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Editorial: Understanding ocean ridges, a new frontier for science and development

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Editorial on the Research Topic
Understanding ocean ridges, a new frontier for science and development

Ocean ridges form where new lithospheric crust is generated by seafloor spreading at tectonic plate boundaries. Some stretch for tens of thousands of kilometres through the oceans, but others can be quite short e.g., in back arc basins. They host a range of habitats including active and inactive hydrothermal vents, peripheral areas, rocky slopes and soft sediments, all connected to the pelagic environment above. Active vents harbour exceptionally productive ecosystems fuelled by chemosynthesis and are colonized by endemic species. Seafloor massive sulfide deposits are formed over long periods of time at hydrothermal vents and may be rich in metals including copper, zinc, lead, gold, and silver. Recent interest by the mining industry in these minerals has stimulated scientific projects to better understand these poorly-known environments, including their biodiversity, functioning and connectivity. New knowledge is needed to inform management plans and ensure the protection of the marine environment.

To date most research on ocean ridges has focussed on active hydrothermal vents and their unique fauna, but mining activities are likely to be directed at inactive and extinct hydrothermal vents. The impacts of mining, in addition to those from deep-water fisheries at some depths, could significantly affect other surrounding seabed and pelagic habitats. There are many scientific knowledge gaps (Amon et al., 2022) including the need to understand the fine-scale distributions of different taxa and their connectivity along and between ridges, as well as the potential impacts of mining activities including those caused by particle load and potential toxicity of mining plumes (Weaver and Billett, 2019). This Research Topic brings together results aimed at filling the most important gaps in our understanding of ocean ridges. Some of the papers are reviews of our knowledge of mid-ocean ridge ecosystems in the Atlantic and Indian Oceans. Others describe new research including on the Juan de Fuca Ridge and East Pacific Rise in the

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Pacific Ocean and on the Scotia Ridge in the Southern Ocean. The Research Topic includes results relating to four of the seven contractors to the ISA for polymetallic sulphides (China Ocean Mineral Resources Research and Development Association, The Government of the Republic of Korea, Institut Francais de Recherche pour l'Exploitation de la Mer (Ifremer) and The Government of Poland).

Boschen-Rose and Colaço provide a comprehensive review of fauna at active vent locations and at hydrothermally inactive habitats on the northern Mid-Atlantic Ridge (MAR). A regional biogeographic analysis identified distinct faunal groupings related to depth and the chemical composition of active/inactive chimneys. They describe the biodiversity of communities, and report on ecosystem functioning, connectivity, trophic relationships, temporal variability, ecosystem resilience and recovery. The authors conclude that ecological data need to be collected over a range of time scales from hours to decades at multiple locations to establish robust baseline information that can be used in monitoring studies to distinguish between natural phenomena and impacts from mining. This highlights that deep-sea mining contractors cannot complete environmental studies within a period of two to three years, but require steady, planned and comprehensive data collection over longer timescales.

The unique ecosystems and biodiversity associated with mid-ocean ridge hydrothermal vent systems contrast sharply with surrounding deep-sea habitats and both may be increasingly threatened by anthropogenic activities including mining and climate change. It is thus of utmost importance to be able to evaluate the mechanisms by which these ecosystems function and respond to oceanic, crustal, and anthropogenic forces. Matabos et al. provide an extensive review on the development of deep-sea observatories at hydrothermal vents, examine recent scientific and technological advancements and give recommendations to support future studies. Notably, they evaluate their potential to monitor the long-term dynamics of deep-sea ecosystems through a multidisciplinary approach as well as to define effective environmental monitoring plans including the characterization of biological and environmental baseline states, the evaluation of natural versus anthropogenic changes and the assessment of degradation, resilience and recovery of faunal communities after disturbance. These approaches can represent valuable tools for environmental impact assessment in the context of deep-sea mining. The proposed recommendations include, among other things, the establishment of common global scientific questions and the identification of Essential Ocean Variables (EOVs) specific to Mid-Ocean Ridge systems.

Perez et al. provide a similar review to Boschen-Rose and Colaço but focus on ultra-slow spreading hydrothermal sites on the Western Indian Ocean ridge. Most of the information relates to fauna at active hydrothermal vents. To date, thirteen hydrothermally active locations have been identified on this ridge. Connectivity of fauna appears to be influenced by distance and geomorphological barriers. However, contrasting differences in gene flow have been documented across species. The authors note that a much better understanding of the reproductive biology of species on Indian Ocean ridges is required. Data from a wider variety of benthic size classes, including microbes, meiofauna and fish as well as information on inactive sulfide chimneys and the surrounding seabed should be acquired. As for Boschen-Rose and Colaço a detailed appraisal assessment is made of knowledge gaps and research needs.

Radziejewska et al. review current knowledge of benthic ecosystems within the Polish Exploration Contract Area for polymetallic sulfides on the MAR. The contract was signed with the ISA in 2018 and will run for 15 years in the first instance. This study identified that apart from research at two hydrothermal areas, with markedly different hydrothermal and ecosystem histories, very little is known about the fauna in the wider area. Many knowledge gaps remain. The paper recognises the challenge for contractors in generating environmental baseline studies sufficient to be used in Environmental Impact Assessments. Furthermore, they emphasize the time and investment needed in expertise and best practice sampling technologies to generate suitable data in this challenging environment.

Sarrazin et al. report on a new type of faunal assemblage dominated by gastropods at hydrothermal vent sites between c. 800 and 3500 m on the MAR. Two different gastropod species dominate, between the shallowest Menez Gwen vent field (850m, Lepetodrilus atlanticus) and the deepest Lucky Strike and Snake Pit vent fields (1700 m and 3450 m respectively, Peltospira smaragdina) depending, possibly, on the depth of the locality. The gastropod assemblages occur at sites with environmental characteristics - notably temperature and vent fluid chemistry - mussels in low temperature habitats and 2) shrimps in warmer habitats. The gastropod assemblages appear to play an important role in the functioning and dynamics of MAR hydrothermal vent communities and may even constitute one of the first steps of Atlantic vent ecological succession.

Guéganton et al. provide a detailed study of symbiotic microbial communities in the digestive systems of two common and dominant species of caridean shrimps on the MAR. Using molecular 16S RNA techniques, the authors assessed whether different microbial assemblages occurred in different compartments of the digestive systems of *Rimicaris exoculata* and *Rimicaris chacei.* Different microbial groups dominated in different gut compartments in both species, however, the same microbes occurred in the two shrimp species. In contrast, there were highly significant differences between the two species in the structure of the gut. While the habitats of the adults of the two species are well known, knowledge of the juvenile and larval stages and their associated microorganisms are still required.

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Plumes of sediment-laden water with a toxic component will be generated by the mining process on the seafloor and dewatering of ores on the support vessel (Weaver and Billett, 2019). These will spread away from the mine site where they may have negative impacts on both the benthic and pelagic fauna. Morato et al. modelled the potential magnitude and spread of these plumes using three-dimensional hydrodynamic models of the Azores region combined with a theoretical commercial mining operation of polymetallic sulfides to simulate the dispersal of plumes originating from different phases of mining operations and to assess the magnitude of potential impacts. The models showed considerable variability between locations along the ridge axis but predicted impacts at least 10-20 km away from the mine site covering areas up to 150 km^2 and extending more than 800 km into the water column. In some cases the predictions show impacts to areas where cold-water corals are predicted to occur.

The impact of the plumes will depend on their particulate content and their toxicity plus the susceptibility of the organisms impacted. Carrreiro-Silva et al. present results of a controlled aquaria experiment that tested the effects of suspended polymetallic sulfide (PMS) particles generated during simulated mining activities on *Dentomuricea aff. meteor* (low case), an important habitat-forming octocoral in the Azores. Their results show how relatively low concentrations of suspended small PMS particles (2-3 mg/l) can impair the physiology of cold-water octocorals, ultimately resulting in their death within a short period of 2 to 4 weeks. The high sensitivity of corals to PMS particles likely resulted from the combined and potentially synergistic toxicological effect (high copper) with the mechanical effect of the angular shape of PMS particles.

Priede et al. examine the drivers for biomass and biodiversity of the non-chemosynthetic fauna of the MAR which has greater richness than that of the adjacent but deeper abyssal plains even though the primary productivity in surface waters does not differ. Most of the bottom fauna on the ridges is composed of "normal" deep-sea species that are directly or indirectly dependent on fall-out of food material from the surface ocean. Priede et al. estimate the quantity of particulate organic matter reaching the sea floor to be in proportion to surface export production scaled by bathymetry. They estimated that the MAR would receive 1.3 to 3 times the flux received by the adjacent abyssal plains due to its elevated position, and that this accounts for the increased species richness and biomass on the ridge. The ridge also has a variety of habitats from hard rock to soft sediment covered slopes and plains over a wide range of water depths, creating niches for a high diversity of species. The ridge also forms an overlap zone between the faunas of the western and eastern basins allowing counts of species from both.

Little is known about the transport and export of chemoautotrophic produced organic carbon to deep-sea habitats surrounding hydrothermal vents. Roohi et al. examine vent carbon export and its influence on benthic food webs in sediments at the Rainbow vent field located on the MAR at ~2200 m depth. Two sites were considered along the dispersal direction of the Rainbow vent plume: a first near-vent site located in the close vicinity at about ~30-100 m and a second "off-vent" site at 4 km distance to the nearest venting area. At both sites, box corers were used to sample sediments and their fauna while a turbidity sensor was used to identify the presence of the vent plume in the water column. Suspended particulate organic matter was sampled from the plume as well as from surface waters at 75 m depth. Nitrogen and carbon stable isotopic analyses showed that carbon derived from *in situ* chemoautotrophy was the main nutrition source of the "near-vent" infauna while fauna at the "off-vent" site showed a signature more typical for photosynthetic-derived material. The abundance and biomass of the fauna were variable but not different at the two studied sites. This study emphasize the need to take into account the connectivity of vent and non-vent habitats when designing spatial management plans with regard to deep-seabed mining.

Vecchione and Bergstad report on numerous observations of strange linear sets of holes in sediments at a depth of about 2100 m on the MAR. A series of stunning images were captured using a Remotely Operated Vehicle during the Census of Marine Life field project MAR-ECO (2000-2010). The holes extended from less than a metre to many metres. The authors contrast their observations to several other studies which have noted similar marks on deep-sea sediments. While the source of the holes remains unknown, the authors note they bear a strong resemblance to reported ichnofossils and therefore are likely to be a feature of deep-sea sediments for a very long time. The authors also note that the holes introduce local small-scale heterogeneity into the mid-ocean ridge environment which potentially influence the distributions of smaller organisms. This may be important when considering sampling strategies in baseline studies and subsequent monitoring programmes if mining goes ahead.

Woods et al. describe how relict, inactive black-smoker chimneys on the East Pacific Rise can in some cases be colonised by large numbers of suspension-feeding brisingid sea stars at a depth of about 2300 m on the summit of a seamount. A detailed analysis of the spatial distribution of these sea stars demonstrates that they are clustered on the inactive chimneys and are absent from active vents and much less common on other hard substrata in the area. This study demonstrates that inactive chimneys can act as particular habitats for certain species.

Neufeld et al. address the distribution of non-vent fauna living in proximity to hydrothermal vents and which might be impacted by mining activities. Specifically, they studied two localities on the Juan de Fuca Ridge in the north-western Pacific Ocean using a Remotely Operated Vehicle. Fauna studied included megafaunal sponges, antipatharian and alcyonacean corals, actiniarians, ophiuroids, crinoids and ascidians. Very few corals occurred within 50 m of an active hydrothermal vent, and almost none within 25m. Notable differences in the composition and distribution of corals were also noted between different localities. Slow growing deep-water taxa, such as corals and sponges, will be particularly sensitive to mining impacts, including smothering by sediment plumes and possible toxicity of weathered sulfides.

Lim et al. provided a detailed characterization of geochemistry of surface sediment from Onnuri vent field (OVF) in the middle region of the Central Indian ridge (CIR). Based on their report, OVF is about ~12 km from the ridge axis along the CIR. They found that the OVF sediments were characterized with high concentrations of Fe, Si, Ba, Cu, and Zn, derived from hydrothermal fluid and S and Mg from seawater. However, these sediments did not have depleted C-S isotope compositions and contained abundant hydrothermally precipitated minerals (i.e., Fe–Mn hydroxides, sulfide and sulfate minerals, and opal silica). The occurrence of pure talc and barite indicated strong hydrothermal activity at this site. Furthermore, their sulfur and strontium isotope geochemistry suggested that the seawater was well mixed with high-temperature fluid. They argued that the OVF is a good representative of off-axis, high-temperature vent circulation system and could be the most common type of hydrothermal activity in the CIR. Overall, this study provide some good insights into vent system along mid-ocean ridges.

Namirimu et al. conducted metagenomics analysis of microbial communities of three sediment samples collected from the Invent E and Onnuri vent fields (OVF) and found that microbial communities were similar and dominated by Bacteria. Proteobacteria, Firmicutes, Bacteroidetes and Euryarchaeota. Analysis of KEGG categories indicated that microbial communities have capabilities of conducting aerobic respiration, carbon fixation through the Calvin-Bassham-Benson cycle and the reverse tricarboxylic acid cycle. They also have reductive acetyl-CoA pathway and sulphur and nitrogen metabolic functions. When comparing metagenomics information with those from different ridges in the world oceans, they found that microbial communities differed between highly active and low active vents, which further support the early findings showing the relationship between venting activities and microbial community structures. Overall, this study provided the first hand information on microbial community structure and functions in sediments from two newly discovered vent fields in mid-Indian Ocean ridge area.

Jang et al. assessed the influence of geological and geographic factors on the divergence of symbiotic bacteria of deep-sea hydrothermal vent mussels *Bathymodiolus* from the CIR (slow spreading ridge) and the eastern Pacific Ridges (fast-spreading ridge). They concluded that the differentiation of symbiont populations was the highest between these two geological locations, followed by inter-ridge sites between the East Pacific Rise and the Pacific Antarctic Ridge. A biogeographic physical barrier have played a very important role in population differentiation for both symbionts and their host mussels. Within a single ridge, the degree of differentiation was driven by geological distance in the CIR whereas this factor hardly played any role in the eastern Pacific ridges. The authors argued that different ridge spreading rates are main drivers of spatial and temporal connectivity of vent habitats. However, this observation is not supported by other recent studies on endosymbiont population genetics of deep-sea mussels. Based on analysis of population divergence processes of both symbionts and hosts from three ridge segments of the CIR, the authors argued that historical and physical constraints for habitats and dispersal between vents in the CIR affected dynamics of microbial population divergence.

Pereira et al. evaluated the role of magmatic fluid influx in vent systems of the East Scotia Ridge located in the Scotia Sea. For this, they analysed the chemical and isotopic compositions as well as fluid inclusions from three chimneys and showed that hydrothermal fluids varied over time within the studied basin. They conclude that the observed depletions in some fluid-mobile elements, since the previous fluid sampling 9 years before, was due to leaching. Their results also indicated that high-temperature fluid-rock interactions were key in setting the composition of the fluids. In particular, the cation-to-chloride ratios suggest a common “root zone” for the studied vent sites. The concentrations of dissolved gases provided new insights in the connection between magmatic degassing and its influence on end-member vent fluid composition and results point to a minor influx of magmatic vapour. When comparing the concentrations of conservative elements in the fluids of the different sampling sites, Pereira et al. found different behaviour, reflecting either sub-seafloor mixing between end-member fluid and seawater or the combination of abiotic and biotic reactions. Thermodynamic computations confirm that the East Scotia Ridge system is dominated by sulfide oxidation as a major catabolic pathway, favourable to sustain a robust sub-seafloor biosphere.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Author PW was employed by Seascape Consultants Ltd. Author DB was employed by Deep Seas Environmental Solutions Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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