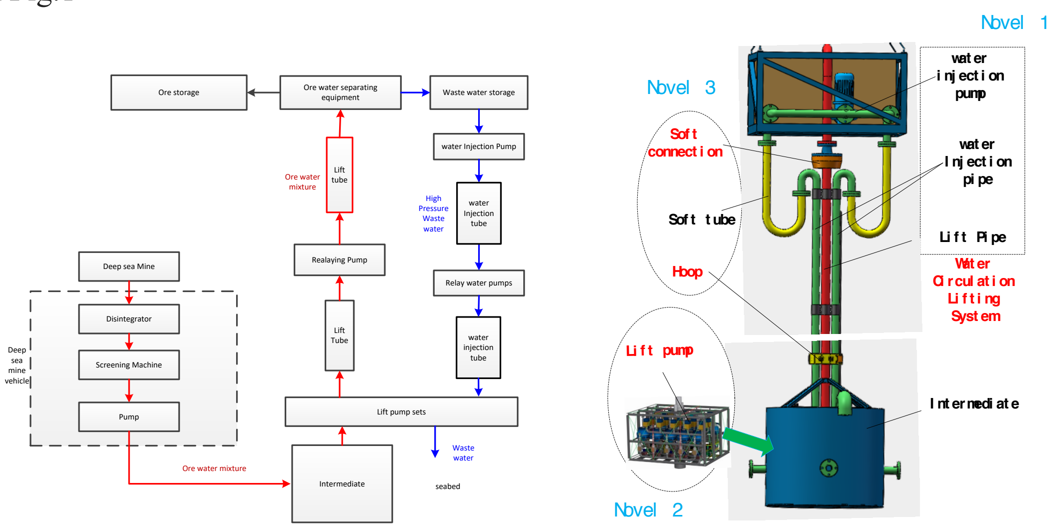

Fig.1 The schema of deep sea mine lifting system

The lift pump is a volumetric diaphragm pump sets, which driven by water to transports ore and water mixture to the sea surface. The multiple sets of pumps and valve groups are combined to control. By the way the flow in the riser tube can be stably and continuously conveyed, the flow resistance loss for energy loss is only in the tube, and the efficiency is high.

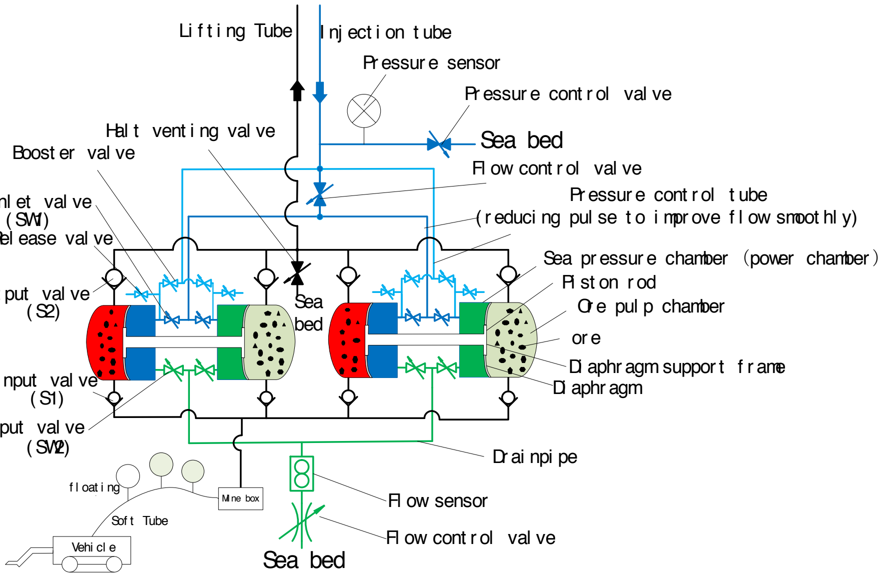

Fig.2 lift pump structure principal

A test device was researched to test the prototype of lift pump and the lifting system. The main research includes two-phase flow of the riser tube and the test of the special lift pump set. The test goal is verifying the flow stability of the dedicated lift pump set control system and riser.


Fig.3 lift system test device

The key structure of the lifting system, pipeline and the mining platform, was designed. They were connected with soft connection which will reduce the stress concentration caused by the swing under the hydrodynamic action of the pipeline. The riser was connected by a soft joint, and the water pipe was U-shaped Hose connection as shown in below. And The lifting and watering pipelines are connected by sections, each section is 19m, and the pipelines are fixed by clamp type connection.

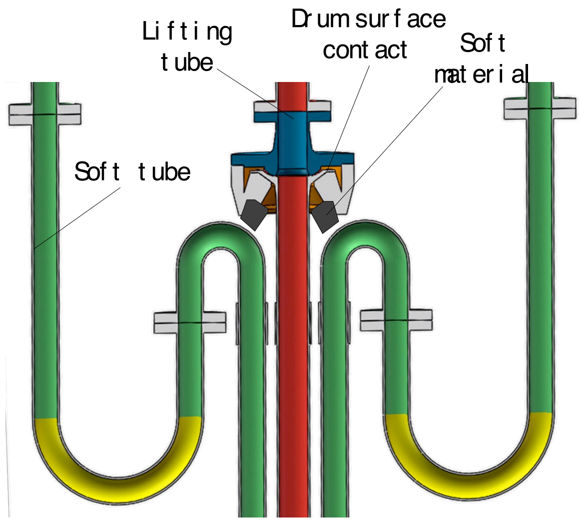

Fig.4 the conception structure of lift tube and platform

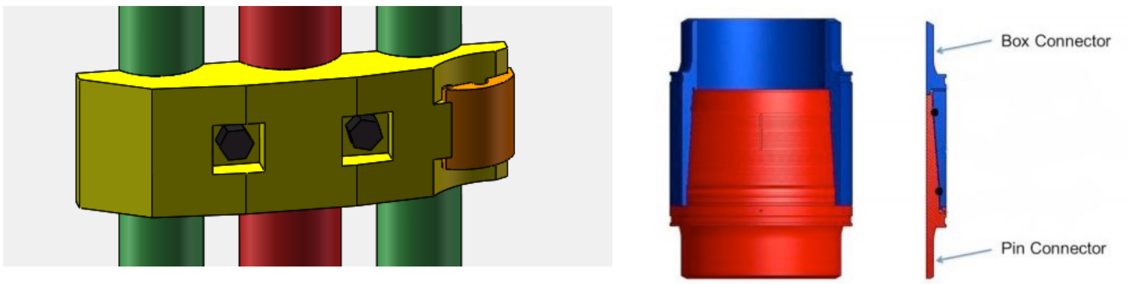

Fig.5 the structure of joint between lift tube and water injection tube

3. Deep-sea Heavy-duty Unmanned Vehicle Research

Based on the deep-sea working condition, the main research on the deep-sea heavy-duty unmanned vehicle includes the general structure design, travel performance analysis, hydraulic drive and control system design, reliability analysis.

3.1 General Structural Design

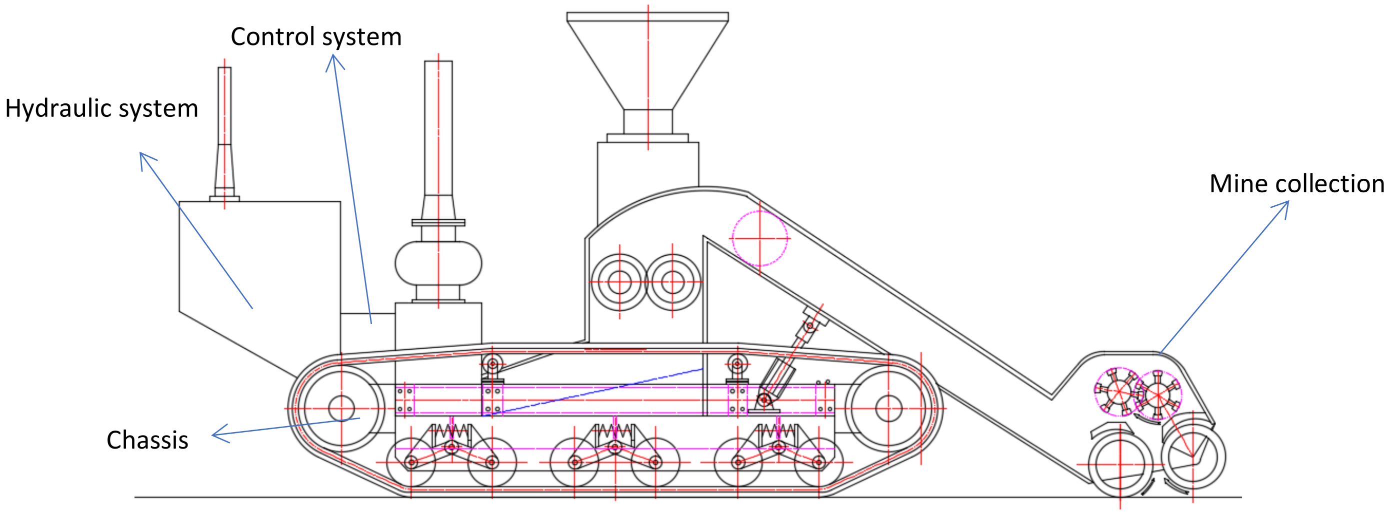

Fig.6 The general structural design of the deep-sea heavy-duty unmanned vehicle

According to the requirement of the working conditions, the structure of the deep-sea heavy-duty unmanned vehicle is shown in Fig.6

(1) Chassis: the crawler chassis is adopted for the large traction force, high load capacity, operational easy.

(2)Power system: the hydraulic power system is designed for the big output and highly power density.

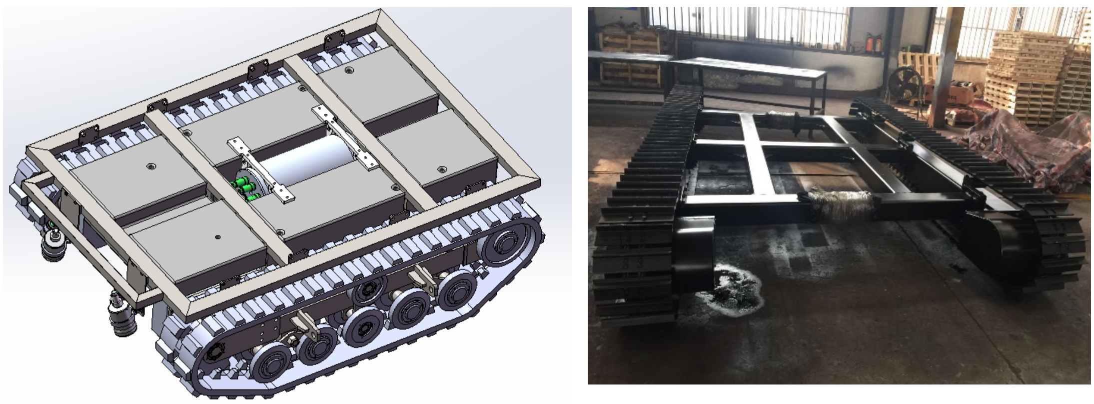

Fig.7 chassis design and prototype

3.2 Travel Performance Analysis

According to the general structure design, the travel performance analysis of the vehicle is researched including below content:

- Geological Characteristics of Deep-sea mining area
- Interaction between crawler and ground
- Vehicle travel performance analysis
-

3.3 Hydraulic Drive and Control System Design

For the energy saving, a variable frequency pump control hydraulic system is designed to driver the vehicle. The scheme of the system is shown below.

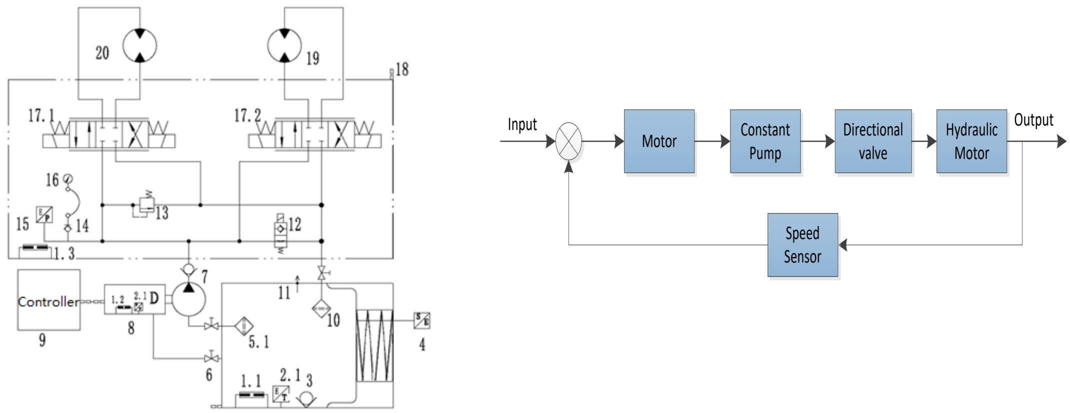

Fig.8 hydraulic system and control scheme

3.4 Reliability Analysis

The Faults of vehicle can be manifested in a variety of ways. By Fault Tree Analysis (FTA), Failure Mode Impact and Hazard Analysis (FMECA) to analysis the reliability of the vehicle, the analysis results is shown in below.

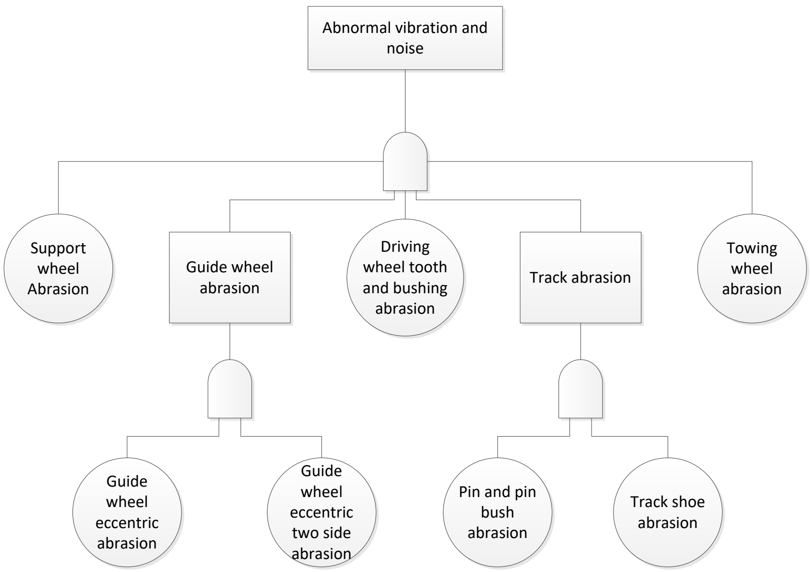

Fig.9 FTA Analysis of Vehicle

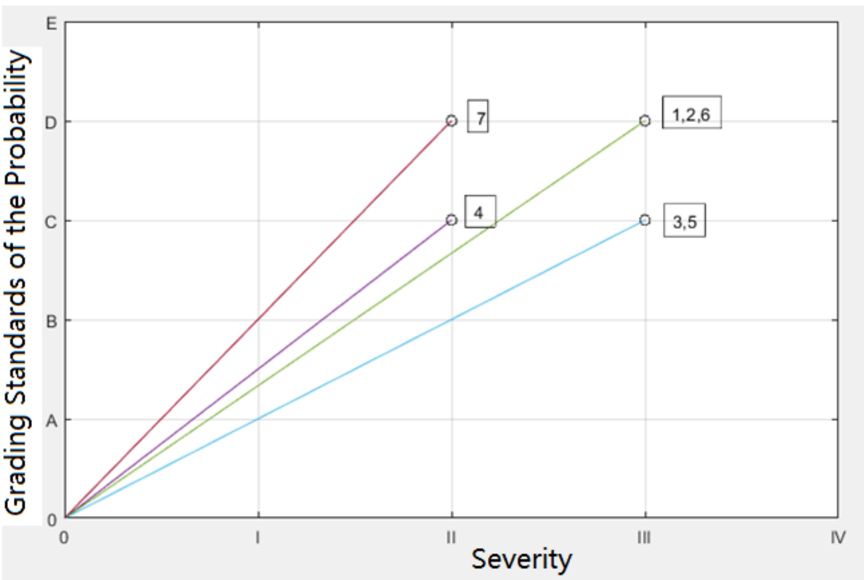

Fig.10 Risk Matrix of Track Chassis Fault

Keywords: Deep-sea mining equipment, Lifting systems, Deep-sea Heavy-duty Unmanned Vehicle

Lu Daohua

Professor Lu Daohua is a chief expert of Marine Equipment and Technology Institute, Jiangsu University of science and technology. He is also an academic leader for Innovation Project of Jiangsu Province. Now, he research interests deal with design, manufacture and control of marine equipment. Up to now, he has presided more than 40 scientific research projects, include "National Key Research and Development Program of China", "High-tech ship project of the Ministry of Industry and Information Technology", and declare and authorize 40 items of invention patents.

Determining and communicating marine mineral resource estimates to the broader minerals industry

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Abstract

Over past 10 years there has been an exponential increase in the consumption of minerals required for the green economy. This has been mostly driven by the move away from petrol powered vehicles to electric and hybrid vehicles. This has resulted in key minerals like cobalt being in strong demand. Securing cobalt supplies presents some issues as it occurs mostly as a by-product, in smaller deposits (outside the DRC) with vast majority of the known resources occurring in stratiform sediment hosted deposits in the DRC.

Significant abundances of cobalt, nickel and copper occur within crusts and polymetallic nodules on the seafloor. Much of these deposits are known from oceanographic studies undertaken during the 1970s to 2000s. In the last 10 years there has been an increase in private and government sponsored companies trying to assess the economic potential and the mineability of these deposits.

RSC has been working with several of these groups who are trying to utilise historic sample data, mainly collected from freefall grabs, and estimate mineral resources on the seafloor. In order to be able to communicate with the broader mineral industry the technical studies and resource classifications are typically undertaken in accordance with the JORC Code (2012) or NI43-101 reporting guidelines.
The challenge for the seafloor mining industry is how to assess a mineral resource that cannot be visited, has unique depositional controls on mineralisation and yet still needs to show it can be commercially exploited.

Keywords: Poly-metallic nodules; cobalt; nickel; copper; resource estimation; resource classification

Campbell McKenzie

Campbell has a background as an exploration geologist and holds a BSc (Hons) in Geology. He has worked globally in the minerals industry for twenty years with experience covering mineral exploration and mining, business development, stakeholder relations, investment promotion and joint industry – academia research. He has held upper management roles with mineral sector consultancies, government and industry. This has included managing the minerals group for the New Zealand government for a period, as New Zealand Country Manager for marine minerals explorer Neptune Minerals Plc, and more recently CEO of Kenex – a New Zealand based consultancy providing GIS and exploration services to the industry.

Campbell has had involvement in the marine minerals sector for over 15 years, including an extended period working alongside Chatham Rock Phosphate Limited.

Campbell is based at RSC's Wellington office and manages the company's Business Development.

Titanium Concentration in the Mineral Phases of Ferromanganese Deposits from the N-W Pacific

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Abstract

The research presents results of titanium concentrations in mineral phases of ferromanganese deposit (FMD) with different genesis formed in N-W Pacific at active and stable tectonic settings. The data are show that the distribution of titanium in the mineral phases of the FMD from the N-W Pacific is an additional criterion for their genetic classification. The potential ores of the Magellan seamounts-Guyots contain 2.6 million tons of easily recovered titanium, which brings them closer to the reserves of titanomagnetite placers of the coastal strip of the marginal seas of the Far East of Russia Federation.

Introduction

Titanium, manganese, and chromium are critical ferrous metals according to the doctrine of the economic development of Russia's mineral resource base (Bortnikov et al., 2016; Peterson et al., 2016). All known titanium terrestrial deposits are composed of oxide minerals. The largest Ti deposit in the World is confined to the Yaregskoi fossil (Devonian) placer of leucoxene close to Southern Timan. The proven reserve of this deposit is tens of million tonnes of ore that accounts for about 50% of Russia's total reserves (Ivanova, 2002). In the North-East of Asia, quaternary titanomagnetite placers are known in the coastal belts of the west of the Tatar Strait, the Kuril Islands, Kamchatka, and several other places. Forecasted titanium resources in these placers are estimated to be about a million tonnes (Andreev, 2014). The presence of fine phases of titanium minerals in deep sediments and ferromanganese deposits (FMD) is considered a criterion for a terrestrial source.

The titanium is delivered to the global ocean as dissolved and suspended forms by river and atmospheric (eolian, pyroclastic) flow. However, the amount of titanium added annually from the continent (0.12 million tons) does not agree with the data on the annual accumulation of titanium in oceanic sediments (2.12 million tons). This deficit (2 million tons per year) is supplemented by the hydrothermal fluids (Kurnosov, 1986).

Marine FMD of different genesis contain variable amounts of titanium. The maximum content is characteristic of hydrogenous cobalt-rich crusts and decreases consecutively to diagenetic nodules and reaches a minimum in hydrothermal crusts. The average titanium content in the hydrogenetic FMD of the PCZ Pacific is 1.16% (Peterson et al., 2016). This high concentration of titanium was the basis for considering it as a potential source of strategic metal. The Ti content in the hydrogenic crusts of the tropical zone of the northern Pacific is 1.27% on average and begins to decrease as the continent approaches 0.96% in the FMD of the Marshall Islands (Bau et al., 1996).

A study has been carried out on the distribution of titanium in the main (four) mineral phases of FMD in the central equatorial Pacific (Hein, Koschinsky, 2014). It has been established that in hydrogenic FMD the main value of titanium is concentrated in the hydrous Fe oxide phase, with a minor amount in the residual phase. Diagenetic and hydrothermal samples of FMD show the maximum values of titanium content in the residual phase, and in the hydrous Fe oxide phase it is very small. These facts made it possible to suggest that titanium, realized in the hydrous Fe oxide phase, represents a discrete (separate) hydrogenic titanium phase, probably $Ti(OH)_4$ (Hein, Koschinsky, 2014). The distribution of titanium in the mineral phases of various genetic types of FMD in the North-West Pacific is not known. This message is devoted to solving this issue.

Materials and Methods

Samples for the study were selected from sediments and FMD of the main genetic types dragged from various morphostructures of the seabed of back-arc basins and close areas of the North West Pacific. Modern sediments were recovered from the Derugin Basin of the Sea of Okhotsk, hydrothermal Fe crusts (ochers, umbers) from the slopes of the local basin of the Philippine Sea, hydrothermal manganese crusts from the underwater Belyaevsky Volcano in the Sea of Japan, hydrogenetic ferromanganese crusts from the underwater Volcano 1 (Zonne Ridge) and the tectonic mountain in the Kashevarov Trough in the Sea of Okhotsk and, in addition, cobalt-rich crusts of Detroit and Yomei Guyots (the northern closure and the central part of the Imperial Range, respectively), Seth (western end of Markus-Wake), Magellan and Marshall Islands, and diagenetic nodules from Deriugin Basin and Yomei Guyot. The study of the distribution of titanium in the mineral phases (easily leachable adsorbed cations and carbonates - 1 phase, manganese oxides - 2 phase, iron hydroxides - 3 phase and residual - 4 phase) was carried out by sequential selective leaching on the ICAP6500 Duo spectrometer (Thermo Electron Corporation, USA) in at the Laboratory of Analytical Chemistry of the Far East Geological Institute, Shared-Use Center.

Results

The results indicate that the first phase is characterized by the minimum values of titanium content (hundredths and thousandths part %). The lowest values are characteristic for hydrothermal both iron and manganese differences (0.08 - 0.3 ppm). Increase is observed in hydrogenic crusts in marginal seas, as well as diagenetic nodules and biogenic-terrigenous sediments (0.11 - 0.53 ppm). And then is increased in cobalt-rich crusts of guyots as the distance from the continent (0.85-1.00 ppm) to the middle of the Pacific (1.06 - 1.53 ppm).

In the Mn oxide phase (2), low titanium contents have also been obtained. The minimum values are determined in all hydrothermal deposits and sediments (0.04 - 6.4 ppm). Above the concentration in the hydrogenic crusts of the marginal seas (10-97 ppm) and at the guyots (6-83 ppm, and in individual layers increase to 153 ppm) are observed. High values are characteristic for diagenetic nodules (151 ppm).

In the hydrous Fe oxide phase (3), the maximum variability in the content of titanium is observed. Hydrothermal formations (both iron and manganese) contain a minimum of titanium (1.2 - 55 ppm). A little higher than the values noted in the sediments (104 - 157 ppm), then they increase in diagenetic nodules (692 - 1193 ppm) and the marginal hydrogenic crusts (792 - 4982 ppm) and the maximum values are reached in the hydrogenic crusts from guyots 5534 - 11282 ppm).

In the residual phase (4), the lowest titanium content is found in hydrothermal iron crusts (3.9-40 ppm), and in hydrothermal manganese crusts it is higher (68-470 ppm). Hydrogenic crusts of Yomei Guyot (170 ppm), Seth Guyot (380 ppm), and Magellan seamounts (62 - 617 ppm) are characterized by similar values. The content of titanium in the hydrogenic crusts of the marginal seas (244-1 1160 ppm) and the Marshall Islands (380-1311 ppm) is slightly higher. The amount of titanium in diagenetic nodules (290 - 1344 ppm) is the same range. The maximum quantity was found in both detrital sediments (1543 - 2980 ppm) and hydrogenetic Detroit Guyot crusts (2050 - 2540 ppm), located close to the continent.

Discussions and Conclusions

The relative distribution of titanium in the mineral phases of FMD and detrital sediments of the N-W Pacific is shown in the figure and indicates a visible difference between these genetic types. In all hydrogenic FMD, the total amount of titanium is distributed in phase 3 (69% on average - the marginal sea and 87% - oceanic guyots) and phase 4 (29% and 12%, respectively). Diagenetic and hydrothermal FMD samples, as well as modern sediments, show a different distribution (figure). These data indicate that the distribution of titanium in the mineral phases of the FMD from the N-W Pacific is an additional criterion for their genetic classification.

The dry ore reserves of cobalt-rich crusts from the five Magellan Guyots of the North Pacific Prime Zone are estimated at 337.4 million tonnes (Andreev, 2007). The ores contain 0.81% titanium (an average of 212 tests (Melnikov, 2009)). According to our data, the hydrous Fe oxide phase of FMD Magellan Guyots contains 96% of the titanium. Consequently, the potential ores of the Magellan Guyots contain 2.6 million tons of easily recovered titanium, which brings them closer to the reserves of titanomagnetite placers of the coastal strip of the marginal seas of the North-East of Asia.

The study was supported by project 18-17-00015 of Russian Science Foundation.

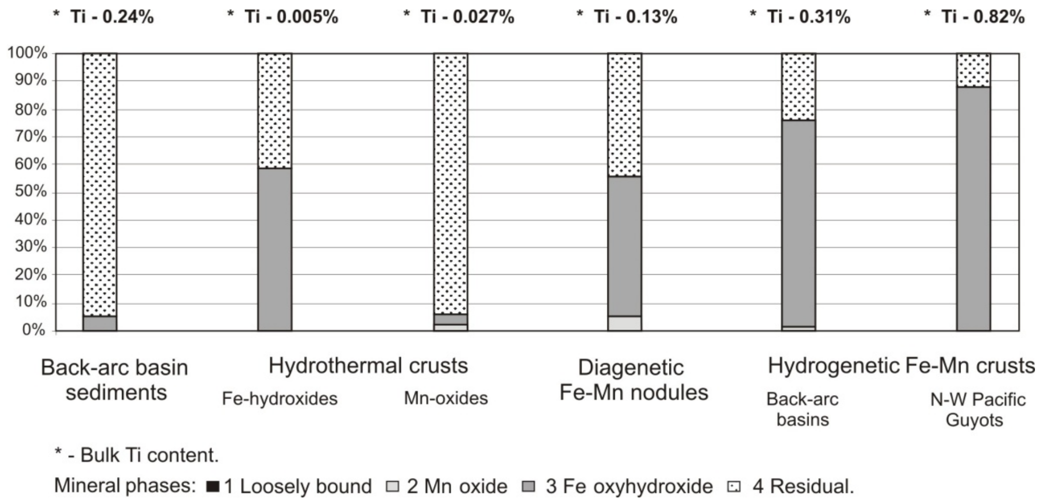

Figure. Distribution Ti in mineral phases of detrital sediments and ferromanganese deposits from the N-W Pacific.

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Keywords: ferromanganese deposits, titanium, strategic element, mineral phases, N-W Pacific

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.”

A review of the structural health monitoring for marine risers/pipes

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Abstract

Marine risers play an important role in deep-seabed mining. They are used to lift nodules from the deep-seabed to offshore facilities. Unfortunately, risers are also at high risk of being damaged due to their exposure to harsh environmental conditions such as a currents, pressure, high tension, and vortex induced vibration. Therefore, the ability to preemptively protect a riser's performance as well as detect damage before riser failure, is imperative. For these reasons, an accurate health monitoring method for marine risers should be developed to detect and localize potential damages. Many studies have been assessed to detect and locate the damages of various risers such as flexible risers, steel catenary risers, top-tensioned risers, etc. This study provides a review of the structural health monitoring for risers including damage detection methods, field monitoring researches and related sensing technologies, under water nondestructive inspection machines.

Keywords: Structural health monitoring, Marine pipes, Riser, Damage detection, Deep-seabed mining

Cheonhong Min is a senior researcher in Korea Research Institute of Ships & Ocean engineering (KRISO). He had studied at Korea Maritime University for Ph.D. degree. He has researched on structural health monitoring, prognostic health management and experimental vibration analysis.

A study on the simulation-based design technology of the subsea equipment using DIMS toolkit

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Abstract

This paper concerns the simulation-based design study for subsea equipment using DIMS toolkit developed by KRISO & VM (Virtual Motion, Inc.) in Korea. Research on subsea equipment and systems, including a deep-seabed integrated mining system, are very difficult due to influences of high water pressure, extreme ocean environment, and hydro dynamics. To tackle this problem, simulation-based research and engineering technologies are being actively studied and utilized in these subsea R&D fields. Especially, dynamics-based simulation technologies are very important because the subsea equipment composed of several objects are installed and operated under various load conditions. For these reasons, the Korean research team developed the DIMS toolkit using multibody dynamics for the simulation-based research and engineering of the subsea equipment and systems.

The DIMS toolkit is developed as an add-on toolkit in ANSYS/Motion software. The DIMS toolkit can simulate not only the dynamic analysis of the equipment and systems but also structural analysis, thermal analysis, and eigenvalue analysis of the equipment and systems because it shares the various analysis functions of the ANSYS software. So, we have used this toolkit for design of subsea equipment in deep-seabed integrated mining system and various subsea systems such as offshore riser systems and ROVs.

In this presentation, we will introduce application examples of the DIMS in various offshore R&D fields.

DIMS toolkit

At the end of 19th century the UK Challenger found for the first time deep-ocean manganese nodules. In 1970, some developed countries begun the full-scale research and study of manganese nodule mining systems. For mining manganese nodule at 300 tons per hour, it is necessary that a DIMS (Deep-Seabed Integrated Mining System) can run freely on the seabed and gather manganese nodules.

As shown in Figure 1, DIMS represents the integrated mining system in deep sea. In other words, force entities define loads and compliances on bodies. The forces are used to model spring and damping elements, actuation and control forces, elastic connectors, and many interactions between bodies. This chapter introduces force entities and how to formulate, create and modify forces.

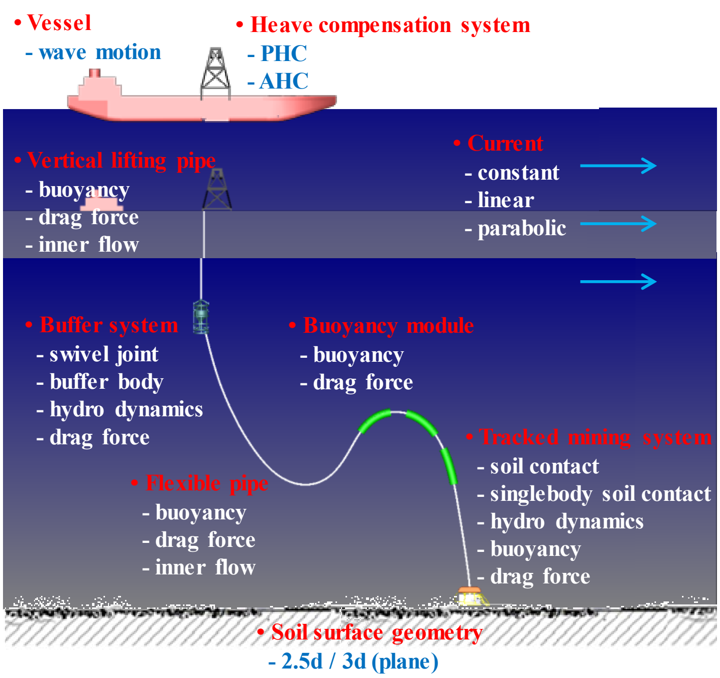

Figure 1 Overall composition of Integrated Mining System in the Deep-seabed

The integrated mining system is made up of a vessel, vertical lifting riser pipe, an intermediate buffer, riser, buoyancy material, and self-propelled miner (mining robot). The entire mining system`s dynamic behavior analysis is an important component technology of deep seabed mining technology. To develop pre-pilot track vehicles for driving on seabed sediment, there are many simulation-based design techniques to take advantage of for the modeling and simulation.

The DIMS toolkit can model by using a tracked system toolkit that exclusively tracks vehicle dynamics analysis in ANSYS/Motion software. It was developed by an integrated system so that it might model easily each component analysis of the deep seabed. The integrated mining system compensated for that lack of functionality of each component analysis. So it is an exclusive tool kit developed to perform mining system simulations on a single integrated environment under various conditions.

Keywords: Simulation-based design, Subsea equipment, CAE technology, DIMS, Multibody dynamics

Jaewon Oh

He received his Ph. D. (2016) degree in mechanical engineering from Hanyang University, South Korea. He is working as a senior researcher in Korea Research Institute of Ships & Ocean engineering (KRISO). His present research interests are in the multibody dynamics and simulation-based design, especially on concept & detail design method, simulation model development and production design method in machinery industries and offshore plant industries.

A preliminary study on the geological continuity of polymetallic nodules in the deep-sea basin between guyots Suda and Scripps of the western Pacific based on coverage from Towed Camera Sledge

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1 INTRODUCTION (Poster Presentation)

Polymetallic nodules (nodules) are strongly enriched in Ni, Cu, Co, Mo, Zr, Li, Y, and REEs, and the resources of Mn, Ni, Co, Mo of polymetallic nodules in C-C zone alone are comparable to those corresponding terrestrial reserves (Hein et al., 2013). Polymetallic nodules occurring around the interface of seawater and sediments of deep ocean basin are technically feasible to be mined. In 1978, Ocean Mining Inc. conducted a Pilot Mining Test in more than 5250 m of water in C-C zone and successfully recovered over 800 metric tonnes of nodules (Lipton et al., 2016). Furthermore, nodules are technologically feasible to be processed (Flentje et al., 2012, and reference therein). Therefore, Fe-Mn nodules are capable of being complements for metal resources for the sustainable development of world economy when an economic mining pattern of nodules emerges.

The estimated cost of the nodule exploration partly depends on the amount of sites and profiles, which in turn depends on the geological continuity of polymetallic nodules in an exploration area. The level of geological confidence for the estimated resources of nodules depends on the amount and location of sites and profiles, which should be designed during exploration based on geological continuity of polymetallic nodules. Therefore, it is critical to delineate the geological continuity of polymetallic nodules during the exploration.

The nodules in the west Pacific are characterized by the relatively high Co concentrations and high abundance. In the paper, we will conduct a preliminary research on the geological continuity of the nodules from the deep-sea basin between guyots Suda and Scripps of the western Pacific based on data of Towed Camera Sledge (TCS).

2 Data and methods

2.1 Nodule Coverage data from Towed Camera Sledge

In this study, three Towed Camera Sledge (TCS) profiles (P1606, P1801, P1804) were collected in the deep-sea basin between guyot Suda and guyot Scripps (Fig. 1), two of which were recovered by *R. V. Dayang Yihao*, and one by *R.V. Xiangyanghong 10*. The pixels in the nodule photos of TCS profile were identified by a deep convolutional neural network method and the coverage of nodules are calculated by dividing the sum of nodule pixels with the total pixels of photos (details in the initial reports of the cruises by the above two research vessels).

2.2 Coverage data processing method

Fig. 1 and Fig. 3 show that the nodule coverage of three profiles vary significantly. In order to delineate the geological continuity of nodules in the region, we proposed the following data processing method (Fig. 2): (1) we input the data from photos of TCS profiles, including longitude, latitude, coverage, and distance between every two photos; (2) we defined a pair of start point and end point (k_{min} and k_{max}), then calculated the distance (L) between every two points, and then defined a function: F=L*Coverage; (3) we defined the variation ranges (±15%) of F and Coverage; (4) we calculated the possibility (P) when the coverage of a random point lies in the variation range of Coverage (±15%); (5) if P is more than 90%, we increased the end point (k_{max}), and went back to step (2); if not, we output the coordinates of k_{min} and k_{max}, which is the sampling spacing in which one sampling site is capable of providing the estimated coverage in the range of ±15% averaged coverage in this spacing at the possibility of >90%. If the abundance can be calculated from the corresponding coverage, this method can be used to define the sampling (box corer) spacing for abundance.

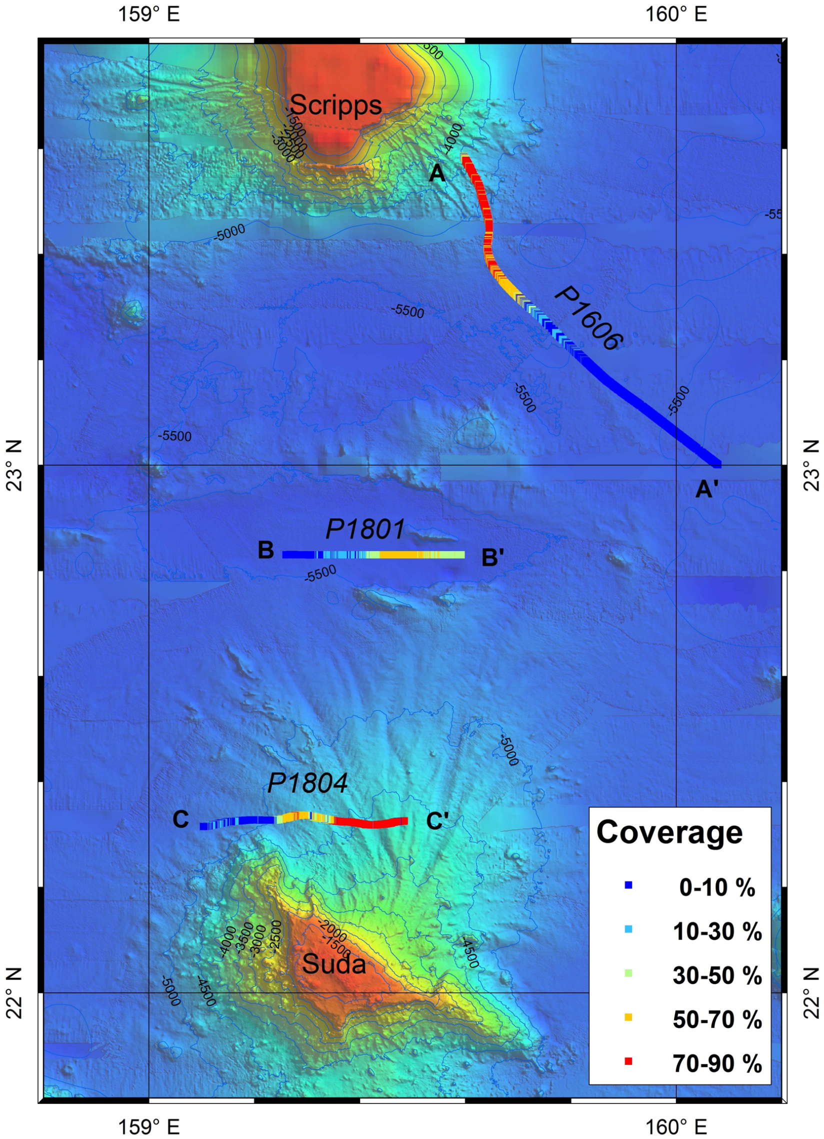

Fig 1 the profiles of Towed Camera Sledge

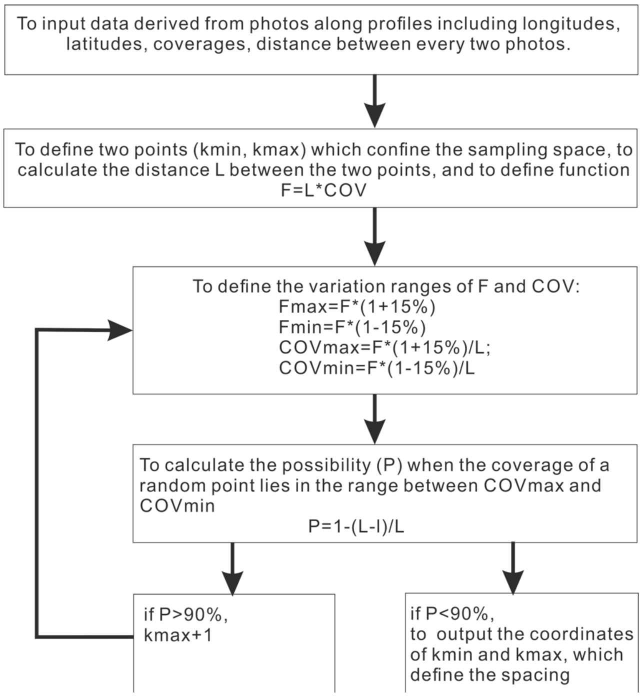

Fig. 2 flowchart for processing coverage data from TCS photos

3 Results and discussion

The data processing results are shown in Fig. 3. Although the coverage along the profiles varies significantly, the processed results describe the continuity of nodules clearly. The longest spacing is 34.508 km for TCS profiles P1606; for the profile P1801, the longest spacing is 9.376 km, and the second long spacing is 4.226 km; for the profile P1804, the longest spacing is 16.130 km, and the second long spacing is 5.704 km. Those segments with long sampling spacing on the profiles are profitable candidates for nodule ore body because of the less sampling sites and consequently low exploration costs. Relative to the long spacing, the short spacing ranges from tens of meters to hundreds of meters (Fig. 3) and characterized by significant variation and/or low coverage. Those segments are not proper candidates for nodules ore body in the sense of exploration.

The profiles P1606 and P1804 are located near the guyot Scripps, and guyot Suda, and are characterized with the long spacing for ore body. In contrast, the profile P1801 is located in a small basin between guyot Scripps and guyot Suda and is characterized with relative short spacing for ore body. We suggest that the area near guyots is promising exploration area for nodule ore body.

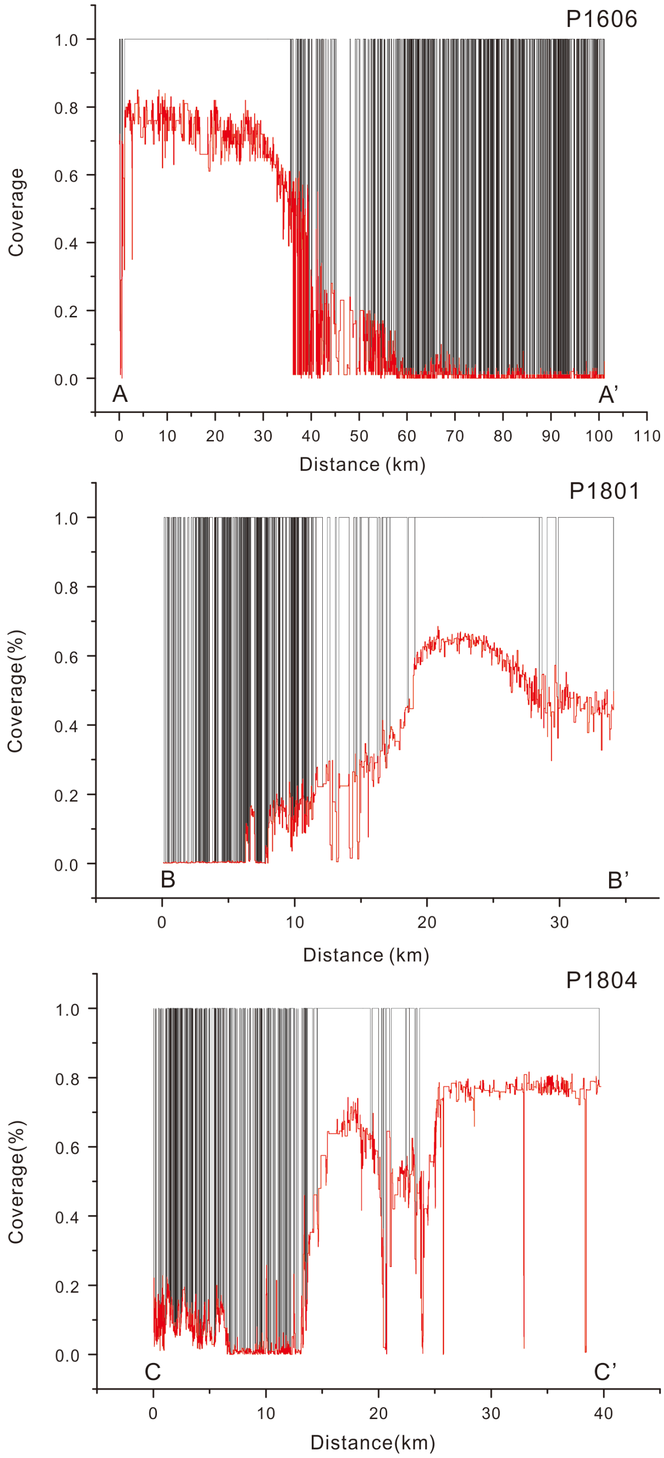

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Fig 3 the division of sampling spacing for coverage and abundance
(The red curves are the coverage of nodules along the three profiles, and the black vertical lines are the boundaries for spacing)

4 Conclusions

In this research, we proposed an effective TCS data processing method for describing the continuity and delineating the ore body of nodules. Five relative long sampling spacing are identified on the three profiles of TCS between guyots Scripps and Suda, which are 34.508 km for P1606, 9.376 km and 4.226 km for P1801, and 16.130 km and 5.704 km for P1804. Those spacings are capable of delineating ore body for polymetallic nodules. In this area the geological continuity of polymetallic nodules may controlled by the local topography.

Keywords: polymetallic nodules, geological continuity, Towed camera sledge, west Pacific

Acknowledgements

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Ren Xiangwen

Dr. Ren received a Master's degree in petrology and geochemistry from the Jilin University in 2002, and PhD in marine geology from Institute of Oceanography, China Academy of Sciences, in 2005. He worked as a postdoc in the First Institute of Oceanography, State Oceanic Administration of China, from 2006 to 2010. Since 2010, he has been working as an associate researcher in the First Institute of Oceanography. In 2015, he worked in PCMSC of USGS as a visiting scholar. He has taken part in five cruises on the exploration of ferromanganese crusts and polymetallic nodules. He has been carrying out his research on the mineralization of Co-rich ferromanganese crusts and polymetallic nodules since his PhD study, and hosted six projects on ferromanganese crusts and polymetallic nodules from China Ocean Minerals Resources Research & Development Association, and Natural Science Foundation of China respectively. His research concerns the formation mechanism of ferromanganese crusts, and the resources estimation of ferromanganese crusts and polymetallic nodules, on which he authored 20 papers.

Uranium in seafloor massive sulfides at the Mid-Atlantic Ridge

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Abstract

The recent study demonstrates the enrichments in uranium of SMS from some hydrothermal fields of the Mid-Atlantic Ridge (MAR) (Torokhov et al., 2002; Fouquet et al., 2010; Ayupova et al., 2018). However, the data of U content in SMS at the MAR is still limited. Here, we present preliminary data of U content in SMS deposits related to ultramafic and mafic rocks and to different geochemical types of massive sulfides.

100 samples of seafloor massive sulfides were recovered during several cruises of RV Professor Logatchev (Polar Marine Geological Exploration Expedition) from Logatchev, Ashadze, Semyenov, Pobeda, Irinovskoe ultramafic-hosted and Krasnov, Peterburgskoe, Jubileynoe, Zenith-Victoria and Puis des Folles mafic-hosted sites. The mean content of U is **3.53 ppm** (N=76, excluding Pobeda samples). Average concentration of U in SMS related to mafic rocks (N=42) is **4.04 ppm** and to ultramafic-hosted (N=34) deposits is **3.00 ppm**. SMS are represented by different geochemical types: Fe-rich (N=17), Cu-rich (N=27),

Cu-Zn-rich (N=21). Uranium concentration in Fe-rich samples is **3.48 ppm**, Cu-rich - **4.09 ppm**, and Cu-Zn-rich - **2.06 ppm**. Based on the obtained mean values, uranium shows close values in SMS associated with different types of hosted rocks. Any correlation with geochemical specialization of SMS is absent as well.

The samples from Pobeda site are presented separately due to the highest uranium concentrations in SMS from this deposit. The value of U varies from 0.2 ppm up to 130 ppm with average 24.86 ppm (N=22). Any connection with geochemical types is not observed. The specific feature of SMS samples from Pobeda is the correlation between U content and age. The age is estimated > 177 ka (Gablina et al., 2018) which is rather older than SMS from other hydrothermal fields within the MAR (Cherkashov, 2017). Thus, Pobeda site is represented as example of long-lived hydrothermal system with several active and inactive periods. The highest U value (up to 130 ppm) is corresponding to the samples with relatively young age from 14.6 to 4.8 ka while low concentration is mainly observed in samples with age more 50 ka (up to 177 ka) (Fig. 1). We suppose that correlation between U grades and age are related to redistribution and re-deposition of U during active periods of Pobeda mature hydrothermal system evolution.

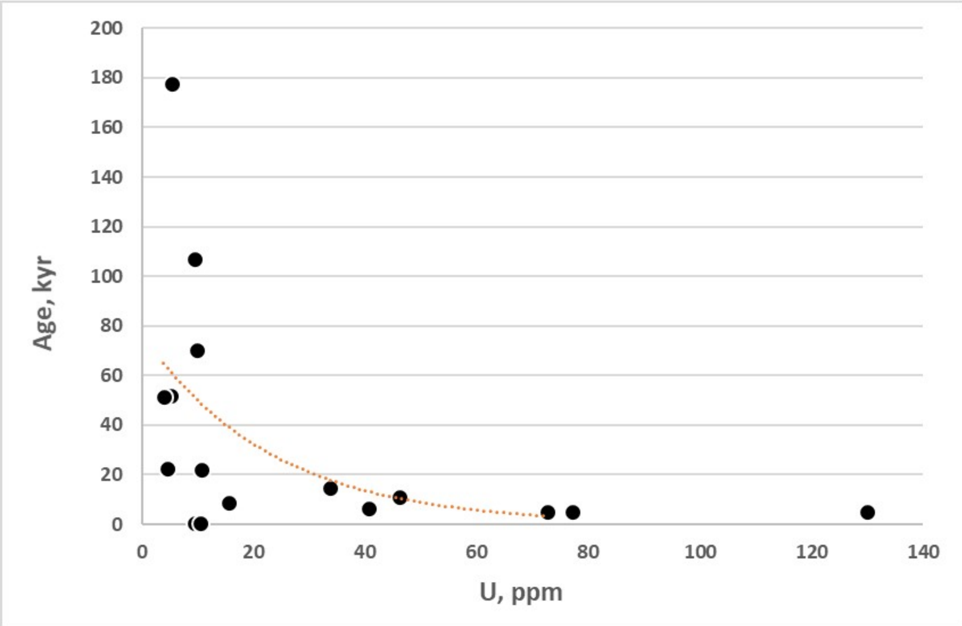

Figure 1. Age vs U content in SMS of Pobeda.

The factors affected to U enrichment are a still big challenge and need more investigations.

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Keywords: Mid-Atlantic Ridge, seafloor massive sulfides, SMS, uranium

Anna Sukhanova

Anna Sukhanova graduated from St. Petersburg Mining University (Russia) in 2015. Since 2015 she has been working at VNIIOkeangeologia (Department of Geology and Mineral Resources of the Ocean, Russia). In 2018 she became a Ph.D. candidate with dissertation about mineral and chemical composition of seafloor massive sulfides from Mid-Atlantic Ridge. The primary focus of her research is mineral and chemical composition of SMS, geostatistical studies and modelling.

Copper-rich disseminated sulfides near a transform fault on the southern Carlsberg Ridge: Implications for off-axis seafloor massive sulfide mineralization

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Abstract

To date, more than 380 hydrothermal mineralization sites have been discovered throughout the modern seafloor (Petersen et al., 2018). Most active, magmatically-driven hydrothermal systems and seafloor massive sulfide deposits (SMS) are associated with mid-ocean ridges, back-arc basins, and volcanic arcs (Hannington et al., 2005). Only a total of 26 sites have been found at transform faults and fracture zones on spreading centers, which are considered to be amagmatic areas along these centers (Gartman and Hein, 2019). Among these, 12 sites related to high-temperature hydrothermalism, low-temperature hytrothermal alteration, and serpentinization were found along the slow-spreading Mid-Atlantic Ridge. Additional research is needed, however, to identify the range of mineralization types associated with a low magmatic heat budget and transform faulting.

The Carlsberg Ridge in the northwest Indian Ocean is one of the least-explored ridges in the world in terms of hydrothermal mineralization. In the past 13 years, research has primarily focused on the ridge axis from 3.5–7°N, discovering hydrothermal plumes (Murton et al., 2006; Ray et al., 2008, 2012; Jiang et al., 2017) and SMSs (Tao et al., 2013; Wang et al., 2017). During cruise DY49-V of the Chinese *RV Xiangyanghong 10* in the summer of 2018, we performed dredge sampling and a shipboard bathymetry survey near

the Baochuan transform fault (2.9°N) on the southern Carlsberg Ridge. Overall, 40 kg of samples, including sulfide-bearing altered basalts (~75%), gabbro (~20%), and quartz breccias (~5%), were collected near the transform fault, at a depth of ~2400 m and ~20 km off-axis (Fig. 1). Multibeam coverage and structural analyses revealed that the adjacent morphology of the present dredge location is a topographic high at a ridge-transform inside corner. It is a typical megamullion dome (the Baochuan megamullion) and rises from a depth of 4000 m to a depth of 1500 m over a distance of approximately 7.5 km. This feature is considered to be a detachment fault in a relatively magma-starved condition. Based on the NOVEL-1A model (DeMets et al., 1994), the present day full spreading rate of this particular segment was determined to be 29 mm/yr, which is typical for slow-spreading crust.

We examined the mineralogy and mineral chemistry of disseminated sulfides in the quartz breccias and partly altered basalts in order to determine the possible sulfide formation history. Three mineralization stages and their associated mineral assemblages (Figs. 2A–D) were identified in the quartz breccias: (1) a high-temperature stage characterized by mineral assemblages of chalcopyrite, isocubanite, and pyrrhotite; (2) a medium- to low-temperature stage with mineral assemblages of pyrite and sphalerite; and (3) a late stage of waning temperatures and seafloor weathering distinguished by mineral assemblages of Fe-hydroxide phases, secondary Cu-sulfides, and Cu-oxides (e.g., covellite and cuprite), as well as Cu-chlorides, including paratacamite and atacamite. Sulfides, such as pyrite and chalcopyrite, also occur as late veins cutting through the Mg-chlorite+quartz-altered basalts (Figs. 2E and F). The chemical compositions of the sulfides from the Baochuan site exhibited high concentrations of Co in pyrite (1.10 wt.% on average, n = 4), isocubanite (0.29 wt.%), and pyrrhotite (0.22 wt.%), suggesting significant influences from mantle rocks. Near the sampling location, tectonic activity around the Baochuan megamullion may have promoted hydrothermal circulation and subsequent chloritic alteration in basalts, eventually inducing hydrothermal mineralization in these rocks.

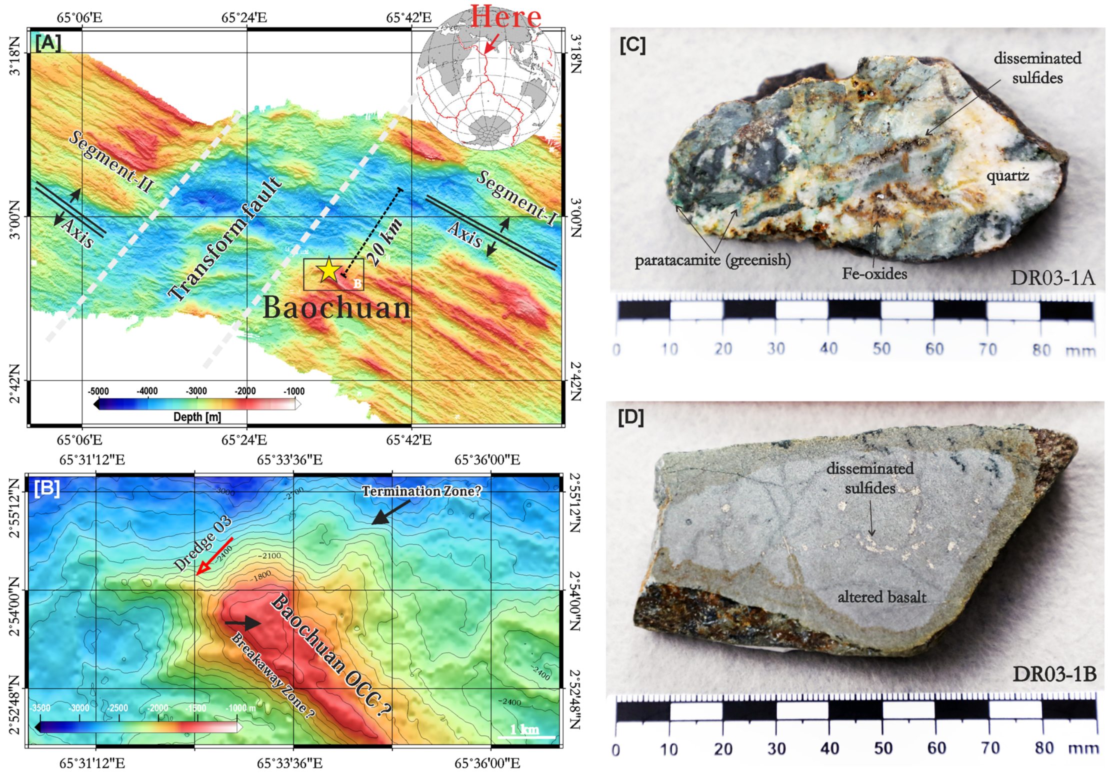

Figure 1. Location map showing (A) the Baochuan transform fault in the southern Carlsberg Ridge, (B) the dredge location (DR03, ~800 m in length at seafloor) on an inactive oceanic core complex. Representive hand specimens of (C) copper-rich quartz breccia, and (D) dissmeminated sulfide grains in altered basalt.

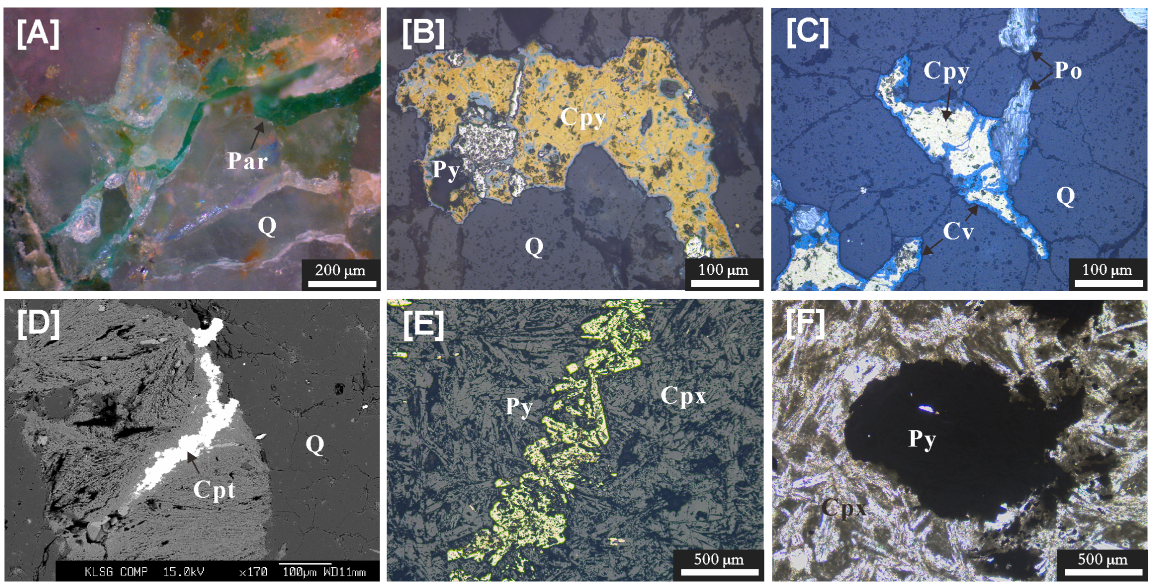

Figure 2. Photomicrographs of ore minerals. Veinlet-dissemination paratacamite (A), chalcopyrite-pyrite (B), chalcopyrite-pyrrhotite-covellite (C), and cuprite vein (D) in quartz breccia; veinlet-disseminated pyrite (E&F) in altered basalt samples.

Yejian Wang

EDUCATION AND CAREER

May-June 2019, visiting scholar at the Research School of Earth Sciences, Australian National University

June-August 2014 & October-November 2017, visiting scholar at the GEOMAR Helmholtz Centre for Ocean Research Kiel

Since 2012, research scientist at the Second Institute of Oceanography, MNR

2009-2012, Ph.D student at the Department of Earth Sciences, Zhejiang University

2006-2009, studying marine minerals at the Second Institute of Oceanography

2002-2006, studying geology at the Chengdu University of Technology

SCIENTIFIC INTEREST

Formation and evolution of seafloor hydrothermal systems

Mineralogy and geochemistry of submarine massive sulfides

RESEARCH CRUISES

Participated 10 research cruises along the mid-ocean ridges worldwide, such as the DY49V cruise in 2018 in the Indian Ocean as the chief scientist, and the DY38I cruise in 2017 as the submersible diving scientist discovered the submarine hydrothermal sites.

Transparency, public participation and access to justice in the context of deep sea mining: luxury or legal obligation?

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Abstract

Beyond the boundaries of national jurisdiction, the ocean floor and its resources escape sovereignty claims and are governed by a complex regime, which determines by whom and under which conditions these natural resources can be mined. The rules and principles of the United Nations Convention on the Law of the Sea and the 1994 Implementation Agreement are further developed in regulations and procedures issued by the International Seabed Authority (ISA), governing prospection, exploration and exploitation of deep seabed resources. The Authority already issued rules for the first phases of mining activities (prospection and exploration), but is yet to adopt exploitation regulations. A draft version, which provides a good indication of the current state of play and the way forward, is however developed and official approval of these exploitation regulations is expected during the summer of 2020.

With regard to transparency and public participation, major improvements can be identified in the Draft Exploitation Regulations, as the environmental plans which the applicant needs to submit are subsequently published on the Authority's website and stakeholders have the opportunity to make comments and remarks. However, given the influence that NGOs can have and their crucial role as watchdogs, the power of third party

stakeholders can still be considered fairly limited: there is no certainty that the Legal and Technical Commission will value the comments accordingly, a negative advice by the Legal and Technical Commission which was inspired by the public consultation can be disregarded by the Council and a decision of the Council can above all not be challenged by third party stakeholders. The value of the generally pursued transparency, expressed by the rule that information regarding marine environmental protection cannot be considered classified, equally diminishes by not stating how a third party stakeholder can act when one encounters irregularities during the exercise of the mining activities and the existing prospection and exploration regulations do not include any public participation procedures. It therefore appears desirable to introduce clear procedures that enable environmental organizations and other stakeholders to lodge objections in all phases of deep sea mining activities and it can moreover be considered to offer them the possibility to appeal a questionable grant of an exploitation contract, if only in certain circumstances. This last suggestion will probably be considered excessive by many, but given the current developments in international law, the clear objective of marine environmental protection and the status of the deep seabed and its natural resources as common heritage of mankind, access to justice for third party stakeholders seems not at all absurd. In my presentation, I will analyze the existing principles and options regarding transparency, public participation and access to justice in all phases of deep sea mining activities, identify the main weaknesses and suggest possible corrections, all the while assessing whether such provisions should be considered a luxury or rather the implementation of an enforceable legal obligation.

Keywords: law of the sea, deep seabed, seabed mining, transparency, public participation, access to justice

Dr. Klaas Willaert

In 2012, Klaas Willaert graduated as Master in Law (summa cum laude) at Ghent University and he added a Master in Maritime Science (summa cum laude) to his resume in 2013. After finishing his studies, Klaas became an academic assistant at the department of European, Public and International Law of the Faculty of Law and Criminology of Ghent University. Besides providing academic support for several courses, he coordinates the subsequent master program MSc in Maritime Science, manages the Port Management course series, is a member of the steering committee for the annual Maritime Symposium and is part of the editorial board of De Grote Rede. He wrote a doctoral thesis on maritime piracy ('Modern Piracy in East and West Africa: legal framework, counterstrategies and prosecution') under the supervision of Prof. dr. Frank Maes and Prof. dr. em. Eduard Somers, which he successfully defended in December 2018. Through the years he presented different aspects of his research at several national and international conferences and he produced many academic publications, in the form of journal articles, book chapters and a book. The law of the sea is his area of expertise and he is now conducting postdoctoral research into the legal aspects of deep sea mining. He already wrote multiple innovative reports and articles on the subject and was part of the Belgian delegation for the meetings of the 25th Session of the Council of the International Seabed Authority.

Numerical Study on Settling and Floating Movements of a Sphere Particle Flowing in a Vertical Pipe

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Abstract

The solid-liquid two-phase flow with a large particle is a basic research object in the two-phase transportation field, such as the deep-sea mineral transportation. This paper presents a coupled Resolved CFD-DEM approach to simulate settling and floating movements of a sphere particle with different diameter flowing in a vertical pipe, and numerical results are compared with experimental studies. The numerical simulation results are in good agreement with the experimental results. The paper also performs a numerical study on hydraulically collecting a sphere particle to analyze the flow field and particle movements. The method used in this study is suitable for studies of large particle solid-liquid two-phase flow.

Keywords: solid-liquid two-phase flow; vertical pipe; Resolved CFD-DEM; settling and floating movements; hydraulically collecting

Numerical Study on Settling Movements of a Sphere Particle

The settling and floating movements are the basic movement forms for the solid-liquid two-phase flow, which is important for the hydraulic lifting. When the pump is in a state of emergency shutdown in the process of conveying in a vertical pipe, the settling particles may result in the pipe flow clog. The particle lifting velocity is the key to hydraulic lifting. Therefore, the paper focus on the numerical study on settling and floating movements.

The sphere particle whose diameter is d_p and density is ρ_p is acted upon by different force while it moves unsteadily in the flow field. The forces can be classified according to the way of action: (1) the forces resulting from the particle or fluid properties difference, such as gravity, buoyancy and inertial force. (2) the forces resulting from a relative velocity between the particle and the fluid, whose direction is along the relative velocity, like drag and Basset drag. (3) the forces resulting from a relative velocity between the particle and the fluid, whose direction is perpendicular to the relative velocity, such as Magnus force and Saffman force. The equations of motion for the particle on x-axis and z-axis are presented below.

x-axis: $$m_p \frac{du_p}{dt} = F_{dx} + F_{vmx} + F_{slx} + F_{mlx} + F_{bx} + F_{px} \quad (1)$$

z-axis: $$m_p \frac{dw_p}{dt} = F_{dz} + F_{vmz} + F_{slz} + F_{mlz} + F_{bz} + F_{pz} - F_g \quad (2)$$

Where, F_d,F_{vm}, F_{sl}, F_{ml}, F_b, F_p, F_g represents drag force, virtual mass force, Saffman force, Magnus force, Basset drag, pressure gradient force and gravity respectively. In this study, the interaction forces considered were the drag force, the gravity and the buoyancy force. Other forces, such as from particle rotation (Magnus force), particle acceleration (virtual mass force) or a fluid velocity gradient leading to shear (Saffman force), were not considered here. So is the CFD-DEM simulation test. The equation of motion on z-axis is simplified:

$$\frac{dw_p}{dt} = \frac{2\rho_p}{\rho_p + \rho_f}\left[\frac{3C_d}{4d_p\rho_p}(w_f - w_p)|w_f - w_p| + \frac{3\rho_p}{2\rho_f}\frac{dw_f}{dt} + \left(\frac{\rho_p}{\rho_f} - 1\right) g\right] \quad (3)$$

Where, ρ_f and w_f represents the fluid density and velocity. For the particle settlement in static water, the particle begins sinking increasingly as gravity is greater than drag force. The more the particle velocity, the more the drag force. The velocity is increasing to a constant until gravity is equal to drag force. Then the particle acceleration is zero, and the fluid is static except locally around the particle. The particle settling velocity is calculated as:

$$\omega_p = \sqrt{\frac{4(\rho_p - \rho_f) g d_p}{3C_d\rho_f}} \quad (4)$$

Where, C_d is the drag coefficient as a function of the particle Reynolds number Re_p. The particle Reynolds number is expressed as:

$$\mathrm{Re}_p = \frac{\rho_f d_p |w_f - w_p|}{\mu_f} \quad (5)$$

There are some influencing factors for single particle settlement velocity, like particle size, density, shape and boundary condition. The paper focus on the size of the spherical particle, and other influence factors keep constant. It can be concluded that the settlement velocity increases as the particle diameter increases from the equation.

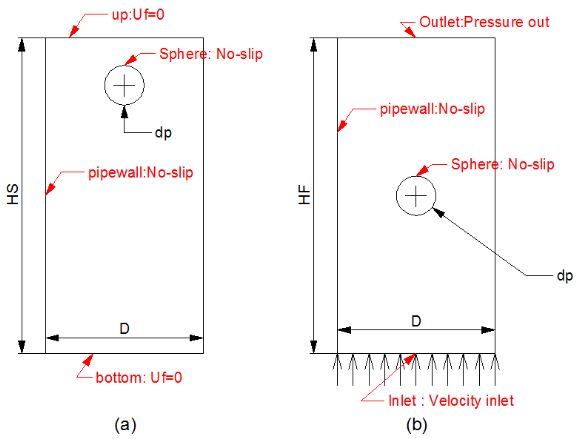

Fig.1 Computational domain and boundary conditions (a) settling movements ;(b) floating movements

Fig. 1 shows the computational domains and boundary conditions of the particle's movements, including settling movements and floating movements

The diameter D of the circular tube used in the numerical model is 20cm. The height of pipe HS is set enough for the particle velocity reaching final settling velocity completely. The particles diameters are 1cm, 2cm, 3cm, 4cm and 5cm respectively. The initial mesh numbers are 645120, 533520, 457275, 138240 and 138240 respectively.

The particle density is 2450kg/m^3. The fluid density and dynamic viscosity is 1000kg/m^3 and 0.001 Pas.

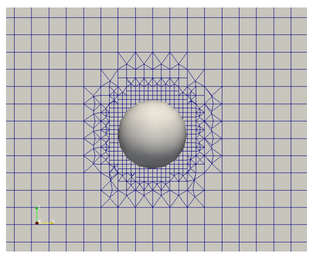

Fig.2 Particle with d_p=1cm and the CFD grid around it

Fig.2 shows the particle with d_p=1cm and the CFD grid. Fig.3 shows the time histories of the particle settling velocity with different result included the corrected empirical solution, CFD result and CFD-DEM result with d_p=1cm. For the settling velocity, CFD result is close to the corrected empirical solution, and CFD-DEM result is smaller than other two. For the relaxation time, the corrected empirical solution is fastest to reach the steady velocity, and CFD-DEM result is next, and CFD result is last. CFD-DEM result is no better than CFD result, but allow for the gigantic mesh number by CFD, resolved CFD-DEM approach is effective to simulate the solid-liquid two-phase flow.

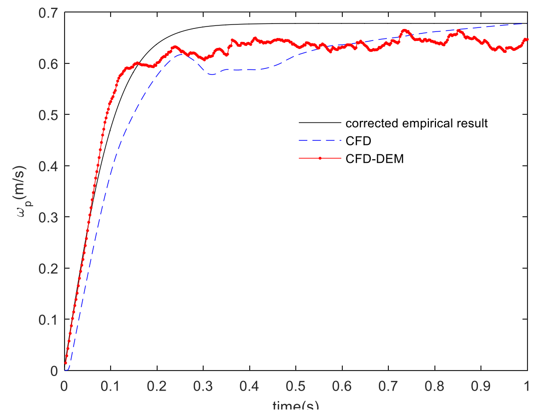

Fig. 3 Time histories of the particle settling velocity with d_p=1cm

Fig.4 shows the comparisons of the settling velocity between literature data and CFD-DEM result with different diameter. The literature data is the experiment result from the paper (Chen et al., 2010). It is observed that the literature data are slightly higher than CFD-DEM result, and the error is in the range of 8%. This is possibly due to dealing with the boundary by IBM and mesh number constraint. Resolved CFD-DEM approach has less advantage when it's used to deal with single particle, but it's very effective to deal with more particles.

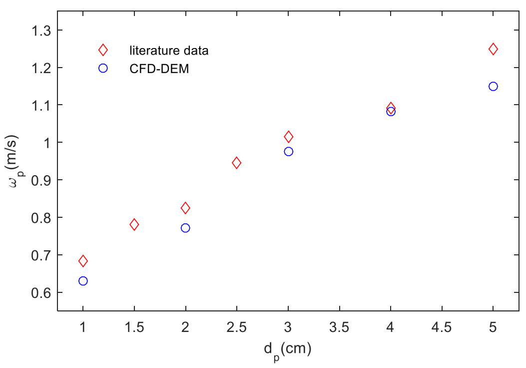

Fig.4 Comparisons of the settling velocity between literature data and CFD-DEM result with different diameter

Numerical Study on Floating Movements of a Sphere Particle

The floating movement is the basic movement form for the solid-liquid two-phase flow. The part is presented the simulation of the floating movement of a sphere with five diameter and the flow field with d_p=3cm.

As the same as the settling movements, while a particle is floating in the moving water, different force exerts on the floating particle, like gravity, buoyancy, drag and pressure gradient force and so on. The velocity and acceleration of the particle are zero.

The properties of particle or fluid in the numerical study on floating movement are set the same as the properties on settling movement. The pipe height HF is set to be 0.44m, 0.44m, 0.8m, 0.8m and 0.8m respectively.

The initial position of the particle is in the middle of the pipe. Fluid flows into the pipe from the bottom of the pipe. The initial inlet velocity of the fluid is set the settling velocity, then the particle moves continually, affected by fluid disturbances, and the particle cannot be still. Therefore, the inlet velocity of the fluid changes constantly to keep the particle velocity at zero or so. The fluid inlet velocity is equal to the particle floating velocity when the particle velocity fluctuates around zero.

The drag of the particle in the fluid is mainly the viscous drag and the shape drag. The shape drag becomes more and more obvious as the fluid velocity increases.

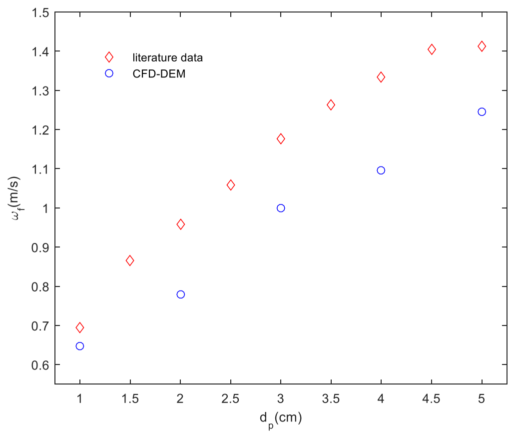

Fig.5 Comparisons of the floating velocity between literature data and CFD-DEM result with different diameter

Fig.5 shows the comparisons of the floating velocity between literature data and CFD-DEM result with different diameter. The literature data is the experiment result from the paper (Chen et al., 2010). It is observed that the floating velocity increases as the particle diameter increases and the experimental results are higher than CFD-DEM results, and the error is in the range of 18%. This is possibly due to neglecting some force exerting on the particle in the numerical study and the difference of the wall roughness between the numerical models with the experiment.

The rule of the floating particle movements is investigated from time histories of particle velocity and position and flow field presented in the figure.

Fig.6 shows time histories of particle velocity and position. The particle is impacted by fluid at first time, and it moves upward with a large velocity. The gravity and drag is downward, and the particle velocity decreases fast and fluctuates around zero. The particle position fluctuates around 0.4.

Fig.7 shows the particle velocity and flow field at time t=0.2s, 1s, 2s, 2.8s, respectively. From the figure, the particle does not suspended at a stationary location in a steady stream, but is constantly changing position. The flow velocity is large in the middle of the pipe, while the flow velocity is small near the wall, and particle velocity will change with the location in pipe.

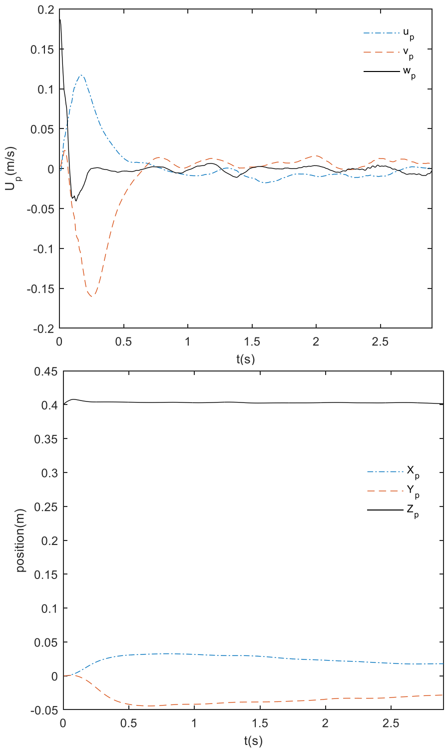

Fig.6 Time histories of the particle velocity and position with d_p=3cm

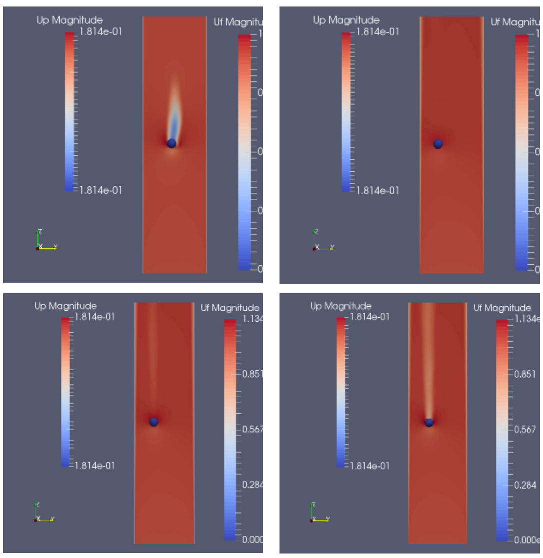

Fig.7 Particle velocity (Up) and flow field (Uf) at time t=0.2s, 1s, 2s, 2.8s with d_p=3cm

Numerical Study on hydraulically Collecting a Sphere Particle

This part focus on a sphere particle being hydraulically collected. The particle is static on the ground at first. The fluid velocity at the outlet is changing from 0.2m/s to 2.5m/s as time varies. Fig. 12 shows the computational domains and boundary conditions.

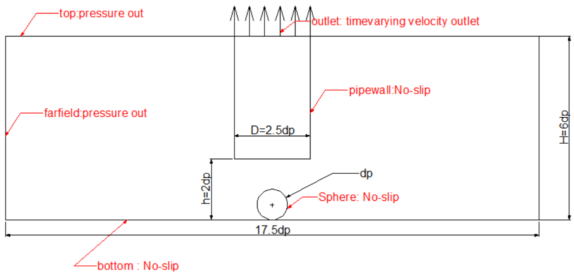

Fig. 8 Computational domain and boundary conditions

The particle density is 2050kg/m^3, as the manganese nodule' density is about 2050 kg/m^3. The particle diameter d_p =4cm. The fluid density and dynamic viscosity is 1000kg/m^3 and 0.001 Pas, respectively.

As the fluid velocity increases, the drag force on the particle increases. When drag force is larger than some value, the particle is starting to lift and leave the ground with a velocity. The fluid velocity is defined as the starting velocity w_{fs} at present. We define its numerical value is the fluid velocity at the outlet when the numerical value of particle velocity is equal to the 10% of particle diameter. Dimensionless quantity C_d is introduced to analyze the correlation between results and particle parameters.

$$C_d = \frac{F_d}{(1/2)\rho_f(w_f - w_p)^2\pi(d_p/2)^2} \qquad (6)$$

Where, F_d is the vertical drag force.

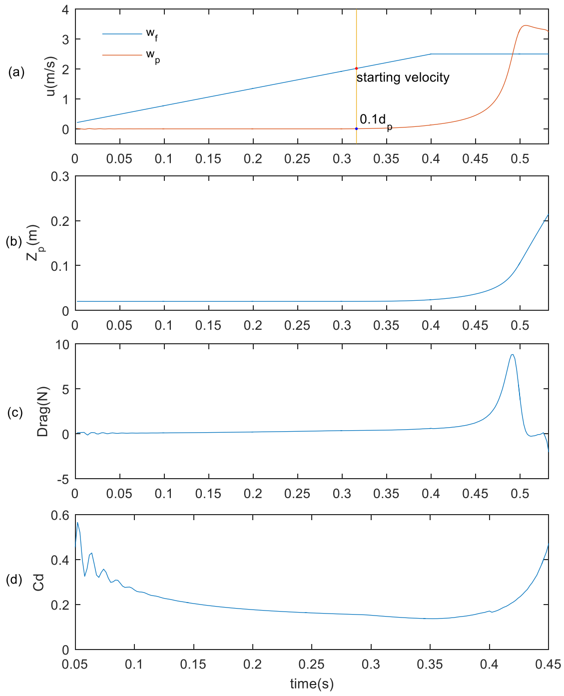

Fig. 9 Time histories of some functions with d_p=4cm. (a) particle and fluid velocity; (b) vertical particle position; (c) vertical drag force; (d) drag coefficient.

Fig. 9(a) shows time histories of particle velocity and fluid velocity at the outlet with d_p=4cm. The initial fluid velocity is 0.2m/s at time t=0s. While fluid velocity is less than the starting velocity w_{fs}=2.017m/s, the particle keeps static on the ground. Particle velocity increases as fluid velocity increases, and then fluid velocity keeps 2.5m/s after time t=0.4s while particle velocity increases to 3.4m/s and then it decreases. Fig. 9(b) shows time histories of particle position on z-axis. Fig. 9(c) shows time histories of vertical drag force. The vertical drag force increases as fluid velocity increases, and it increases to the maximum value when particle velocity is equal to the fluid velocity. Then vertical drag force decreases. C_d is a function of particle Reynolds number which is relates to the relative velocity between particle and fluid. So the calculation of maximum drag force relates to the limit question of relative velocity. Fig. 9 (d) shows time histories of drag coefficient. The drag coefficient decreases as time increases during the range of 0.1s< time <0.35s. The particle is static, so the relative velocity increases and the drag coefficient decreases as fluid velocity increases. After time >0.35s, the relative velocity decreases. The drag coefficient is in the disturbance when time <0.1s as the fluid velocity changes suddenly at time t=0s.

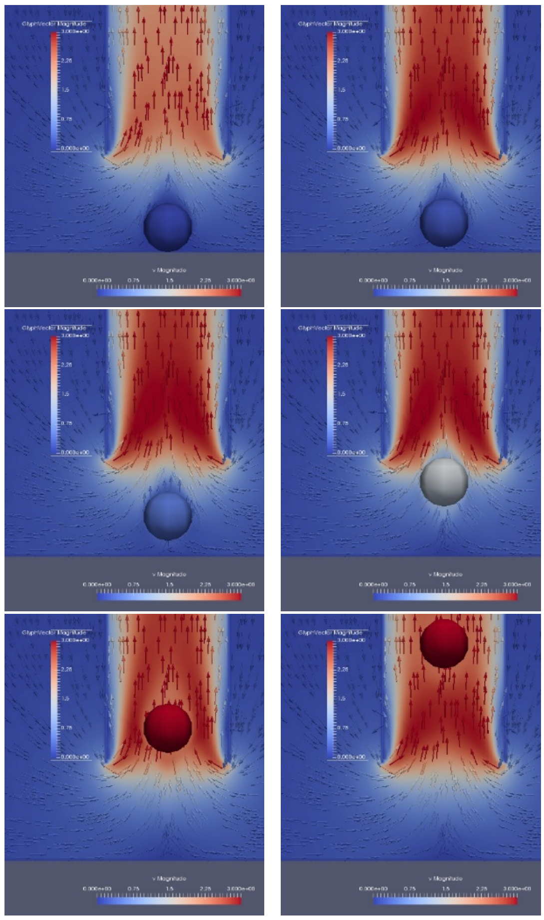

Fig. 10 Particle velocity (Up) and flow field (Uf) at time t=0.32s, 0.4s, 0.44s, 0.48s, 0.5s, 0.52s with d_p=4cm

Fig. 10 shows the particle velocity and flow field at time t=0.32s, 0.4s, 0.44s, 0.48s, 0.5s, 0.52s, respectively. The particle is starting to lift with a fluid velocity w_f=2.04m/s at time t=0.32s. Then the particle leaves the ground with a small particle velocity at time t=0.4s and it accelerates, and the fluid velocity keeps 2.5m/s from this time. The particle reaches the bottom of the pipe at time t=0.48s and gets into the pipe with an accelerated velocity.

By means of resolved CFD-DEM approach, the settling and floating movements of a sphere particle flowing in vertical pipe were simulated in the paper. The numerical simulations on hydraulic collecting a sphere particle are performed. The method used in this study is suitable for studies of large particle solid-liquid two-phase flow.

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He received his Bachelor's degree in 2007 and his PhD in 2012 from Harbin Engineering University. In 2014, he joined the Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences. Now he is interested in deep-sea mining technology and related research topics.

Xiong Hong

He received his Bachelor's degree in 2013 and his Master's degree in 2016 from Shanghai Jiaotong University. In 2016, he joined the Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences. Now he is interested in deep-sea mining technology.

Feasibility study of combined mining of rare-earth element rich mud and manganese nodules by pulp-lift in Japan's EEZ

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Abstract

An examination of technical and economic feasibility of the rare-earth element rich mud (REE-rich mud) mining in Japan's exclusive economic zones (EEZ) is introduced. The previous study showed that the mining of REE-rich mud was not economically feasible. Therefore, in the study three changes to improve economy are proposed. The first one is a combined mining with manganese nodules. The second one is introducing a pulp-lift system that can lift both REE-rich mud and manganese nodules at high concentration. The third one is reuses of the waste mud and the processed slag for construction materials. The evaluation results show from a slight negative to a quite positive economy depending on the mixing ratio of REE-rich mud and manganese nodules in pulp-lift.

Introduction

Deep-sea REE-rich mud on the Pacific seafloor which contains high concentrations of rare-earth elements was reported by Kato et al. (2011). They also suggested the potential as a rare-earth element resource in the paper. A feasibility study of the mining reported the difficulty in economy and proposed an in-situ chemical concentration for improving the economy (Bashir et al., 2012). In 2013, further higher concentration area was found by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) near Minami-Tori-shima (Marcus Is.) in Japan's EEZ (JAMSTEC, 2013). The feasibility of mining

REE-rich mud in the area was examined on the basis of manganese nodule mining technologies (Yamazaki et al., 2014). The result showed a quite negative economy.

REE-rich mud

Two high concentration areas of REE-rich mud, 500-1,500 ppm, such as off Hawaii in the north-eastern equatorial Pacific and off Tahiti in the south-eastern Pacific, were pointed out by Kato et al. (2011). Some are located inside of the EEZs and considered to have chances for the mining target. However, because of the thick overburden sediment layer with poor REE, only few feasibility studies were conducted for the mining (Abe et al., 2012; Wolgamot et al., 2013). The REE contents of 500-1,500 ppm and the overburden layer are weak points of the mining. In 2013, further higher concentration area of 5,600-5,800 m deep was found by JAMSTEC near Minami-Tori-shima in Japan's EEZ. There are REE dense layers of 5,000-6,500 ppm within 10 m below seafloor (JAMSTEC, 2013).

Previous economic evaluation

Three economic measures calculated in the previous study (Yamazaki et al., 2014) were the net present value (NPV), the internal rate of return (IRR), and the payback period. The economic balancing points of the project are 0 in NPV, 8.0 in IRR, and 13 in the payback period, respectively. Though the REE prices given in the study were very expensive ones in 2012 and the waste disposal cost was not included, the results presented in Table 1 are not attractive in economy. The main reasons are the lower concentration of slurry in the lift pipe and the lower income from the product sales.

Table 1 Results of economic evaluation of REE-rich mud mining (Yamazaki et al., 2014)

NPV (M$)	IRR (%)	Payback period (year)
-549	-2.73	N/A

Co-distribution with manganese nodules

In 2016, a vast manganese nodule area of co-distribution with REE-rich mud was found by JAMSTEC near Minami-Tori-shima in Japan's EEZ. The location and the nodule distribution aspect are shown in Figs. 1 and 2 (JAMSTEC, 2016). The area size is expected 44,000 km^2 and the metal contents of nodules are similar to cobalt-rich manganese crusts on the Pacific seamounts.

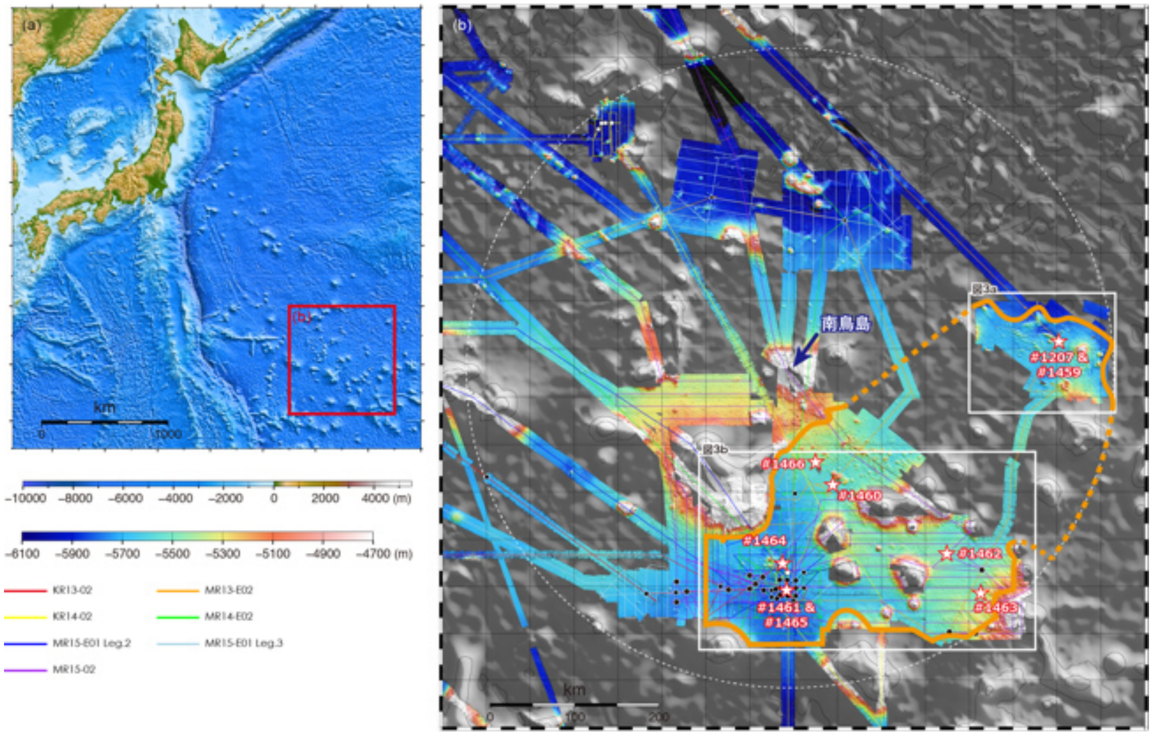

Fig. 1 Manganese nodule distribution area around Minami-Tori-shima (JAMSTEC, 2016)

Fig. 2 A dense field of nodules around Minami-Tori-shima (JAMSTEC, 2016))

Mining model of REE-rich mud and manganese nodules by pulp-lift

Because of the co-distribution, a quite unique lift method is applicable for both the REE-rich mud and the manganese nodule mining. The method is called pulp-lift. It was investigated under French manganese nodule R&D program in 1980s (Bernard et al., 1987). A non-Newtonian solid-water mixture with high solid volumetric concentration of 55~60 % was created by mixing crushed manganese nodules, deep-sea sediments, and water. Then the mixture was circulated in the 15 m vertical experimental pipeline by a piston pump as show in Figs. 3 and 4. Because of the drastic reduction of frictional resistance between pipe wall and the high concentration, it was clarified that the pipe diameter would be about a-half of the one of the same nodule mass transportation under a normal solid-liquid slurry. The pump power necessary was quite lower was also found. The pulp-lift has never used in any deep-sea mining program, but the method is popularly applied in the coal water mixture (CWM) in many coal electricity power stations. CWM created by powder coal and water with mass concentration of about 70 % is supplied to the boiler (Ogawa and Shibata, 1990).

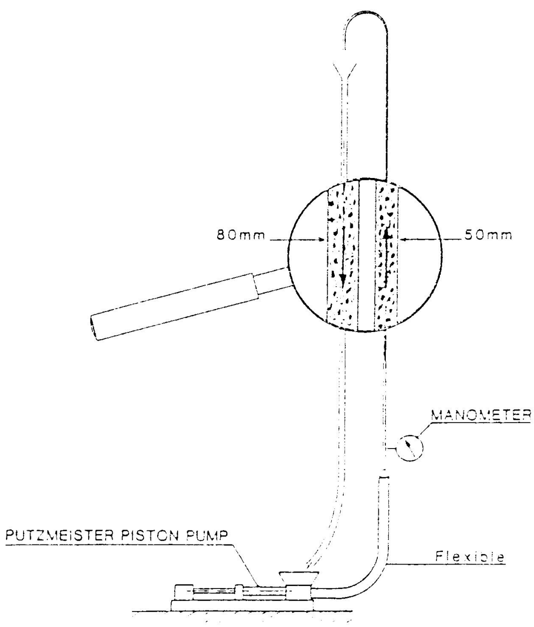

Fig. 3 Experimental setup of pulp-lift (Bernard et al., 1987).

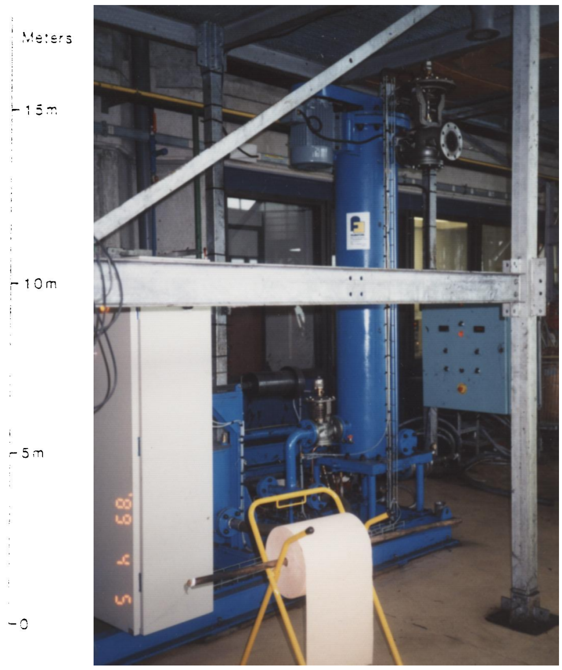

Fig. 4 Piston pump in the setup

In the mining model of REE-rich mud and manganese nodules in the study, the following assumptions are selected as a basic condition:

- Production rate of 6,000 t/d in REE-rich mud and 3,000 t/d in manganese nodules
- Volumetric concentration of 55 % in pulp-lift
- Water depth of 5,800 m
- Transportation of 2,000 km to the leaching and processing location
- Leaching by HCl with recovery ratios of 24 % in Ce and of 92 % in the other REE
- Brock making by adding cement powder to the leached mud after neutralization and providing for construction material under free of charge
- Processing by smelting and chlorine leach method with recovery ratios of 80 % in Mn and of 94 % in the other three metals
- Processed slag sales as concrete aggregate in 100 $/t
- Calculating CAPEX and OPEX of the mining model except the brock making and the processing by Eq. 1 on the basis of the ones in the previous study (Yamazaki et al, 2014)

  $$C_A = C_B \left(\frac{a_A}{a_B} \right)^n \quad ---- \quad (1)$$

  where, C_A is the value in the study, C_B the value in the previous study, a_A total mass in the study, a_B total mass in the previous study, n = 0.6 scale factor (JCDTCC, 1993)
- Calculating CAPEX and OPEX of the brock making on the basis of Sekimoto (2018)
- Calculating CAPEX and OPEX of the processing by Eq. 1 on the basis of Kojima (1996) and Park et al. (2002).

Because the quite higher concentrates of REE-rich mud and manganese nodules and less seawater from the pulp-lift system come up to the mining vessel, everything underwater and onboard including the vessel herself become smaller. The CAPEX and OPEX of the mining system are less expensive than the previous study as shown in Table 2. In the recovery of REE-rich mud on the seafloor, it is difficult to remove the overburden sediment layer of less REE content. An averaged REE concentration from the seafloor surface to the target REE-rich depth, the same one in Abe et al. (2012), is assumed in the mining model as shown in Table 3. The metal concentration in manganese nodules by JAMSTEC (2016) is assumed in the mining model as shown in Table 4. The manganese nodules are cobalt-rich like cobalt-rich manganese crusts on the Pacific seamounts and different with the ones in Clarion-Clipperton Fracture Zone.

Table 2 Estimated CAPEX and OPEX under basic condition

	CAPEX (M$)	OPEX (M$)
Mining	179.7	80.7
Transportation	223.8	33.7
Leaching (REE)	198.3	261.9
Brock making	155.6	226.0
Processing (Mn)	863.6	110.8
Total	1621.0	713.1

Table 3 Element concentration in REE-rich mud assumed

Elements	Concentration (ppm)
Ce	177.9
La	154.0
Pr	46.2
Nd	192.6
Sm	44.9
Eu	11.1
Gd	49.0
Tb	7.3
Dy	45.4
Y	277.2

Table 4 Metal concentration in manganese nodules assumed

Metal	Concentration (%)
Ni	0.4
Cu	0.2
Co	0.5
Mn	20.0

Economic feasibility of REE-rich mud and manganese nodule mining

On the basis of 5-year average prices in 2013-2017 of REE to exclude the higher ones in 2012 and 10-year average prices in 2008-2017 of the four metals and their recovery ratios assumed in the mining model, the revenues of the mining model under the basic conditions are calculated as shown in Table 5. It is obvious that the revenues from manganese nodules are 4.7 times more than the ones from REE.

Table 5 Assumed price and estimated revenue with their production under the basic condition

Element and metal	Price ($/t)	Yearly revenue (M$)
Ce	15,000	1.2
La	15,000	3.8
Pr	125,833	9.6
Nd	83,333	26.6
Sm	35,000	2.6
Eu	1,500,000	27.6
Gd	100,000	8.1
Tb	1,033,333	12.5
Dy	508,333	38.2
Y	56,666	26.0
Ni	16,121	51.8
Cu	6,678	11.3
Co	34,698	155.6
Mn	2,463	354.7
Total		729.6

In the economic evaluation, the first 3 years are assumed as construction and no income, the fourth year is assumed as test operation and 50 % income. Then 16 years, from 5th year to 20th year, are assumed full mining and 100 % income. The total yearly income is calculated as about 780 M$, because the revenues listed in Table 5 and about 50M$ from the slag sales are the total. The same three economic measures, NPV, IRR, and the payback period, are calculated as shown in Table 6. The results show a slight negative economy. Because the revenues from manganese nodules shown in Table 5 have larger effects on economy, a sensitivity analysis by manganese nodule production rate is examined. In the analyses, the production of REE-rich mud is fixed as 6,000 t/d and the one of manganese nodules is increased from 3,000 t/d to 7,000 t/d. In each the analysis, the CAPEX, the OPEX, and the income are recalculated. The results of NPV are summarized in Fig. 5. About 4,000 t/d is found as the point NPV=0.

Table 6 Result of economic evaluation under basic condition

NPV (M$)	IRR (%)	Payback period (year)
-526.7	3.66	15

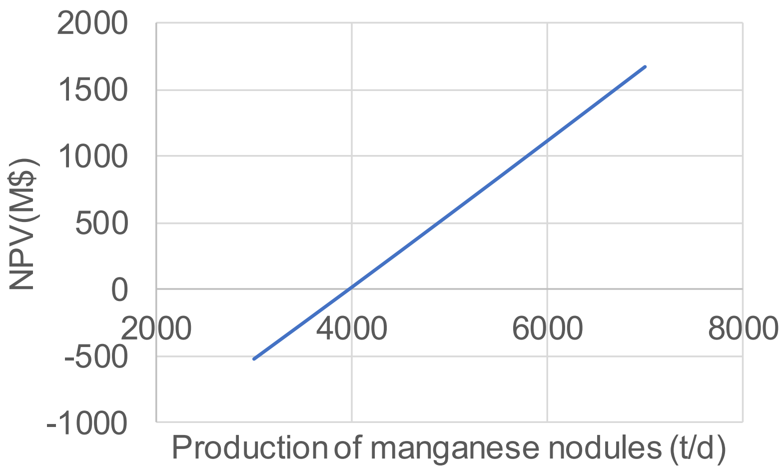

Fig.5 Sensitivity analysis of NPV by manganese nodule production rate

Concluding remarks

The co-distribution area of REE-rich mud and manganese nodules in Japan's EEZ has a chance for commercial mining. The following three changes in the mining model have improved the economy;

- Combined mining with REE-rich mud and manganese nodules,
- Pulp-lift system,
- Waste mud and processed slag reuse for construction materials.

The production ratio 6,000 t/d for REE-rich mud versus 3,000 t/d for manganese nodules is slightly negative in economy. More manganese nodules in the pulp concentrates are necessary for better economy. A good size distribution of manganese nodules for pulp-lift must be clarified experimentally at first. To crush manganese nodules is not difficult, however, to make nodule powder on the seafloor is not easy. How to get the good size distribution of manganese nodules for pulp-lift should be the second technical challenge.

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Keywords: Combined mining, Economy, Manganese nodule, Pulp-lift, Rare-earth element rich mud

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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
2019-Present	Economic and environmental evaluation of mound type gas hydrate mining

CO2 outgassing suppressed by enhanced biological pump in the Eastern Tropical Pacific

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Abstract (Poster Presentation)

Contractors are licensed by the International Seabed Authority to explore manganese nodule resources in the Eastern Tropical Pacific (ETP). KIOST has maintained a long-term monitoring station in the ETP (Station KOMO) since 2003 to examine the deep-sea environmental properties and particle fluxes. We examined the composition and flux of particles sinking to the deep ETP from 2003 to 2013. This region is known as the largest oceanic source of carbon dioxide to the atmosphere. We observed that the flux of particulate organic and inorganic carbon to a depth of 4,950 m increased as the climate variability called “Pacific Decadal Oscillation” shifted from a positive to a negative phase (more La Niña events) in 2008. Total particle flux data exhibited a unimodal seasonal pattern: an average flux of 49.2 ± 31.0 mg m^{-2} d^{-1} for December–May and 18.8 ± 9.3 mg m^{-2} d^{-1} for June–November. These seasonal pulses agree well with the temporal variation in satellite-derived NPP, providing tight coupling between biological production in the surface ocean and particle fluxes. The biological pump efficiency, i.e., how efficiently biological production of organic matter is transported to the deep ocean, also increased during La Niña years. To investigate how biological production affects the CO_2 exchange with the atmosphere, we estimated export of carbon from the surface layer based on our flux data at 4,950 m and the current understanding of carbon flux attenuation with depth. CO_2 outgassing was largely suppressed by enhanced biological pump enhanced during the La Niña events in the negative PDO phase.

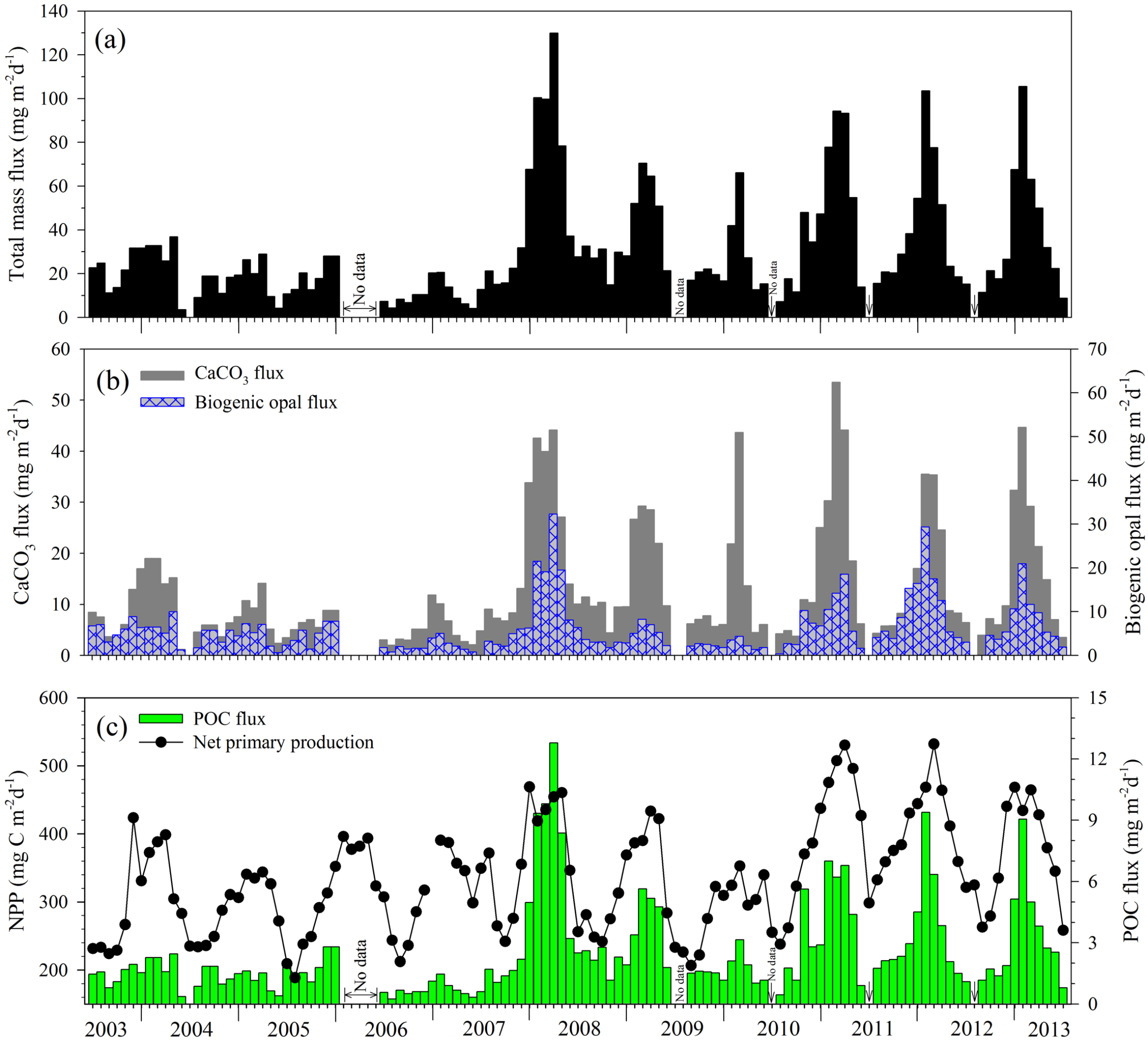

Figure 1. (a) Fluxes of total mass, (b) $CaCO_3$, and biogenic opal at Station KOMO from July 2003 to June 2013. (c) Satellite-derived net primary production (NPP) and observed particulate organic carbon flux.

Keywords: Particle flux, Sediment trap, Pacific Decadal Oscillation, Eastern Tropical Pacific

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Visual Simulation of Deep-Sea Mining System

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Abstract (Poster Presentation)

Aiming at the problem that the deep-sea mining system is not visible in the deep dark sea, a visual simulation system for deep sea mining based on VC++ and Vega Prime was proposed. The MultiGen-Creator software was used to build a three-dimensional model of the mining system, including the mining vehicle, the rigid pipe, the buffer station and the flexible hose. The Terra Vista software was used to generate the seabed topography. Then LynxPrime was used to drive the simulation system. The API function of Vega Prime was called on the VC++ platform to realize the interactive function, and finally the trajectory of the motion of the mining vehicle was drawn by OpenGL. In addition, features such as switching perspective and environment settings have been added. The sample of visualization interface is shown in Figure 1.

Keywords: deep sea mining; simulation; visualization; real time

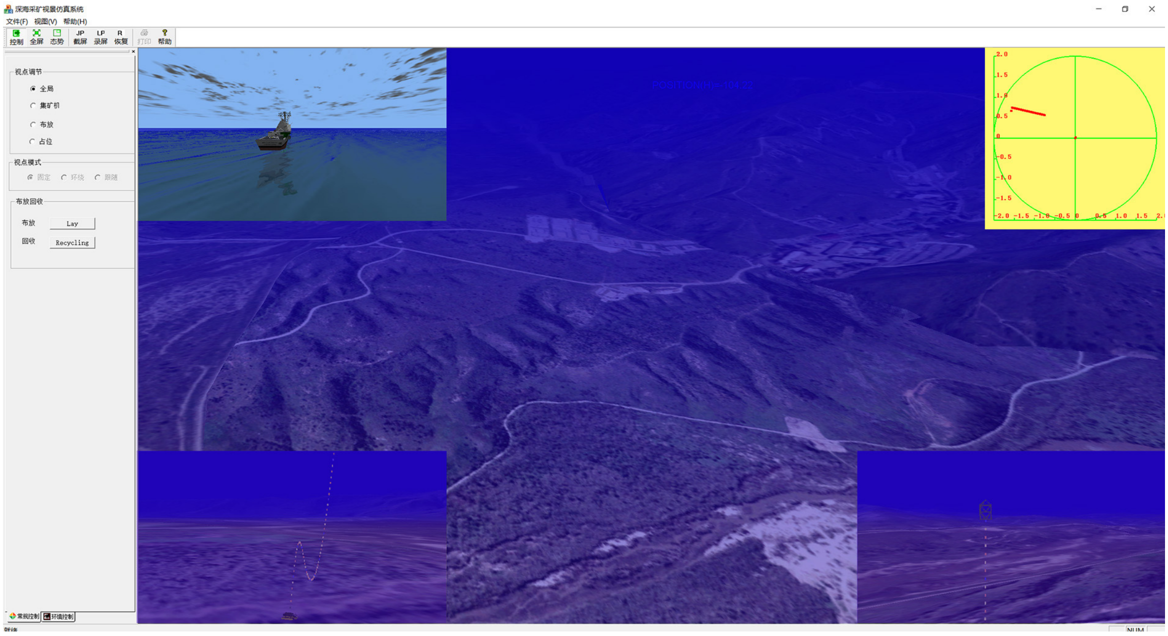

Fig.1 The sample of visualization interface

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Current Situation and Prospect of Technological Development in Deep Sea Mining by China Minmetals Corporation

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Abstract

China Minmetals Corporation (CMC) was established as the result of a strategic recombination of two Fortune Global 500 companies – the former China Minmetals and the Metallurgical Corporation of China (MCC). With metallic minerals as its core business, in 2019, it ranked 112th among the Fortune Global 500 companies.

The Minmetals has abundant metal mineral resources. Overseas mines are located in Asia, Oceania, South America and Africa. It has a number of world-class mines such as Bangbas Copper Mine, Dugar River Zinc Mine and Baxinruimu Nickel-Cobalt Mine. The output of copper and zinc ranks in the top ten in the world, and the resources of tungsten, antimony and bismuth rank the top in the world.

China Minmetals takes "the world-class powerhouse in the metals and minerals industry" as its vision. Strategically, it positions itself as "a main force to ensure security of resources; a national team to upgrade the metallurgical industry; an integrated service provider in the industry." China Minmetals has taken the lead in operating across the whole industry chain from resource acquisition and exploration to project design, construction, operation, distribution, and further processing in the global metals and minerals sector. It has formed a business system featured by "four beams and eight columns." The four beams consist of metals and minerals, metallurgical construction, trade and logistics, and finance and real estate. The "eight columns" are composed of mineral development, metallic materials, new

energy materials, metallurgical engineering, basic construction, trade and logistics, financial services, and real estate development.

Changsha Research Institute of Mining and Metallurgy (CRIMM) is a scientific research institution affiliated to MINMETALS, has more than 30 years' research history in the field of deep-sea mineral resources development. It has successively completed lake test of mining system at 130 meters deep depth, ore lifting system sea test at 300 meters depth and seabed ore collecting test at 500 meters depth.

In May 2017, CMC and ISA formally signed an exploration contract. So far, CMC has carried out three voyages of resource exploration and environmental investigation in the CCZ area of the Pacific Ocean, and Preliminary selected the mining test area. At present, an environment-friendly continuous mining system for deep-sea polymetallic nodules is being planned. The system includes seabed collect vehicles, underwater buffer stations, delivery pipelines, lifting pumps and surface support platforms. The feasibility and assessment environment of the mining system will be verified by conducting in situ tests in the mine.

This paper will briefly introduce the research progress of CMC and CRIMM. The implementation of exploration tasks and the progress of mining technology in the mining area are also briefly introduced.

Keywords: MINMETALS, seabed collect vehicles, lifting pump, feasibility, deep-sea mineral resources development.

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2015.08-2018.04 General Manager of Intellectual Property Department of Science and Technology Management Department of China Minmetals Group
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