Progress in marine scientific research and Innovation (2020–2024):

An Expert Analysis by the S.H.E. Community - ISA's Global Mentoring Programme 'See Her Exceed'

A publication of the

S.ee H.er E.xceed
Mentoring Programme

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S.ee H.er E.xceed Mentoring Programme

The S.H.E. Global Mentorship Programme, launched in 2023 by the International Seabed Authority (ISA) under the Women in Deep-Sea Research (WIDSR) initiative, supports gender equity in ocean science by equipping women scientists from developing states with the mentorship, skills and professional networks needed to excel in deep-sea research and related fields.

Through a structured 12-month cycle, mentees receive personalised guidance on their scientific, professional and leadership goals, aligned with the ISA's Action Plan for Marine Scientific Research. The programme promotes skill-building, knowledge exchange and career visibility, while fostering a growing community of practice for women working in deep-sea exploration.

By strengthening technical capacity, leadership pathways and global networks, S.H.E. supports greater participation and representation of women at sea and contributes to a more inclusive and equitable deep-sea science workforce.

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ACKNOWLEDGEMENTS

This report was developed under the framework of the International Seabed Authority's See Her Exceed Global Mentoring Programme - S.H.E., a flagship initiative of the Women in Deep-Sea Research project.

The content and analysis are grounded in the independent assessments conducted by the S.H.E. community: Lucy Njue, Nezha Mejjad, Oluyemisi Oluwadare, Orji Ijeoma and Randa Mejri (mentees), Ann Vanreusel, Annemiek Vink, François Charlet, Gao Xiang, Marzia Rovere, Pedro Madureira, Rahul Sharma and Samantha Smith (mentors) and Mr. John Astony Mataro, Dr. Rahul Sharma, Dr. Samantha Smith and Dr. Pierre Jean Valayer (support group).

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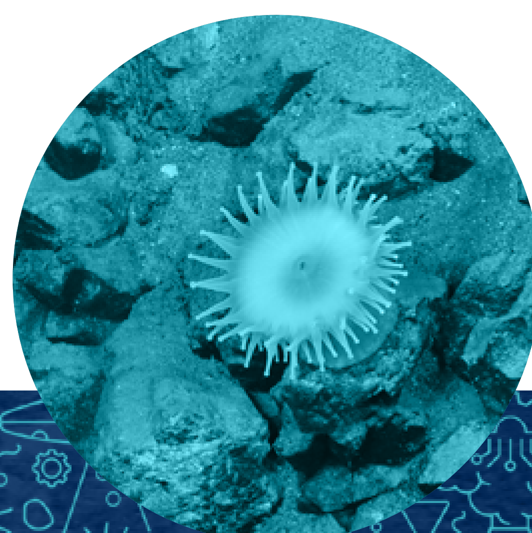


ABBREVIATIONS

APEI	area of particular environmental interest
CFC	cobalt-rich ferromanganese crusts
EU	European Union
ISA	International Seabed Authority
MAR	Mid-Atlantic Ridge
MSR	marine scientific research
PMN	polymetallic nodules
PMS	polymetallic sulphides
REE	rare earth elements
REY	rare earth elements and yttrium
S.H.E.	See Her Exceed Global Mentoring Programme
SWIR	Southwest Indian Ridge
UNCLOS	United Nations Convention on the Law of the Sea

NOTE

The present report is based on an analysis of 431 publications reported by contractors in their annual reports submitted to the International Seabed Authority.

These publications were classified into four major disciplines: biology, geology (including geochemistry), oceanography and engineering. Each discipline included various themes. Geology themes included bathymetry, tectonics, geochemistry, mineralogy and resource assessment. Biology themes included diversity, taxonomy, genomics and ecological functioning. Oceanography themes included physical and chemical processes, modelling and related topics. Engineering themes included mining technology, metallurgical processing and related areas.

While the publication period considered for this report is 2020 to 2023, the actual data-collection, analyses, interpretation and writing would have been completed over several years before that, spanning a few years to a decade. In addition, the publications analysed for this report may not represent the entire database of marine scientific research during the period, as they consider only publications reported by contractors in their annual reports. There are likely many more scientific publications by independent research groups and organizations worldwide, even during the specified period.

It is also recognized that extensive research has been carried out over the past five decades on various topics by several research groups aimed at a better understanding of deep-seabed minerals and their environmental setting, besides engineering, policy, regulation and legal aspects, that may not have been reported in the annual reports of the contractors.

While care has been taken to separate publications by major discipline and research subject themes, there may be some overlap due to the interdisciplinary nature of marine science research.

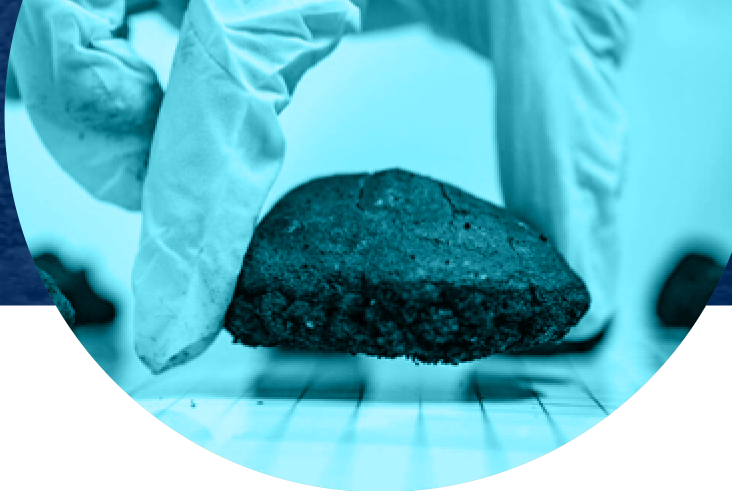
Any views or opinions expressed in this report are those of the experts involved in the S.H.E. Mentoring Programme and do not necessarily reflect the views or positions of the International Seabed Authority.

FOREWORD

It is with great pleasure that I present this report, a significant milestone in the International Seabed Authority (ISA) ongoing efforts to promote marine scientific research, knowledge stewardship and inclusive collaboration in the Area, defined under the United Nations Convention on the Law of the Sea as the seabed, ocean floor and subsoil beyond the limits of national jurisdiction. This scientific analysis, encompassing 431 peer-reviewed publications submitted by exploration contractors to ISA in their annual reports between 2020 and 2023, offers a valuable synthesis of deep-sea research generated under the exploration regime and illustrates ISA's role as a convener and facilitator of knowledge for the benefit of all humankind.

This report holds particular personal significance for me as a woman and oceanographer from the Global South, now entrusted with leading the ISA Secretariat. I am immensely proud that the first report launched under my tenure features contributions from a talented group of women scientists from developing States. It embodies the values we aspire to foster: scientific excellence, meaningful participation and collective progress.

As the second knowledge output of the See Her Exceed Global Mentoring Programme - S.H.E., implemented under the Women in Deep-Sea Research project, this report showcases the talent, dedication and leadership of a dynamic cohort of early-career professionals from developing States. I extend my heartfelt congratulations to those S.H.E. mentees: Dr. Nehza Mejjad (Morocco), Prof. Randa Mejri (Tunisia), Ms. Lucy Njue (Kenya), Ms. Oluyemisi Oluwadare (Nigeria), Ms. Ljeoma Eunice Orji (Nigeria) and Ms. Mpho Lydia Sehlabo (South Africa). I am equally grateful to their respective mentors, Mr. François Charlet (France), Prof. Pedro Madureira (Portugal), Dr. Marzia Rovere (Italy), Dr. Joshua Tuhumwire (Uganda), Prof. Ann Vanreusel (Belgium) and Dr. Annemiek Vink (Germany), whose expert guidance and unwavering support enabled the mentees to achieve this ambitious goal. My sincere thanks also go to the S.H.E. support group, including Mr. John Astony Mataro, Dr. Rahul Sharma, S.H.E. Champion Dr. Samantha Smith and Dr. Pierre Jean Valayer, whose encouragement and contributions made this collaborative achievement possible.



The critical insights shared in this report shed light not only into the scope and thematic trends of marine scientific research related to mineral exploration in the international seabed area but also on the geographic distribution and gender balance of first authors across disciplines. It exemplifies our broader commitment to gender-responsive capacity development, as enshrined in the ISA's Strategic Plan 2024-2028, the ISA's Capacity Development Strategy and the Action Plan for Marine Scientific Research in support of the United Nations Decade of Ocean Science for Sustainable Development. It demonstrates science and capacity development in action: inclusive, rigorous and forward-looking for the benefit of humankind.
As we continue to implement our mandate under the United Nations Convention on the Law of the Sea and its 1994 Implementing Agreement, we remain committed to inclusive ocean governance and scientific excellence. I commend the findings of this report and look forward to building upon this momentum, ensuring that all voices are heard and all talents are empowered to contribute to the shared stewardship of our ocean commons.

Leticia Reis de Carvalho
Madam Secretary-General
International Seabed Authority

EXECUTIVE SUMMARY

This knowledge output, produced under the International Seabed Authority's (ISA) See Her Exceed Global Mentoring Programme - S.H.E., offers an expert analysis of 431 peer-reviewed scientific publications derived from annual reports submitted to ISA by its exploration contractors between 2020 and 2023.

The analysis was conducted by the S.H.E. community, comprising six mentees from developing countries (Kenya, Morocco, Nigeria, South Africa and Tunisia) and six mentors (Belgium, France, Germany, Italy, Portugal and Uganda), with cross-cutting support from three experts (France, India and the United Republic of Tanzania). This collaborative effort not only enhanced mentees' research, analytical and scientific writing skills but also fostered leadership and confidence, empowering the next generation of women scientists to contribute to deep-sea research and technology.

The analysis covers four key research disciplines: biology, geology (including geochemistry), oceanography and engineering (including metallurgy). It demonstrates how exploration activities have advanced fundamental and applied deep-sea science while fostering contributions from the wider scientific community. The analysis further supports ISA's mandate to promote marine scientific research and capacity development under the United Nations Convention on the Law of the Sea, with a specific focus on women's empowerment.

The present report confirms that the Clarion-Clipperton Zone remains the most studied region, reflecting its long-standing exploration focus. The biological studies highlighted efforts in baseline biodiversity assessments, focusing primarily on benthic invertebrates and yielding notable new species discoveries, while identifying the need to expand research into pelagic and midwater ecosystems and into ecosystem functioning. The geological review centred on tectonics, structural geology, geochemistry and resource assessments using advanced methods, including AI. The engineering publications highlighted a strategic focus on metallurgical processes. At the same time, oceanographic studies mostly examined the interplay among ocean processes, geology and ecosystems, which are essential for assessing the impacts of deep-sea mining. Several future research priorities were also identified.

The analysis also assessed the gender distribution of first authors, revealing a persistent gender gap: women are well-represented in biology and oceanography but underrepresented in geology and engineering. Additionally, it examined the countries of the first authors' affiliations and found that deep-sea research is driven by a small group of countries. However, it is understood that the final author may also be the supervisor and the person leading the research. The report concludes with recommendations related to the scientific findings, contractors' reporting standards and the effectiveness of the global S.H.E.

1. INTRODUCTION

As part of its mandate under the United Nations Convention on the Law of the Sea (UNCLOS) and the 1994 Agreement relating to the Implementation of Part XI of UNCLOS (1994 Implementing Agreement), the International Seabed Authority (ISA) is committed to advancing women's empowerment. The activities and projects of the ISA in this domain are anchored in ISA's mandate to promote marine scientific research (MSR) and contribute to the realization of the Action plan of the International Seabed Authority in support of the United Nations Decade of Ocean Science for Sustainable Development adopted in 2020 and acting as an umbrella to catalyse ISA's contribution to the United Nations Decade of Ocean Science for Sustainable Development (United Nations Ocean Decade).

Furthermore, ISA has the duty to encourage the design and implementation of appropriate programmes for the benefit of developing States with a view to strengthening their research capabilities, training their personnel in the techniques and applications of research and fostering the employment of their qualified personnel in research in the Area. As part of its Capacity development strategy, ISA is implementing a series of targeted programmes and initiatives to strengthen the participation of women from developing States, reflecting its commitment to inclusive capacity development.

As part of the Women in Deep-Sea Research project, the ISA launched the See Her Exceed Global Mentoring Programme - S.H.E. in 2023. The S.H.E. facilitates personal growth and career advancement of women scientists from developing countries specializing in deep-sea research. The inaugural cohort of mentees and mentors achieved their personal, professional and scientific goals in June 2025.

This report is one of two knowledge outputs collectively produced by the S.H.E. mentees, mentors and support group. It builds on a comprehensive stocktaking study published by the ISA Secretariat in early 2024, The contribution of ISA to the scientific objectives of the UN Decade of Ocean Science for Sustainable Development, which introduced an open-access repository of peer-reviewed scientific papers reported by contractors as part of their annual reports to ISA from 2020 to 2023. This repository serves as the foundation for the analysis presented in this report. The S.H.E. mentees and mentors conducted an in-depth analysis of the publications available in this repository.

2. MATERIAL AND METHODS

Studies on deep-seabed minerals and their habitats have been fundamental to furthering our understanding of the deep sea for the past decades, since the discovery of the first nodule and crust samples in the nineteenth century (Galka, 2025). Discoveries and subsequent studies on marine mineral resources started with polymetallic nodules (PMN), followed by cobalt-rich ferromanganese crusts (CFC) and later polymetallic sulphides (PMS) within different geological settings of the deep seabed, both within and beyond areas of national jurisdiction (Powell, 2024). These minerals occur at different depths and geological settings in abyssal plains, on the flanks of seamounts and at mid-ocean ridges, respectively (Watling, Guinotte, Clark, & Smith, 2013).

Regulations for the prospecting and exploration of seabed mineral resources were approved and issued by the ISA's Council in 2000, 2010 and 2012, respectively, with amendments issued in 2013 to align all three sets of regulations. Since 2001 and at the time of writing, 31 contracts, sponsored by both developing and developed States, have been signed with the ISA for the exploration of mineral resources in the Area. Nineteen of these are for PMN, with 17 located in the Northeast Pacific within the Clarion-Clipperton Zone (CCZ), one in the Northwest Pacific Ocean, and one in the Central Indian Ocean Basin. Furthermore, seven contracts have been signed for PMS, three in the North Atlantic and four in the Indian Ocean. Five were signed for CFC, four in the Western Pacific and one in the Southwest Atlantic. In 2022, a contractor exploring areas of the Southwest Atlantic voluntarily terminated its exploration contract with the ISA.

In accordance with the UNCLOS and the 1994 Agreement, the ISA is developing the regulations for the exploitation of mineral resources in the Area. This process began in 2014 and included focused expert workshops and open stakeholder consultations. It culminated in the development of draft regulations submitted to the Council for consideration in 2019. The negotiations are ongoing.

Each entity holding an exploration contract with the ISA, referred to as a "contractor," is required to submit an annual report on its programme of activities. In Recommendations for the guidance of contractors on the content, format and structure of annual reports, the Legal and Technical Commission recommends that contractors present a list of relevant publications in peer-reviewed journals published during the reporting year.

Scientific papers reported by contractors in their annual reports submitted between 2020 and 2023 were compiled using the open-access software into a bibliographic repository available on the ISA website for the wider stakeholder community. The ISA had received the annual reports from contractors on their activities in 2024, but they were not incorporated into the current analysis due to timing constraints. The S.H.E. mentees and their mentors analysed these papers as part of their capacity-building activities. The 431 scientific papers reviewed were pooled in a Zotero repository available online on the ISA's webpage and consequently grouped into four disciplines based on the areas of expertise of each mentor-mentee pair. Second, mentors screened the papers within their field of specialization and selected a subset of scientific papers. These selected papers were then reviewed and annotated by the mentees, with guidance and support from their respective mentors.

The objectives of this effort were threefold: to provide an enhanced understanding of the capacity and the focus of the MSR landscape associated with and provided by mineral exploration efforts in the Area, to transfer skills in bibliographic analysis and critical review to the mentees, and to strengthen their scientific writing capacity.

Each paper was assessed across:

- scientific research disciplines of the study: biology, geology (including geochemistry), oceanography and engineering (including metallurgy)
- geographic regions of the study: CCZ, Northwest Pacific, Central Indian Ocean and Indian mid-ocean ridges, Mid-Atlantic Ridge, South Atlantic
- type of mineral referenced: PMN, PMS, CFC
- gender of the first author
- affiliation of the first author to identify the institutions most active in deep-sea research
- country of the lead institution, based on the affiliation of the first author
- collaborative dimension, including the number of coauthoring institutions and the number of countries involved.

Each scientific discipline was further subdivided into subcategories as presented in Table 1 below.

Table 1. Research disciplines and corresponding thematic areas

Scientific discipline	Research themes	
Geological studies	**PMN**	• bathymetric mapping • analyses of nodule densities and distributions (resource assessments) • geochemical analyses of nodules, deep-sea sediments or sediment pore waters • mineralogical analyses of the nodule • sedimentological studies
	PMS	• resource assessments and discovery of new hydrothermal vents • geochemical studies • tectonic and structural geology • fundamental processes in hydrothermal systems • technical implications
	CFC	• geochemistry • geology (mineralogy and structural geology) • resource assessment
Geochemistry	**All three mineral types:**	• fundamental ocean geodynamics • hydrothermal systems
Biological studies	**All three mineral types:**	• diversity and community analysis • taxonomy • connectivity, including geographical distribution of taxa • ecological functioning • impact and impact assessment • trophic aspects • management • genomics
Oceanographic studies	**All three mineral types:**	• modelling • ocean currents and geology • physical oceanography • chemical oceanography • links to deep-sea mining and impacts • oceanography and biology
Engineering studies		• mining technologies • different methodologies for the metallurgical processes of nodules

3. RESULTS AND DISCUSSION

3.1 General

Figure 1 shows the number of scientific papers reported in the annual reports of contractors between 2020 and 2023. The ratio of papers PMN:PMS:CFC in the repository is 202:161:71.

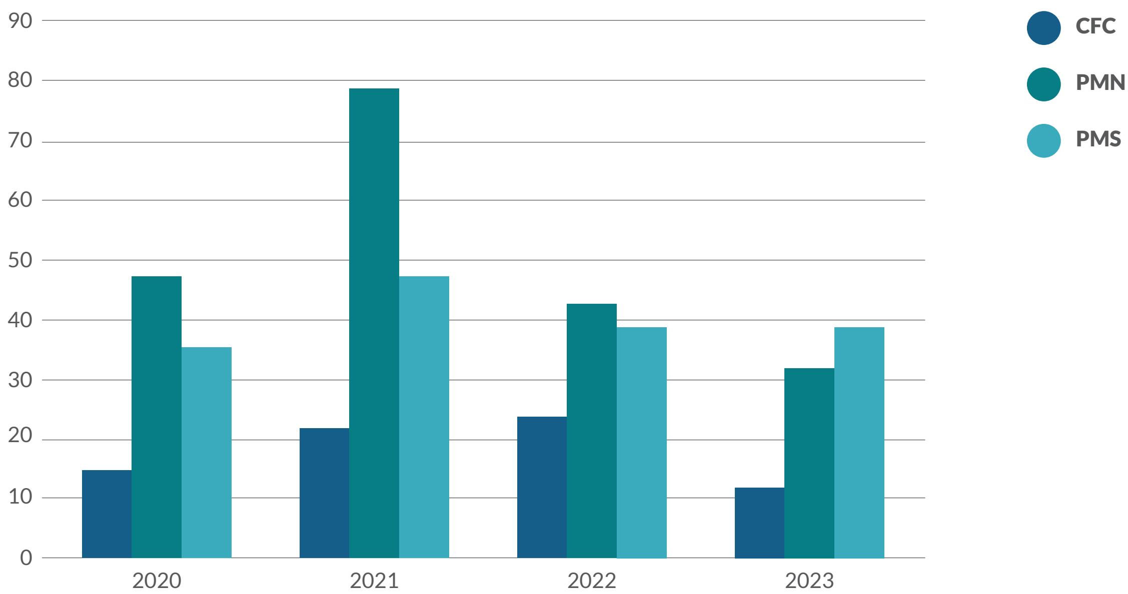


Figure 1. Marine scientific publications reported by contractors (2020-2023)

Figure 2 shows mentors and mentees attributed to scientific disciplines in these papers. The large majority of the publications (90 per cent) come from the field of geology and biology, and engineering and oceanography are represented to a lesser extent. It is important to note that, given the multidisciplinary nature of the studies, some papers may have been analysed under two or more categories.

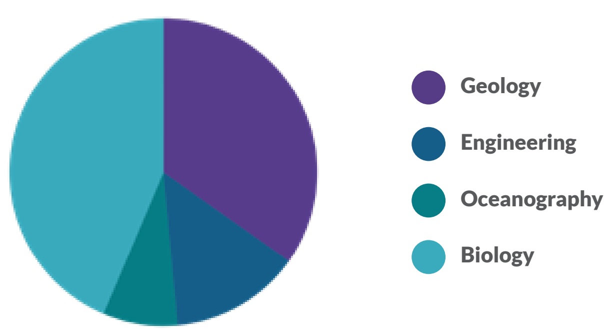


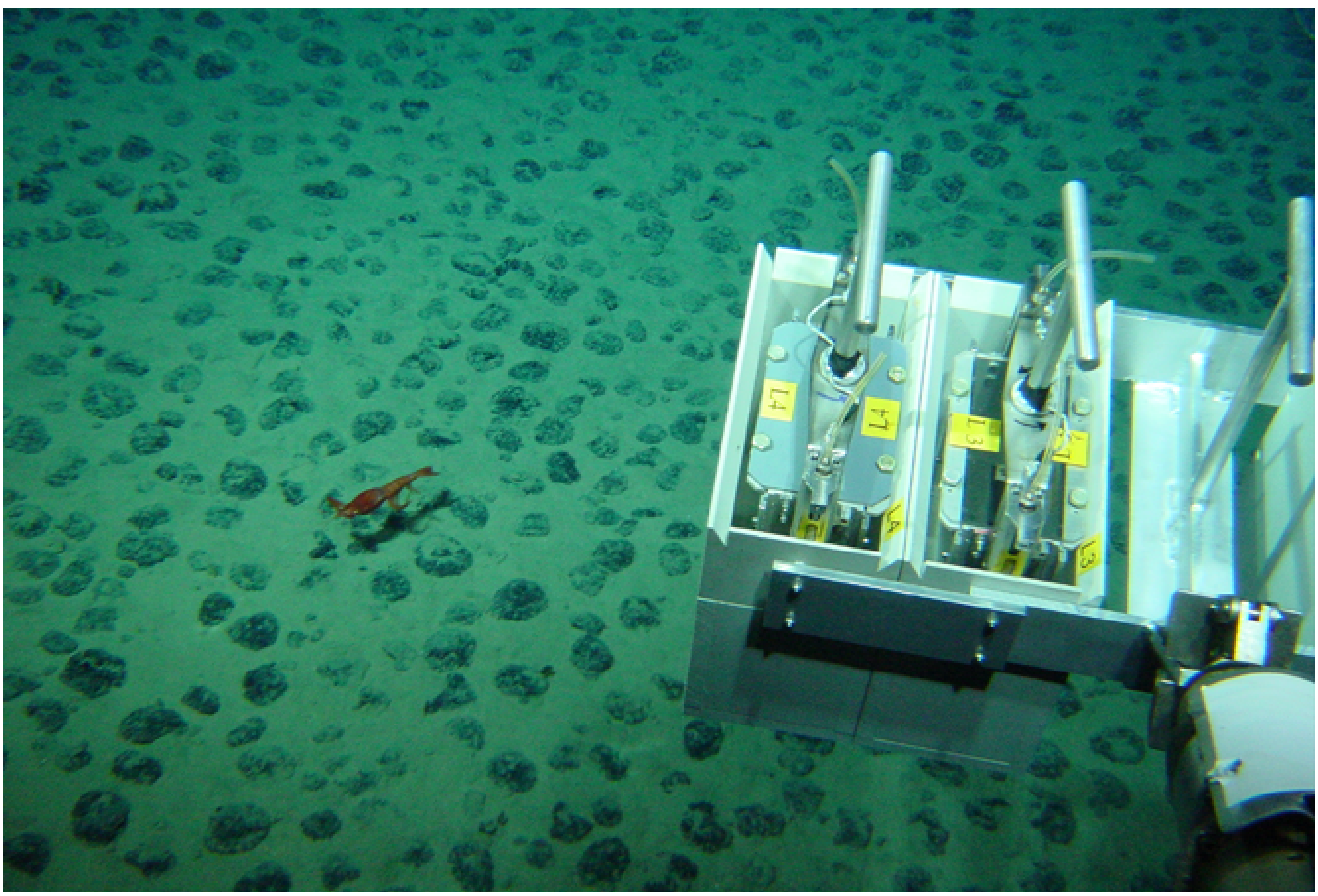
Figure 2. Distribution of publications by research discipline

3.2 Geology

In total, 197 publications in the database were classified under geology. Some of these overlapped with other disciplines, such as biology, oceanography and engineering. To minimize this overlap, 151 publications were classified as purely geological according to the subcategories described in Table 1 (35 per cent of the total publication database) and analysed in greater detail. Of these, 44 (29 per cent) focus specifically on the PMN geology, 80 (53 per cent) on the PMS geology, and 27 (18 per cent) on the CFC geology. These publications include direct analyses of the resources themselves (mapping, geochemistry, mineralogy, resource assessment) and broader studies of tectonic settings and the evolution of basins or ridges in areas rich in marine minerals today and now the focus of exploration.

3.2.1 Polymetallic nodules

PMN are deep-sea minerals formed by the deposition of layers of iron and manganese oxides in ring-like structures around a core. PMNs form over millions of years in areas with low sedimentation rates, specifically on seafloor plains. Although PMN are present in all the major ocean basins, economically viable deposits are localized as they require specific geological conditions for their formation and growth. Manganese and iron are the primary metals in PMN. However, they also contain significant amounts of transition metals such as nickel, copper and cobalt, as well as smaller amounts of molybdenum, titanium, lithium and rare earth elements (REE).



3.2.1.1 Regional distribution

Figure 3 shows that 84 per cent of the PMN geological analyses have been conducted in the Pacific Ocean, and 77 per cent exclusively within the CCZ of the Northeast Pacific. The CCZ is about 6 million km2 in size and is known to contain vast, contiguous deposits of PMN, totalling an estimated 21.1 billion tons (Hein et al., 2013). The CCZ is home to 17 exploration contracts granted by the ISA, which explains the ISA contractors' focus on geological research in this area.

Four publications draw on activities conducted in the Indian Ocean, which currently contains only one PMN exploration contract area. Two papers draw on activities conducted in the Peru Basin off the coast of South America, which is not a typical exploration area but is the site of a surrogate mining-impact experiment conducted in 1989 (Foell et al., 1990). Several papers had a less regional approach to PMN analysis (were resource-oriented) or geochemically analysed deep-sea sediments in relation to their elemental content.

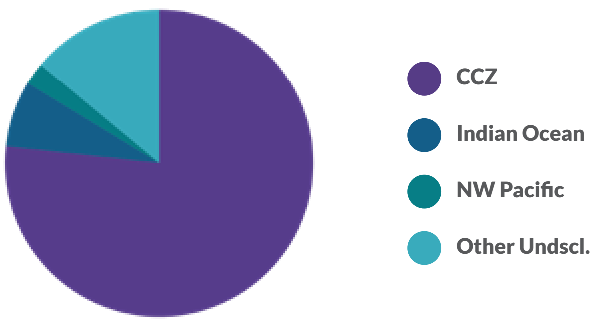


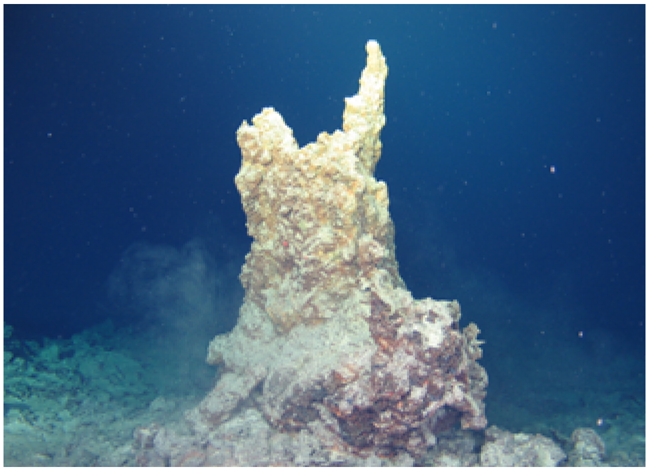
Figure 3. Regional distribution of PMN publications (percentage)

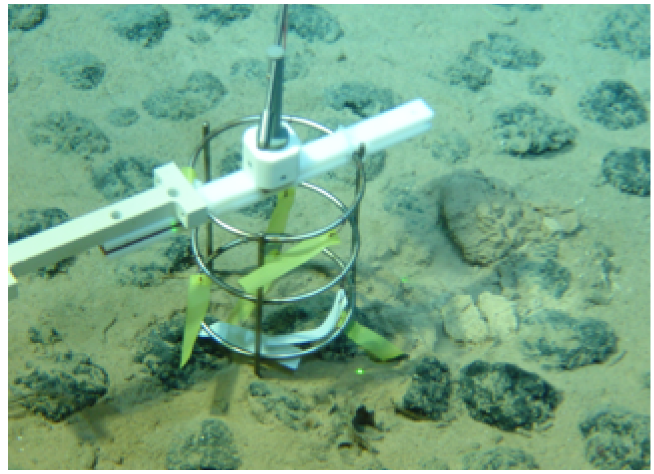
3.2.1.2 Research disciplines

The 44 PMN geological publications were classified according to the research disciplines shown in Table 1.

Sixteen publications focus on geochemistry [9], mineralogy [2] or both [5], either of the PMN themselves or the deep-sea sediments underlying the nodule resource. PMN represent an interesting source of metals. Many studies have focused on geochemical and mineralogical analyses of PMN from different areas and deposits to examine their genesis, geochemical zonations, mineralogical characteristics, growth rates, and metal contents (Sensarma et al., 2020). Such data form the basis for resource assessments. Two studies also analysed the effects of sediment burial on PMN geochemistry and mineralogy (Wegorzewski et al., 2020; Yang et al., 2024). Interestingly, Kim et al. (2021b) reported the major, trace and REE compositions of particles smaller than 63 μm produced by the experimental degradation of two types of PMN from the CCZ, as unrecovered PMN fines may be a key component of return-water tailings. They show that both the amount and the composition of PMN fines are expected to differ significantly depending on the minimum particle recovery size on the mining vessel.

Deep-sea sediments were generally analysed geochemically and/or mineralogically for their Mn/Fe ratios and major and trace elements such as Co, Ni, Cu and REE, as well as for biogeochemical characteristics such as total organic carbon and total nitrogen. The aims were, among other things, to determine their genetic origin, redox zonations and microbial activity and to understand their spatial and temporal distribu-





tions (Volz et al., 2020; Zawadzki et al., 2020; Jung et al., 2022). Special attention was given to the analysis of rare earth elements and yttrium (REY) in sediments, as a potential new REY resource (Milakovska et al., 2022; Kim et al., 2022).

About one quarter of the PMN geological publications focus primarily on resource assessments. These assessments include remote sensing (hydroacoustic analysis, multibeam and side-scan sonar), geostatistical and neural network modelling, machine-learning approaches to optimize resource assessments (image-based resource classifications) and structured economic assessments (Gazis et al., 2021; Mbami et al., 2023; Liu et al., 2021; Neettiyath, 2023; Uhlenkott, 2020; Zhu et al., 2022). The focus was on the possibilities and limitations of image-based analysis of nodules as a tool for resource assessment, often in comparison with other approaches (about half of the papers described here). These publications reflect improvements in AI-based machine learning for advanced PMN detection, which, in turn, have the potential to significantly increase the accuracy of resource estimates.

Twelve publications relate to resource assessments. Two of these introduce a method for assessing PMN abundance using heterogeneous hydroacoustic data and artificial neural network models that classify a given region into low- or high-density PMN areas (Wong et al., 2021; Kuhn et al., 2021). More detailed and accurate resource assessments can be achieved through the geostatistical analysis of geological sampling data (with a box corer) (Baláž, 2021, 2022; Kuhn et al., 2021). Ellefmo et al. (2021) and Mucha and Wasilewska-Błaszczyk (2020) complement such classical resource assessments by integrating seafloor images into their analyses. They find that the use of seafloor photographs (soft data) increases the accuracy and quality of PMN resources estimation. Several publications used seafloor images solely for resource assessment to increase the resolution and reliability of estimates in smaller, prospective parts of the deposit. Use of regression models, such as a general linear model, to link nodule abundance to several independent variables (the percentage of seafloor nodule coverage, nodule genesis and the degree of sediment coverage of nodules), was found to decrease in the standard prediction error (Wasilewska-Błaszczyk and Mucha, 2021, 2023). Mbani et al. (2022) implement an automated workflow (machine learning) for image-based seafloor classification, as increasing capabilities to record high-resolution underwater images make manual approaches for analysis and seafloor classification unfeasible. Machine-learning models can greatly speed up resource, habitat and faunal classifications, but Gazis and Greinert (2021) caution on the influence of spatial autocorrelation on validation performance. Several further studies have used underwater hydroacoustic sensing or video-mapping techniques to map PMN deposits, provide seafloor substrate and habitat classifications, and aid megafauna detection (Kuhn et al., 2020; Mbani et al., 2022).

Occasionally, publications related to the structural geology and/or tectonic history of the large ocean basins hosting PMN were reported. For example, Mirlin et al. (2021) analysed altimetric data in combination with bathymetry and gravimetry to evaluate the structure of the sedimentary cover and the composition and absolute age of basalts within the CCZ. Four publications address geochronological or palaeoceanographic aspects of PMN-rich areas, using foraminiferal dissolution indices, strontium isotope stratigraphy (Wang et al., 2023), lithofacies changes, or geochemical and mineralogical changes in the million-year-old PMN themselves (Park et al., 2023).

3.2.2. Polymetallic sulphides

The PMS form at depths of 1,000-4,000 m. They are associated with the formation of oceanic crust at mid-ocean ridges or back-arc systems. Numerous geological studies have been conducted over the years to unravel active and inactive hydrothermal vent settings, sulphide accumulation and mineralization within ultramafic, sediment and basaltic-hosted rocks. A total of 80 PMS scientific papers from the repository focusing on PMS geology were analysed.

3.2.2.1. Regional distribution

Figure 4 shows that two-thirds of the PMS geological publications in the database derive from the Indian Ocean (Southwest and Central Indian Ocean Ridge), which currently hosts five exploration contracts, while 17 per cent are from the Mid-Atlantic Ridge (MAR) in the Atlantic Ocean, where two exploration contracts are in place.

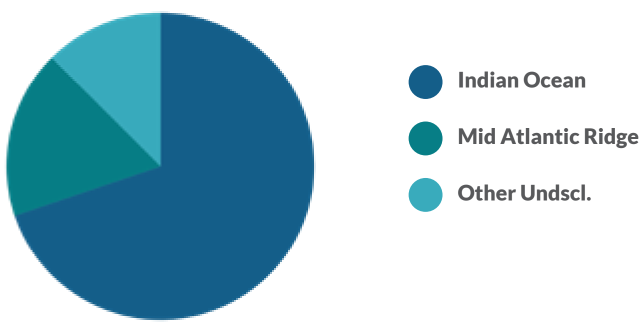


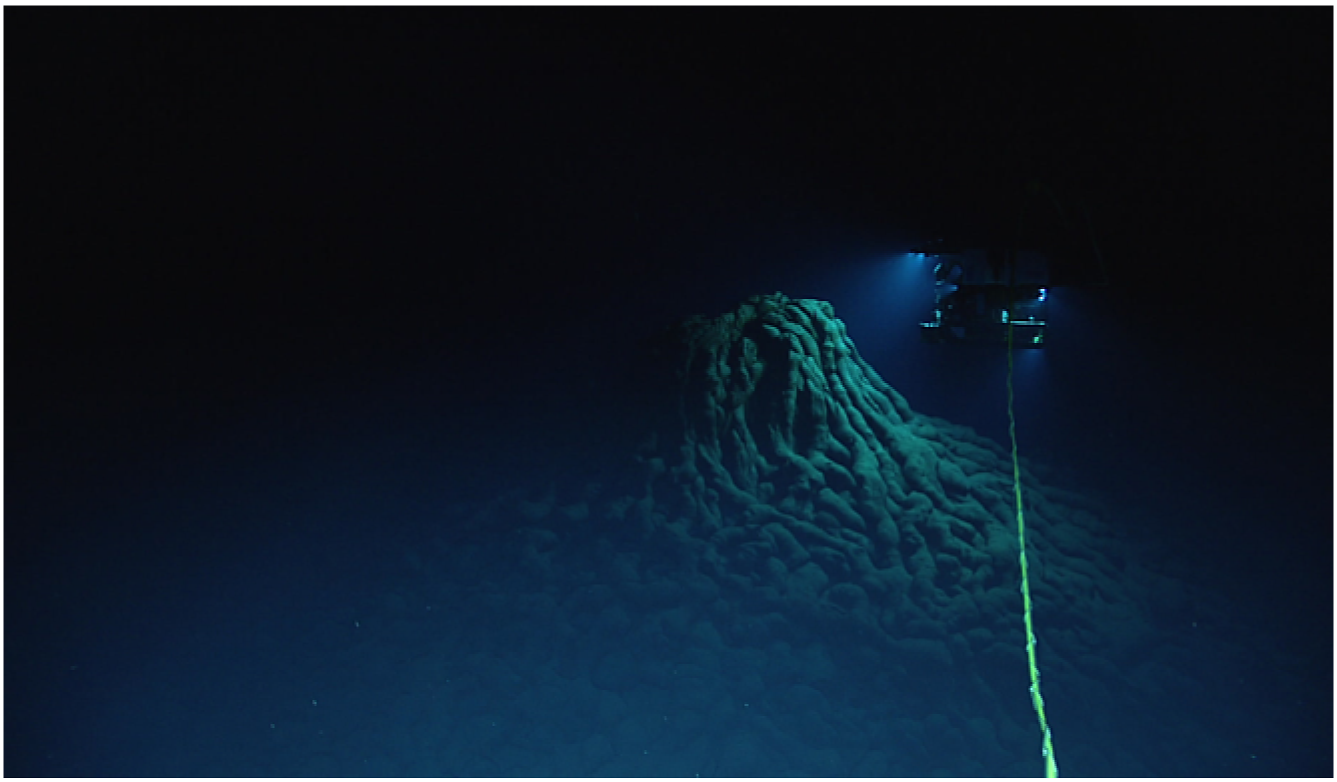
Figure 4. Regional distribution of PMS publications (percentage)

3.2.2.2. Research disciplines

The 80 PMS studies were classified according to the following research disciplines: resource assessments and discovery of new vents, geochemical studies, tectonic and structural geology, fundamental processes in hydrothermal systems and technical implications shown (Table 1).

Studies associated with resource assessments and the discovery of previously unidentified vents focus on characterizing seafloor PMS deposits and assessing their resource potential. Agarwal & Palayil (2022) identified manganese-rich wustite particles in sediments from the Central Indian Ridge, suggesting their utility as proxies for hydrothermal activity and implications for resource evaluation. Cherkashov et al. (2021) and (2023) provide comprehensive assessments of PMS morphology and geochronology in the

MAR, aiding exploration strategies. Firstova et al. (2022) examined sub-seafloor ore-forming processes at slow-spreading ridges, which are critical for targeting potential deposits in these settings. Kurian et al. (2022) offered a regional overview of hydrothermal systems in the Indian Ocean. Li et al. (2020, 2021) identified nine active sites along the Southwest Indian Ridge (SWIR) and used olivine-spinel compositions to infer mantle source heterogeneities, including possible mantle plume influences. Liang et al. (2023) detailed the geological features of a newly discovered active vent field at SWIR, providing insights into both mineral potential and vent ecology. Makoviz et al. (2023) reported on two new ore fields in the MAR, while Maslennikov et al. (2020) contributed vital trace-element analyses of PMS deposits in the Pobeda field, including halmyrolysis-driven transformations. Melekestseva et al. (2023) analysed Zn-rich chimneys and highlighted their economic value. Prakash et al. (2022) identified new hydrothermal activity on the Central Indian Ridge through chemical surveys.



Geochemical investigations aimed to understand the geochemical signatures of hydrothermal systems and trace-metal behaviour. Cao et al. (2021) and Choi et al. (2021) conducted detailed isotopic and mineralogical studies of sulphide chimneys, revealing processes of ore enrichment. Dong Zhen (2021) analysed magmatic evolution in basalts from SWIR, shedding light on mantle heterogeneities. Maslennikov et al. (2023) explored trace-element migration during sulphide oxidation, identifying assemblages linked to ore genesis. Zhang et al. (2021) enhanced understanding of the global distribution and cycling of gallium, a strategic metal, in submarine hydrothermal systems. Trace-element and REE fingerprints were also used by Melekestseva et al. (2023) to assess the mineral resource value and by Maslennikov et al. (2020) to distinguish depositional facies in PMS chimneys.

Several studies investigated the tectonic and structural geological context in which hydrothermal systems form. Bortnikov et al. (2022) linked hydrothermal and magmatic systems in slow-spreading ridges through geochemical data from oceanic core complexes. Dong et al. (2021) used tectonic segmentation and fault analysis to identify new vent sites. Structural control on hydrothermal circulation is further emphasized in the work of Fan (2021), who modelled thermal structure changes driven by faulting and magmatism. The role of detachment faults and non-transform discontinuities in directing hydrothermal flow and deposit formation is documented across numerous studies, including those by Chen et al. (2021, 2023 a,b).

Other studies researched the genesis and maintenance of hydrothermal systems through fluid dynamics, thermal modelling and magmatic interactions. Guo et al. (2020) developed a thermo-hydro-chemical model that explains how anhydrite sealing preserves high-temperature venting. Chen et al. (2021, 2023a-c) offer deep insights into crustal accretion, fault evolution and hydrothermal flow based on data from SWIR. They challenge traditional assumptions about spreading rate and melt supply, contributing fundamentally to mid-ocean ridge geodynamics. Hazra et al. (2021) demonstrated mantle refertilization from boninitic melts, suggesting geodynamic transitions in the Central Indian Ridge mantle.

Finally, technological advancements related to PMS exploration have also been examined. Remote sensing and mapping advances are demonstrated by the development of multi-resolution sonar and autonomous underwater vehicle-based self-potential techniques (Zhu et al., 2020; Zhu et al., 2023; Zhu et al. 2023; Wang et al., 2022). Multibeam and side-scan sonar classification strategies developed for complex hydrothermal terrains are also key contributions to environmentally sound and precise seafloor mapping. Hu et al. (2022) investigated microbial mediation and metal immobilization during sulphide oxidation, providing evidence for natural mitigation of mining impacts.

3.2.3. Cobalt-rich ferromanganese crusts

The CFC are among the least studied deep-seabed commodities in international waters, compared with PMN and PMS. They occur at depths of about 400 to 5,000 m on hard-rock substrates of volcanic origin, such as seamounts, ridges and plateaus, through the slow precipitation of metals dissolved in seawater.

3.2.3.1. Regional distribution

Figure 5 shows that 60 per cent of the studies from the database focus on the South Atlantic, specifically at and around the Rio Grande Rise. During the 2020-2023 period, the Companhia de Pesquisa de Recursos Minerais (Brazil) remained one of the five contractors holding an active exploration contract for CFC, in place since 2015. The remaining 40 per cent of the studies were conducted in the Northwest and West Pacific Ocean, where four exploration contracts are in place.

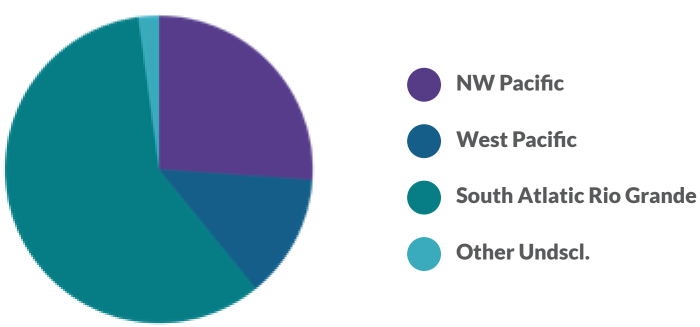


Figure 5. Regional distribution of CFC publications (percentage)

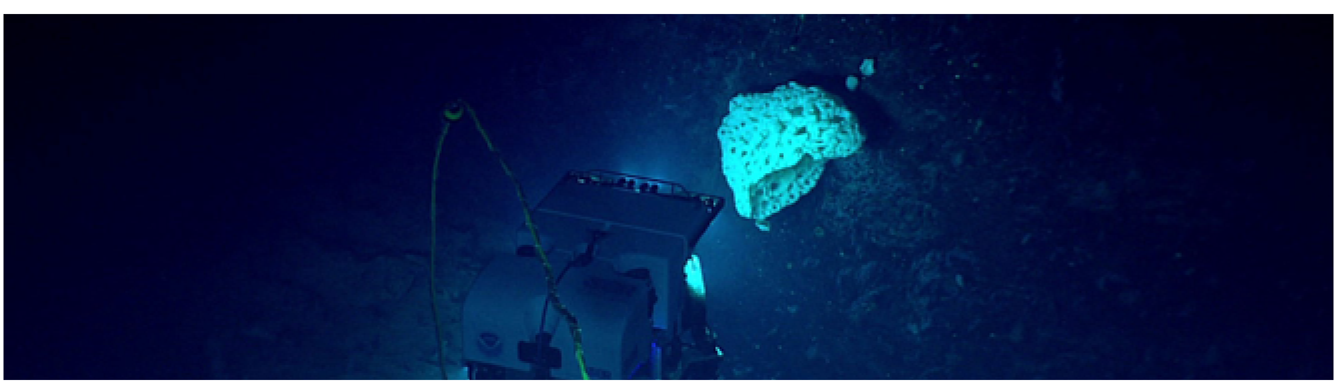
3.2.3.2. Research disciplines

The 27 CFC studies were classified into the following research disciplines: geochemistry, geology (mineralogy and structural geology), and resource assessment (Table 1).

Studies of tectonics, geological history, magmatism, and volcanism in regions such as the Rio Grande Rise are inherently linked to the formation of seamounts and, subsequently, to the development of ferromanganese crusts. For example, Darros de Matos et al. (2021) analysed the track of South Atlantic hotspots on oceanic crust, presenting new evidence for continental migration paths during the South Atlantic break-up. Estep (2020, 2021) focused on oceanic crust formation, spreading rates and crustal thickness in the South Atlantic. In a different setting, (Joo, et al., 2020) employed sedimentological data from deep-towed camera imagery in the Western Pacific Ocean to investigate the thickness of CFCs. Sager et al. (2021) analysed the tectonic evolution of the geological setting of the Rio Grande Rise. Several authors have studied the composition of basalt rocks from this region to determine the ages of seamounts and get insights into mantle plume evolution (Hoyer, 2022; Peretyazhko, 2023; Yamaoka, 2022).

Two studies conducted in the South Atlantic Ocean investigated the mineralogical and geochemical characteristics of Fe-Mn crust distribution at the seamounts (Benites, Hein, Mizell, Blackburn, & Jovane, 2020) and (Benites, et al., 2022). Benites 2021 also analysed phosphatization, a diagenetic process in which phosphate minerals are introduced or replace parts of the crust that can serve as a substrate for crust formation. At both the Rio Grande Rise and the Northwest Pacific, the chemical composition of CFCs and the parameters controlling their compositional variability were investigated, shedding light on their formation (Hino & Usui, 2022, 2023; Sousa et al., 2021). The contribution of Usui (2020) involved the first successful, long-term, on-site experiment on mineral precipitation, advancing our understanding of CFC precipitation and crust-forming mechanisms.

The spatial distribution of CFCs has also been a focus of several studies using underwater technology such as multibeam bathymetry, backscatter and data analytics (Joo et al., 2020; Neettiyath et al., 2022, 2023; Yang et al., 2020). Additionally, volumetric assessments of deposits in the Western Pacific Ocean were conducted through mineralogical analysis of ferromanganese crust (Gaowen, Yong, Zhenquan, & others, 2021). Ota (2022) compared sedimentation rates and bioturbation activity between seamount summits - where CFCs commonly occur - and the adjacent abyssal plain in the Northwestern Pacific, highlighting environmental control on crust development. An emerging topic in resource research was addressed by Schier (2021), who analysed the content of gallium and aluminium in CFCs, two critical metals in the European Union (EU) and the USA. The study suggested that these crusts may represent a potential future unconventional resource of critical metals.



3.2.4. Geochemistry across all resource types

As an example of a cross-cutting geological topic spanning all three mineral resource types, a subset of geochemistry publications was compiled, yielding 46 relevant publications.

Analysis of geochemical publications shows that most studies focus on PMS, hydrothermal vents and associated mineral deposits, primarily along the SWIR and the Central Indian Ridge (18 publications). This trend reflects advanced and intensified exploration along this mid-ocean ridge, which, until recently, has been less studied than the MAR and the East Pacific Rise. As no exploration contracts have been granted by the ISA along the East Pacific Rise, only two papers were reported from that area. At the same time, six PMS-related publications originate from the MAR.

Several of these geochemical studies contribute significantly to our understanding of fundamental ocean geodynamics in relation to PMS. Studies link mantle geochemistry to marine tectonic history, ocean basin development, magmatic processes, volcanism and crust formation over geological time at mid-ocean ridges (Li et al., 2020; Hazra et al., 2021; Peretyazhko et al., 2023; Verencar et al., 2024). Spatial variations in basalt geochemistry were investigated to understand the unique magmatic systems of ultraslow-spreading ridges, shedding light on mantle processes in these geodynamic settings (Zha et al., 2021). Furthermore, geochemical analyses of mid-ocean ridge basalts from the SWIR have provided insights into the interplay between mantle heterogeneity and seafloor spreading processes (Wang et al., 2021). Refined research on the formation of large igneous provinces demonstrates the complexity and interplay between volcanism and tectonism that go beyond simplified hotspot models (Sager et al., 2021).

Kuksa et al. (2021) investigated the geochemical composition of metalliferous sediments from the Pobeda hydrothermal cluster, providing insight into the mineralization processes associated with active hydrothermal systems. Building on this, Kuksa et al. (2023) analysed sediment cores to examine the temporal evolution of hydrothermal activity, providing a reconstruction of past conditions and processes that have influenced the development of the hydrothermal system.

The majority of geochemistry publications focus on hydrothermal vent systems. PMS-related studies generally require sophisticated and adaptable analytical techniques, owing to factors such as limited sample availability, the large variability in mineralization across hydrothermal vents and the varying grades of metals and other minerals that can serve as diagnostic indicators of the geological evolution of hydrothermal systems. In relation to the hydrothermal systems in the SWIR, Cao et al. (2021) and Choi et al. (2021) reported on newly discovered active hydrothermal vent fields, including detailed analyses of the mineralogy and geochemistry of sulphide samples from the surface of chimneys. Surya Prakash et al. (2022) examined the chemical exchanges between hydrothermal fluids and the oceanic crust, highlighting how these interactions shape the geochemical signatures of hydrothermal plumes.

Whereas Kim et al. (2020) investigated the geochemical composition and processes of hydrothermal vent fluids, Prakash et al. (2022) emphasized their role in shaping microbial ecosystems and the cycling of bioactive elements in the marine environment. Yang (2023) explored the potential sequestration of hydrothermal metals (iron, manganese) in marine sediments, with important implications for elemental cycling and long-term geochemical storage in the deep sea.

Six geochemical studies of PMN from the CCZ are available. Kim et al. (2022) focused on the distribution and concentration of REE and yttrium in sediments of the CCZ. Understanding the natural occurrence of these elements enables the identification of geochemical hotspots. Skowronek et al. (2021) examined the chemical and mineralogical processes involved in the formation and growth of PMN, yielding estimates of PMN growth rates.

Complementing this, Yang et al. (2024) investigated the geochemistry of buried PMN, offering further insights into their formation mechanisms. Additionally, Zawadzki et al. (2020) identified patterns of metal accumulation in pelagic sediments from abyssal plains, suggesting high-potential zones for PMN occurrence.

In summary, geochemical papers advance the comprehensive understanding of deep-sea geochemistry, covering aspects like the formation and composition of mineral deposits, the influence of hydrothermal vent processes in metal distribution both in the seabed and the water column, the role of microbial communities in metal cycling and the impact of tectonic and volcanic activities on the marine environment. Most studies focus on the geochemical investigation of mineral deposits, but some use geochemical and hydrochemical proxies to infer faunal dispersal and connectivity across ocean regions.

3.3. Biology

Biological deep-sea research is vital to increasing the understanding of deep-sea ecosystems. In this context, the Legal and Technical Commission's Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area includes a range of biological parameters, such as the characterization of various benthic and pelagic habitats and communities, regional distribution of species, genetic analyses and food web analyses. Establishing a robust, statistically sound baseline is required to evaluate and predict the potential effects of future deep-seabed mining on the seafloor ecosystem and the water column (Christiansen et al., 2022).

Figure 6 shows that 190 papers have a biological focus, of which 148 were further surveyed. Overall, most of the biological studies focused on PMN settings (42 per cent), followed by PMS (31 per cent) and CFC (11 per cent). One study covered REE in sediments.

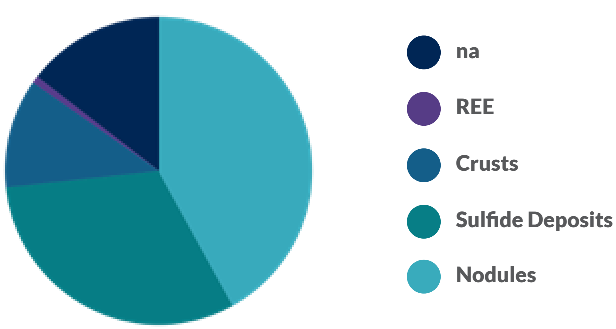


Figure 6. Percentage of biological publications by type of mineral

3.3.1. Regional distribution

Figure 7 shows that research efforts are concentrated in a few areas across ocean regions. The Pacific Ocean, particularly the CCZ, where the first exploration contracts were granted over 20 years ago, is by far the most studied region, as evidenced in approximately 70 publications. The Indian Ocean, notably the ridge systems targeted for PMS exploration, is the next major focus area with around 32 publications. The MAR comes third, with approximately 23 publications, reflecting interest in Atlantic hydrothermal vent sites and crusts, including studies around the Brazilian continental margin.

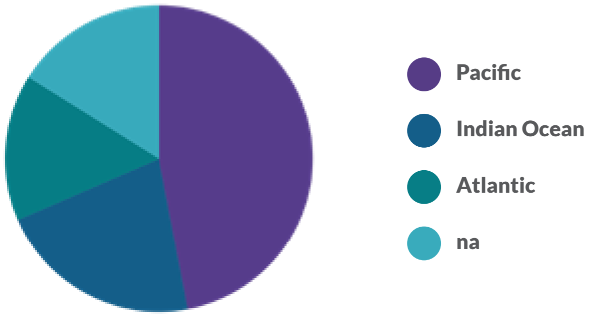


Figure 7. Percentage of biological publications by geographic area

3.3.2. Representation of faunal groups

The CCZ nodule fields located on the seafloor in the Pacific, the world's largest area targeted for exploration encompassing approximately 6 million km2, harbour an estimated 5,000+ benthic metazoan animal species, of which approximately 92 per cent are new to science and undescribed. Species richness models predict 6,000-8,000+ metazoan species in the CCZ alone (Rabone et al., 2023). In contrast, PMS deposits associated with hydrothermal vent fields, typically characterized by low biodiversity and high biomass, support biota adapted to extreme conditions and cobalt-crust seamounts host predominantly coral and sponge communities.

Figure 8 illustrates the distribution of 148 analysed papers, with most studies focusing on the benthos (mainly benthic invertebrates associated with the seafloor; 33 per cent), followed by megafauna (21 per cent) and macrofauna (21 per cent).

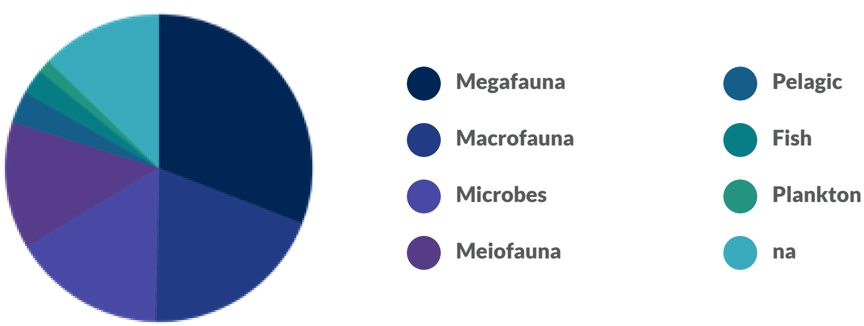


Figure 8. Representation of ecological groups in biological publications

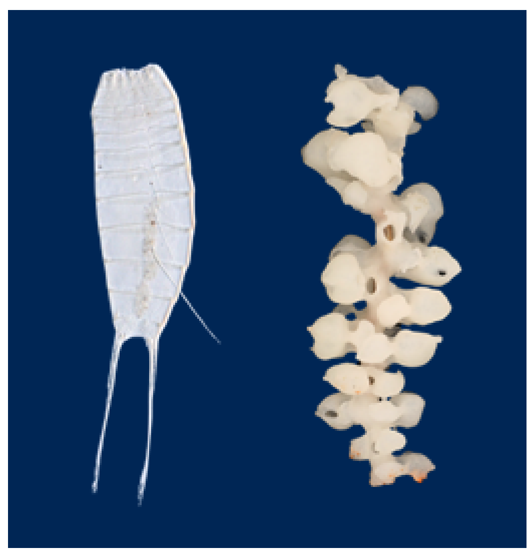
Figure 9 shows that meiofauna is the least studied of all benthic faunal groups (14 per cent). Similarly, microbial communities represent 14 per cent of all biological publications. By contrast, only a handful of papers (less than 4 per cent) studied fish or midwater fauna. This focus aligns with both practical implications and ecological importance. Benthic invertebrates are extremely diverse and numerically dominant in all ecosystems targeted for mining. Microbial communities present another key focus due to their functional importance. Recent studies go beyond cataloguing microbes by analysing their roles in element cycling or as symbionts. This taxonomic skew in faunal groups indicates that most research efforts are going into the analysis of sediment-dwelling invertebrates.

Figure 9. Percentage of species new to science by geographic area

3.3.3. Species new to science

In terms of discoveries of previously undescribed species, every major taxon has yielded up to 48 new species. Annelid worms currently top the list, as 24 new annelid species were reported in PMN studies. Crustaceans (Arthropoda) also contribute strongly, with numerous new isopods and amphipods described from both CFC seamounts and Indian Ocean vent areas. Even lesser-studied groups, such as Hydrozoa (Corallia) and Nematoda, had notable numbers of species new to science in some Indian Ocean vent and CCZ samples. Overall, the ongoing discovery of new taxa, from microbes to megafauna, highlights the biological diversity of these mineral-rich ecosystems.

Figure 9 shows that most of the taxonomic research with new species descriptions included in our survey comes from the CCZ (44 per cent), followed by the Indian Ocean ridge systems (35 per cent). By contrast, the Northwest Pacific seamount province accounts for only 13 per cent of new descriptions and the MAR for only 8 per cent. These proportions likely reflect sampling intensity rather than true biodiversity: the CCZ and Indian Ocean hold most exploration contracts and have also hosted a succession of EU- and contractor-funded research cruises that have returned large sample collections, now being processed by taxonomists. In the Atlantic and Pacific seamount belts, fewer biological expeditions, limited time on remotely operated vehicles, and scant funding for integrative taxonomy mean that vast assemblages remain understudied.



3.3.4. Research themes and key topics

Figure 10 shows that the body of literature covers a range of research themes, which can be grouped into several major categories.

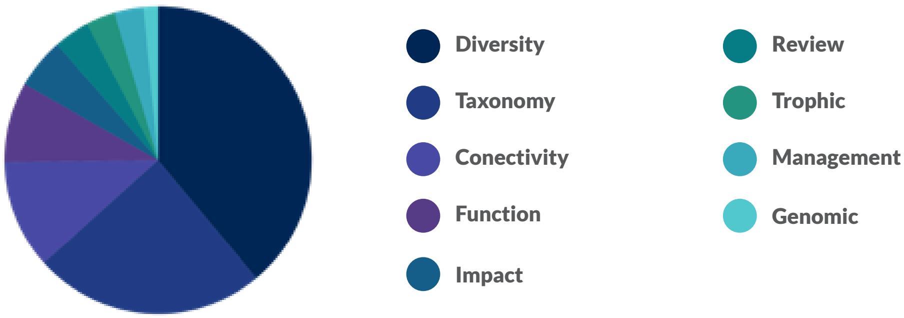


Figure 10. Percentage of biological topics covered

3.3.4.1. Diversity and taxonomy

A substantial portion of studies (61 per cent) provide fundamental biodiversity assessments of deep-sea exploration areas. These include species inventories and community composition, as well as taxonomic analyses. For example, multiple papers inventoried the invertebrate mega-, macro- and meiofauna in PMN fields or PMS active and inactive vent sites, often revealing high numbers of previously undescribed species. These baseline studies enable a description of biodiversity in targeted regions, from microbes to metazoa and often highlight future research priorities, such as the ecological roles of species. A significant taxonomic effort is made across many different taxa and size categories (24 per cent of all biological studies).

In PMN regions, such as the CCZ, fine-scale surveys have revealed hundreds of morphospecies, many of which were previously unknown. For instance, Bonifácio et al. (2020) identified 275 worm morphospecies in samples from the CCZ region, nearly 50 per cent being singletons and only one species shared across multiple contract areas, pointing potentially to species which may be widespread but have an infrequent distribution, low connectivity and/or the results are e a result of under sampling across the analysed regions for those particular species. Similarly, Bitner and Molodtsova (2020) documented five terebratulide brachiopod species on the MAR, expanding the known distribution ranges of deep-sea taxa and highlighting gaps in current records.

Microbial communities are increasingly studied, with several papers highlighting novel lineages and spatially structured assemblages. Barnes et al. (2021) found previously undescribed bacterial and fungal taxa in nodules and sediments from the Central Indian Ocean Basin, while Bergo et al. (2022) reported distinctive microbial signatures on Atlantic seamounts, indicating biogeographic differentiation even at the microbial level.

However, a lack of taxonomic specialists, limited funding for specimen processing and logistical barriers to data-sharing continue to constrain progress. Nonetheless, the analysed body of work supports the view that targeted regions represent biodiversity frontiers and that robust taxonomic baselines are indispensable for assessing species vulnerability and supporting spatial planning under the ISA framework (Barnes et al., 2021; Bonifácio et al., 2020; Bergo et al., 2022).

3.3.4.2. Species connectivity

About 10 per cent of the studies address which species are distributed and connected across deep-sea provinces. This research theme yields insight into metapopulation dynamics, informing how large a conservation area needs to be to maintain and protect species ranges and whether the proposed no-mining zones, so-called areas of particular environmental interest (APEIs), adequately encompass the prevailing diversity. As such, understanding species connectivity is crucial for designing effective spatial management and conservation frameworks in the Area.

Several recent studies use molecular tools to assess genetic structure and dispersal patterns in deep-sea species. Bribiesca-Contreras et al. (2021) conducted a multi-taxon population genetic analysis in the CCZ, identifying over 30 genetic lineages across amphipod species. Importantly, the study found limited overlap in lineages between APEIs and proximate contract areas, suggesting that further studies are needed to confirm that APEIs represent the full range of regional diversity. Jang et al. (2023) investigated the hydrothermal vent snail Alviniconcha along the Indian Ridge and revealed a pronounced north-south genetic break near the Onnuri vent field. This suggests population subdivision along the ridge system and potential barriers to larval dispersal. Similarly, Kaiser et al. (2021) used molecular operational taxonomic units to delineate species boundaries in CCZ isopods of the genus Nannoniscus, identifying up to 12 cryptic lineages and limited distribution overlap, highlighting the complexity of species distributions even in morphologically similar groups. Other studies report connectivity across broader ocean basins. For example, Chan et al. (2020) documented the occurrence of the barnacle Eochionelasmus ohtai in both the Indian and Pacific Oceans, suggesting the possibility of long-distance larval dispersal.

Collectively, these studies underline the need to integrate genetic data into environmental management and show that connectivity cannot be assumed, even within continuous habitats. They also stress the importance of replicating sampling across APEIs and contractor areas to detect dispersal barriers and ensure representativeness in the design of protected zones.

3.3.4.3. Community functioning

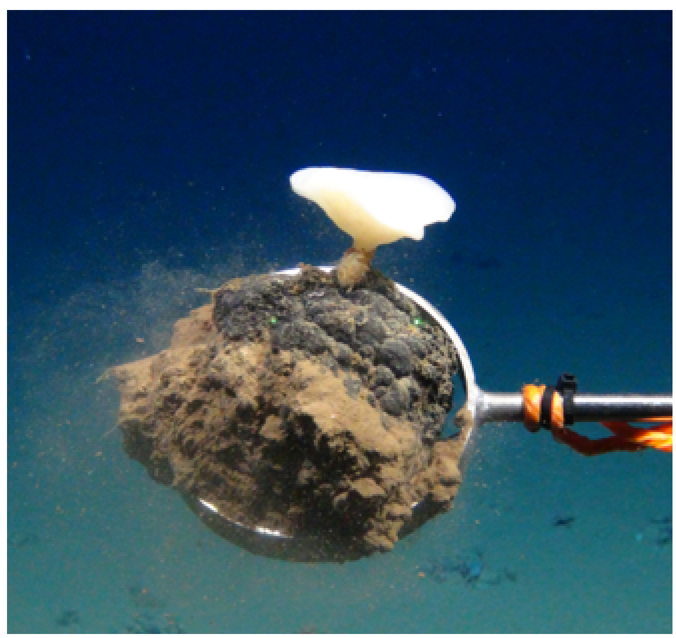
A subset of studies (9 per cent) delves into functional roles of communities or ecosystems, particularly those driven by microbial communities. Several papers investigate microbes in sediments, nodules, or hydrothermal deposits, uncovering novel metabolic pathways. These works move beyond species cataloguing to examine roles in biogeochemical cycles, symbiosis and ecosystem functioning. Some studies also explore species interactions. Overall, ecological studies contribute to understanding how deep-sea communities function and how resilient they might be to disturbance.

A few examples include Adam-Beyer et al. (2023), who conducted a comprehensive assessment of microbial communities in hydrothermal vent sediments of the Central Indian Ridge. Their findings highlight the prevalence of chemolithoautotrophic bacteria, such as Hydrogenovibrio and Sulfurimonas, which oxidize hydrogen and sulphur, critical processes in energy-limited deep-sea environments. Similarly, Wang et al. (2022) used metagenomics to characterize sulphur-oxidizing bacteria in sulphide deposits of the SWIR, revealing novel lineages and dominant taxa involved in sulphur cycling.

At the organism level, Aubé et al. (2022) reported a dual symbiotic relationship in the hydrothermal gastropod Ifremeria nautilei, where two coexisting microbial symbionts contribute to host nutrition through sulphur-based metabolism. This holobiont structure exemplifies the intricate dependencies between fauna and microbial function in vent ecosystems. Functional assessments are not limited to hydrothermal settings. Bergo et al. (2022) showed that microbial communities associated with crust and nodule substrates on Atlantic seamounts display distinct compositions, likely driven by local geochemistry, which, in turn, shape functional potential for N, S and C cycling.

3.3.4.4. Impact assessment

Evaluating potential mining impacts is the research priority addressed in 7 per cent of the studies analysed. Several studies simulate or observe disturbance effects, such as a seamount mining test, which observed ecological impacts beyond the immediate sediment plume footprint. For example, Fukushima et al. (2022) synthesized over 25 years of seafloor disturbance observations, revealing that mining effects can extend beyond the immediate footprint of activity, especially from sediment plumes and physical substrate removal. Additional research on sediment plume dispersion and deposition has informed models of impact distance and sensor-based fieldwork has refined our understanding of plume dynamics. For example, Haalboom et al. (2022) demonstrated the utility of real-time plume monitoring for environmental impact assessments, though challenges remain in linking physical plume data to biological outcomes. Additionally, based on monitoring mining tests conducted in PMN fields, Munos-Royo et al. (2022) found that the plume initially behaves like a turbidity current and remains close to the seafloor, with the heaviest deposition in the direct vicinity of the collector.



Impact studies find that mining activities, including even small-scale tests, can cause measurable changes in community structure and that recovery, depending on the resource type, may be slow and incomplete, reinforcing the need for robust environmental management. These efforts are central to understanding mining-induced change and informing monitoring and mitigation strategies.

From a design perspective, Hao et al. (2020) evaluated benthic similarity, current direction and preservation in reference zones in the CCZ, identifying discrepancies. In addition to macrofauna, several authors emphasize the importance of microbial and meiofaunal indicators. Ingels et al. (2021) argued that microbial processes and sediment-dwelling meiofauna

should be central to ecological monitoring protocols due to their sensitivity and roles in ecosystem function. These studies highlight the need for multi-scale, taxonomically inclusive monitoring and for robust baselines against which impact and recovery can be meaningfully assessed.

3.3.4.5. Trophic studies

Only a fraction of the studies (3 per cent) investigated food web structure and trophic interactions between different components of the communities present. Nevertheless, emerging work provides important insights into chemosynthetic pathways, dietary specialization and potential trophic disruptions linked to mining activities. Recent research has focused on hydrothermal vent communities, where symbiotic associations between fauna and microbes underpin primary production. Suh et al. (2022; 2023) applied stable isotope and amino acid analyses to characterize trophic diversity at the Tiancheng vent field on the SWIR. Their results reveal distinct carbon-sourcing strategies among species, ranging from methanotrophy and thiotrophy to mixed feeding modes, highlighting the ecological specialization of vent-associated organisms. However, Washburn et al. (2023) documented early evidence of food web alteration following a seamount mining simulation, based on experimental data. Changes in faunal composition and abundance in response to sediment plume exposure were interpreted as indirect effects on resource availability and habitat quality. In summary, greater integration of trophic metrics into environmental baseline and monitoring will facilitate the prediction and management of mining-related ecosystem impacts.

3.3.4.6. Environmental management

Regulatory processes within the ISA framework are increasingly inspiring scientific inquiry aimed at strengthening the science-policy interface. Two per cent of the papers explicitly address how to manage and protect biodiversity in the context of mining interests, particularly at the intersection with regulatory aspects. The emphasis here is on ensuring that scientific knowledge translates into informed spatial management, such as buffer zones, reference sites and no-mining areas, to reinforce the science-policy interface under the ISA framework. These works are especially relevant in the context of spatial planning under the ISA and contribute to the design of regional environmental management plans, reference zones and conservation frameworks. For example, Christodoulou et al. (2020) found significant faunal turnover across exploration contracts, indicating that biological heterogeneity must be accounted for in management plans. Drazen et al. (2021) reached similar conclusions for seamount communities. Research is also advancing on ecological thresholds (Hitchin et al., 2023), further informing regulatory development on this topic. Together, these studies argue for adaptive, data-driven management strategies that reflect real biodiversity patterns and ecosystem processes.

3.3.4.7. Overall review

A small number of studies synthesize the broader biological knowledge base for deep-sea environments. These reviews are critical for identifying future research priorities and aligning research outputs with policy frameworks, thus reinforcing the science-policy interface. For example, Amon et al. (2022) and Rabone et al. (2023) reviewed the availability of scientific data and biological data infrastructure, respectively. Amon et al. highlighted the need for better international coordination in research, while Rabone et al. (2023) identified opportunities for ISA's DeepData database and recommended alignment with international biodiversity databases. In parallel, targeted taxon-specific reviews such as Zbinden & Cambon-Bonavita (2020) on Rimicaris exoculata help consolidate scattered knowledge and highlight key model organisms for future monitoring. These review efforts provide essential strategic guidance for research prioritization, data standardization and the integration of biological knowledge into governance frameworks.

3.4. Oceanography

Oceanography is the interdisciplinary scientific study of the ocean and its processes, encompassing the physical, chemical, biological and geological characteristics of the marine environment. It investigates the dynamics of ocean currents, waves and tides, the composition and chemistry of seawater, marine organisms and ecosystems and the structure and evolution of the seafloor (Talley, Goodwin, Ruzic, & Fisler, 2011).

3.4.1. Geographic distribution

Figure 11 shows 33 scientific papers selected for further analysis based on a keyword assessment aligned with the above definitions. The majority of the selected research papers take a broader, global or multi-regional perspective. In contrast, seven papers focus on the CCZ, six on the South Atlantic, five on the Northwestern Pacific and three on the Indian Ocean.

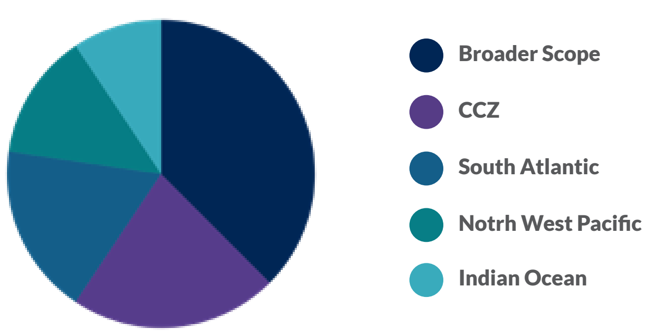


Figure 11. Geographic distribution of the oceanography publications

3.4.2. Research disciplines

Figure 12 shows 33 scientific papers classified into six research disciplines: modelling, ocean currents and geology, physical oceanography, chemical oceanography, links to deep-sea mining and impacts and oceanography and biology.

Approximately 25 per cent of publications focus on the interaction between oceanographic processes and deep-sea ecosystems, making this the most prominent theme. The second most dominant category addresses the links between oceanography, deep-sea mining and its potential impacts. Both chemical and physical oceanography account for 17 per cent of the reviewed publications, while modelling represents the remaining 11 per cent.

The oceanographic papers integrate empirical data, such as current measurements and conductivity, temperature and depth profiles, with modelling approaches. The data primarily covers the deeper layers of the ocean, mostly through the integration of artificial intelligence applications (Chen, et al., 2022). Other studies, such as Morozov & Frey (2021), (Wang, Hu, Feng, Ji, & Jia, 2022), contribute valuable time series observations to track long-term deep-sea dynamics.

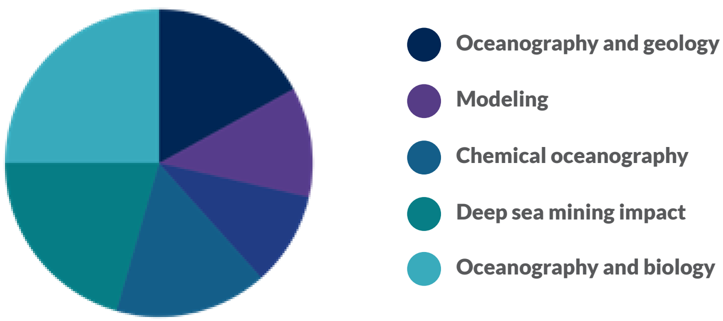
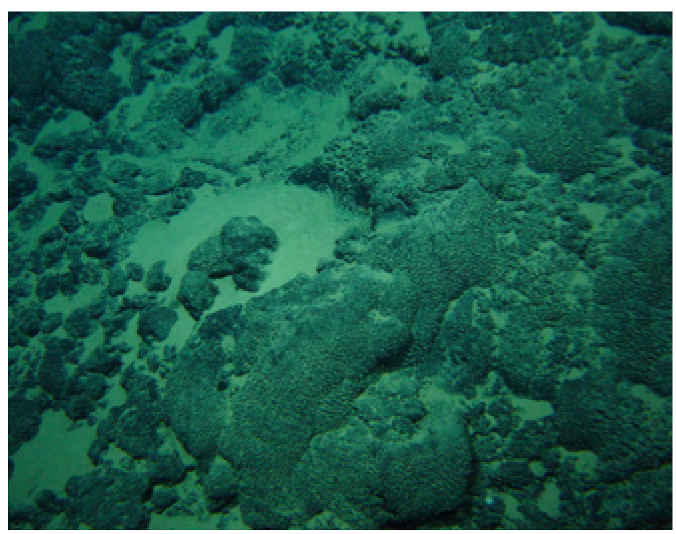


Figure 12. Percentage of oceanographic publications across research disciplines

3.4.2.1. Oceanography and geology

A few studies addressed how ocean currents interact with geological activities. For example, Levchenko et al. (2020) examined how slow-moving ocean currents that follow the shape of the ocean floor, contour bottom currents and influence geological features, such as contourite sedimentary systems. These are layers of sediment (mud, sand, or silt) transported and deposited by contour currents, which, over time, can form distinctive geological formations on the seafloor, such as drifts, mounds or moats. Furthermore, (Ivanova, Borisov, Murdmaa, Ovsepyan, & Stow, 2022) investigate the impact of oceanic currents, such as Antarctic Bottom Water, on geological processes, such as

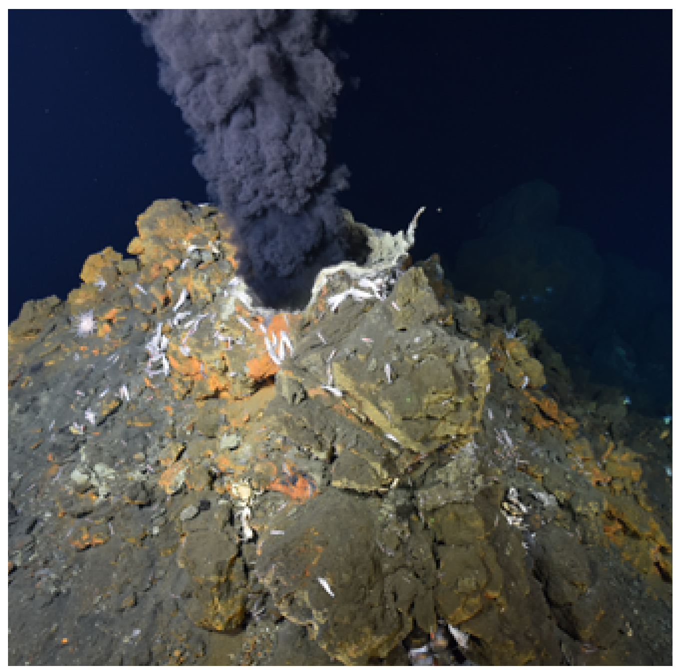


drifts and erosion, that lead to the accumulation of biogenic calcareous sediments. Finally, Dutkiewicz & Dietmar (2021) analysed fluctuations in the carbonate compensation depth over geological time to gain insights into the global carbon cycle. In the same domain, Simon-Lledó et al. (2023) examined variability in carbonate compensation depth across the CCZ and highlighted its implications for biogeographic zoning.

3.4.2.2. Physical oceanography

Xie et al. (2023) studied the evolution of near-inertial waves, a type of internal wave influenced by Earth's rotation, collected at a flat-topped seamount in the Western Pacific. They specifically investigated the mechanisms by which energy is transferred from large-scale flows to smaller-scale inertial waves in the deep ocean. Understanding this energy transfer is crucial for accurately parameterizing mixing processes in global ocean circulation models, which have implications for climate modelling. Another study investigated topographically trapped waves, a type of ocean wave that forms due to interactions between ocean currents and underwater features such as slopes and ridges, demonstrating their role in influencing the speed, direction and pattern of the deep circulation at low-latitude seamounts (Guo et al., 2024). Morozov & Frey (2021) and Morozov et al. (2022) analysed time series of conductivity, temperature, salinity and velocity profiler data across the Vema Channel in the South Atlantic, spanning the entire water column, to study abyssal circulation and bottom flows. These studies help scientists characterize the respective water bodies.

3.4.2.3. Chemical oceanography



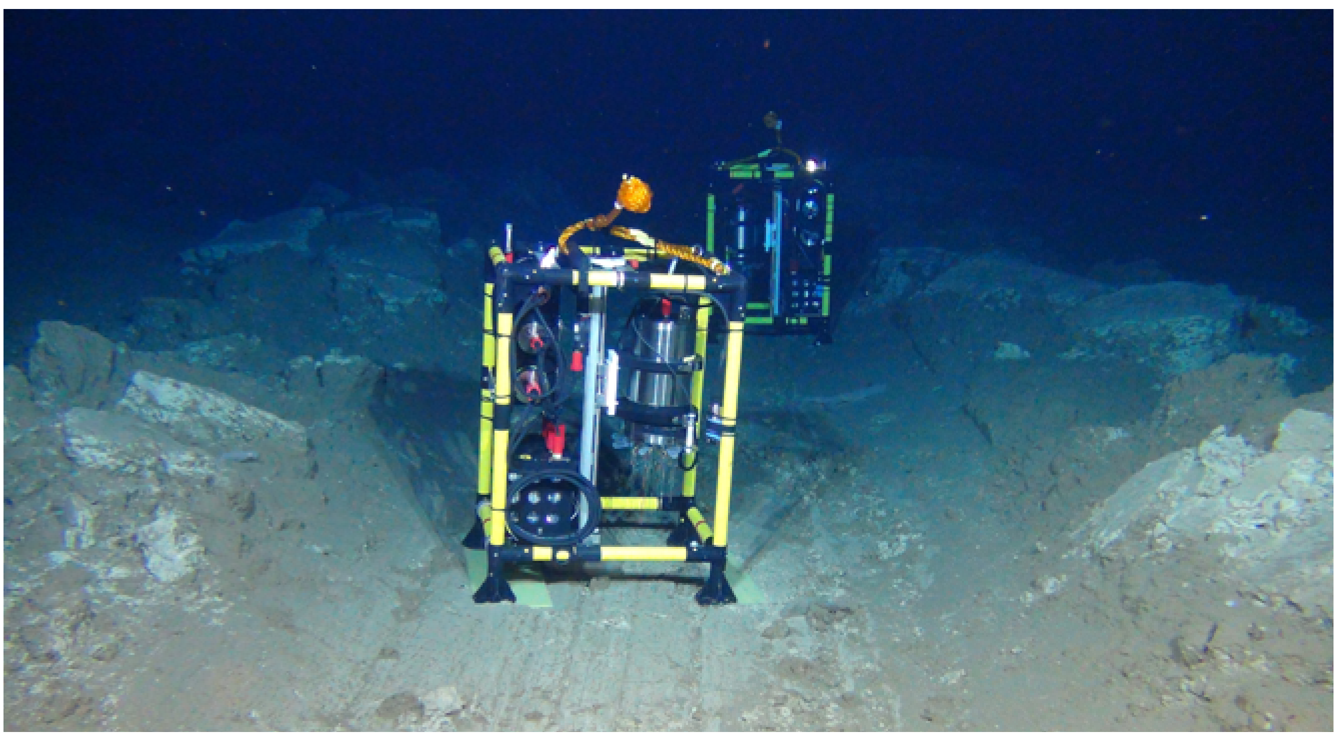
Studies in chemical oceanography have advanced our understanding of hydrothermal activity, particle dynamics and trace-metal analysis in the deep ocean. For example, Prakash et al. (2022) characterized hydrothermal plumes over the Southern Central Indian Ridge to identify and chemically characterize the seafloor. Zhao et al. (2023) found hydrothermal activity and a new hydrothermal vent field in the Southern Central Indian Ridge. The findings of Yang et al. (2021) demonstrate how hydrothermal activity may influence metal distribution in the deep ocean on a broad spatial scale, based on observations from a newly discovered hydrothermal plume in the SWIR. Several authors focused on particle mixing. Kim et al. (2021b) analysed 1 year of sediment-trap data collected 50 metres above the seabed and demonstrated that biogenic particles from export production were the primary source of sinking material. Ota et al. (2021) investigated sediment accumulation and particle mixing on three guyots in the Northwest Pacific, using various parameters, including oceanographic data on particulate organic matter and dissolved oxygen in the water column, to assess their influence on biologically driven particle mixing. Finally, Saito et al. (2023) developed a suspended particle detection model based on deep learning. They trained the model on one month of image data from a deep-sea seamount in the Northwest Pacific Ocean.

This approach enables simulations of temporal variability in suspended particles from naturally occurring fluctuations to abrupt changes, such as those caused by mining impacts, without the need to go offshore for sampling. One author validated a new in situ methodology for analysing trace metals in deep-ocean waters (Schmidt et al., 2022).

3.4.2.4. Links to deep-sea mining and impacts

A growing body of research is directly linking oceanographic processes to deep-sea mining activities, highlighting plume dynamics, environmental impacts and operational considerations. For example, studies investigating the oceanic bottom mixed layer, the lowest part of the ocean water column, found that it plays a key role in dispersing sediment plumes from deep-sea mining. In that context, oceanographic data on the bottom mixed layer are critical to ensure accurate numerical modelling of plume dispersal (S.-Y.S. Chen et al., 2023). Zhao et al. (2023) compared two turbulence models simulating hydrothermal plumes against observational data. This study not only enhances predictive modelling but also helps assess the environmental impact of hydrothermal activity and potential deep-sea mining operations by predicting the dispersion of heat and chemicals. Other authors focused on plumes resulting from mining equipment and dewatering from the production vessel. For example, Haalboom et al. (2022) conducted an in situ disturbance experiment to analyse sediment plume dispersal, using current profilers to provide qualitative insights into the plume's vertical extent. Muñoz-Royo et al. (2021) carried out a field study to model the midwater plume, employing both established and novel instrumentation, including turbulence measurements. Finally, Baeye et al. (2022) presented results from an in situ mechanical disturbance experiment, finding that the dispersion of a deep-sea sediment plume was primarily driven by tidal dynamics.

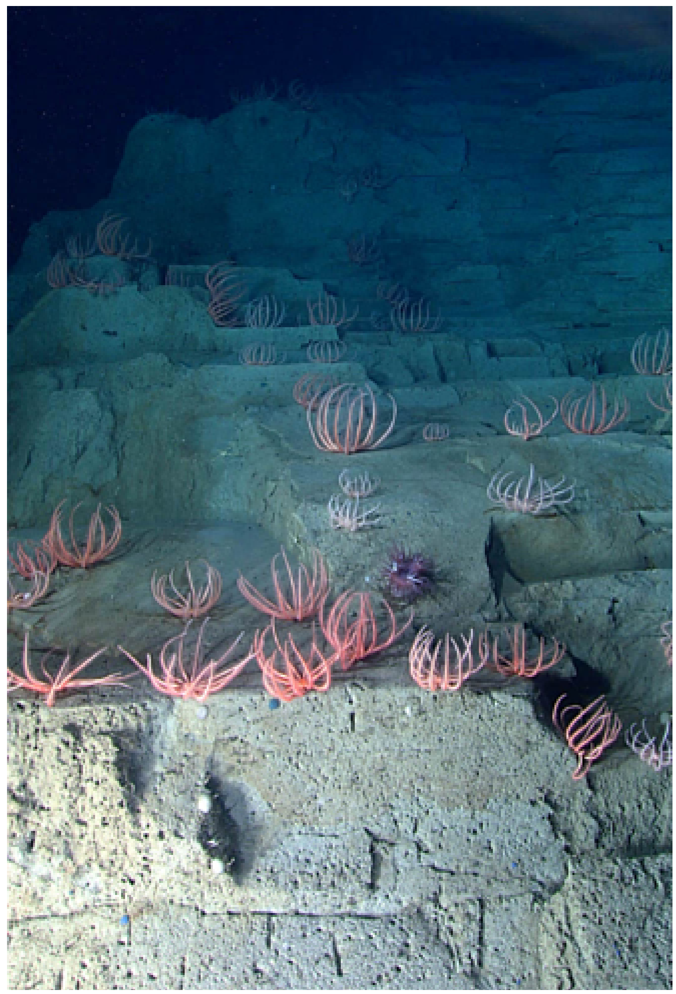
Other authors focus on various aspects of the interaction between oceanographic processes and potential mining impacts. Purkiani et al. (2020) found that current intensification from bottom-reaching eddies was insufficient to trigger sediment resuspension, based on their analysis of the relationship between deep-



sea current variability and the annual variability of ocean surface eddies in a potential future mining region of the CCZ. Furthermore, it was found that the passage of cyclonic and anticyclonic eddies correlates with changes in the vertical structure of micronekton in the Eastern Pacific Ocean (Perelman et al., 2023). This is important because it helps anticipate how these communities will respond to anthropogenic activities, including deep-sea mining. Purkiani et al. (2022) studied eddy-induced seawater anomalies and heat/salt transport, concluding that understanding the dynamics of long-lived eddies that reach the seafloor is also vital for deep-sea mining.

Finally, two studies specifically examined the influence of oceanographic conditions on mining operations. Amudha et al. (2024) investigated the critical suction height parameters required for efficient hydraulic nodule collection through experimental trials. Rong-Yao et al. (2021) analysed the impact of wave dynamics on the deployment of the buffer-retrieve system, with a focus on operational safety.

3.4.2.5 Oceanography and biology



Studies at the intersection of oceanography and biology reveal how physical processes shape deep-sea ecosystems, from microbial communities to megafauna. Building on this, He et al. (2023) demonstrated that the spatial distribution of diverse vent-endemic fauna is strongly governed by vent plume hydrodynamics using a numerical model coupling plume flow with induced matter and energy transport to highlight the physical-biological interactions at hydrothermal vents. Similarly, Corrêa et al. (2022) showed that megafaunal communities were delimited by the transition between two distinct ocean water masses, suggesting hydrographic boundaries influence deep-sea biodiversity. Ferreira et al. (2022) assessed the pelagic microbiome across the entire water column, providing insight into microbial diversity and stratification across oceanic layers. Kim et al. (2021a) studied the biological carbon pump by analysing particulate matter flux at a depth of 4,500 metres in the North Pacific Subtropical Gyre over one year. Their findings underscored the key role of diatom blooms in driving carbon export to the deep sea. Lee et al. (2020) used fossil foraminifera from the MAR to reconstruct past ocean surface conditions, including temperature and salinity, thereby contributing to palaeoceanographic understanding. Simon-Lledó et al. (2023) found that geochemical and climatic forcing influence the distribution of abyssal populations over large spatial scales, highlighting environmental drivers of deep-sea biodiversity patterns. Wear et al. (2021) characterized the bacterial and archaeal biodiversity in the CCZ and identified bottom seawater as a distinct deep-sea habitat with different microbial communities.

3.5. Engineering

Engineering is an inherent component of deep-sea mineral exploration and exploitation, particularly given the remote locations and extreme environmental conditions under which operations must be conducted. The engineering dimensions of deep-sea mining have been previously examined. Kleiv and Thornhill (2022) reviewed a data set of 1,935 journal publications spanning 1968 to 2021. Their analysis revealed that approximately half of the publications focused on environmental aspects, while engineering-related topics, especially vertical transport systems, accounted for about one-third.

For the engineering section, 56 were selected for in-depth analysis based on the journals in which they appeared. Notably, some of the most prolific engineering-focused journals from key publishing countries include Ocean Engineering and The Chinese Journal of Nonferrous Metals from China and IEEE conference proceedings from India.

3.5.1. Regional distribution

Figure 13 shows that a majority of the publications (52 per cent) disclosed the use of material from the CCZ, while 47 per cent specifically addressed PMNs. Only 10 per cent of the studies focused on the Indian Ocean. A small fraction were global in scope (8 per cent). Notably, 30 per cent of the articles did not disclose any geographic source. This lack of specificity is not unexpected, as many of the engineering challenges encountered in deep-sea mining are region-independent.

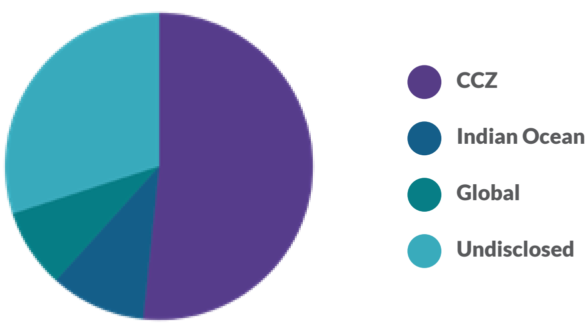


Figure 13. Geographical distribution of engineering publications

3.5.2. Research disciplines

The engineering perspective of deep-sea mining has been analysed by Kleiv & Thornhill (2022), who reviewed 1,935 journal publications spanning from 1968 to 2021. Their analysis revealed that approximately half of these papers focused on environmental aspects. The other half of the papers were further categorized into three main areas:

(1) vertical transport, which concerns hoisting minerals from the seafloor to the surface
(2) processing, which involves transforming the extracted ore into industrial minerals and
(3) other engineering, encompassing diverse aspects related to exploration, accessing, sampling, instrumenting and operating in the deep-sea environment.

These engineering studies are published across a wide range of journals, reflecting the field's multidisciplinary nature.

Vertical transport is particularly complex and requires collaboration across various engineering disciplines. Transporting minerals from the seabed to the surface entails overcoming numerous challenges, including high energy demands (Heinrich et al., 2020), environmental considerations (Heinrich et al., 2020), environmental impact (Muñoz-Royo et al., 2021) and the need for advanced operational modelling through numerical simulations (Purkiani et al., 2022; Wang et al., 2021). These challenges also present significant opportunities for technological innovation and patentable invention.

Figure 14 shows that the majority of 53 scientific publications analysed by the S.H.E. community focused on ore recovery, followed by metal extraction and, to a lesser extent, other engineering aspects. For the in-depth analysis, the focus was placed on the processing of mineral ores into metals, representing the critical transition from raw mineral extraction to the production of refined materials required by end users. Within this context, it was found that 13 out of the 59 repository publications addressed this strategic area, which is central to meeting the growing demand for critical minerals essential to the energy transition (Xun-xiong & Wei, 2021).

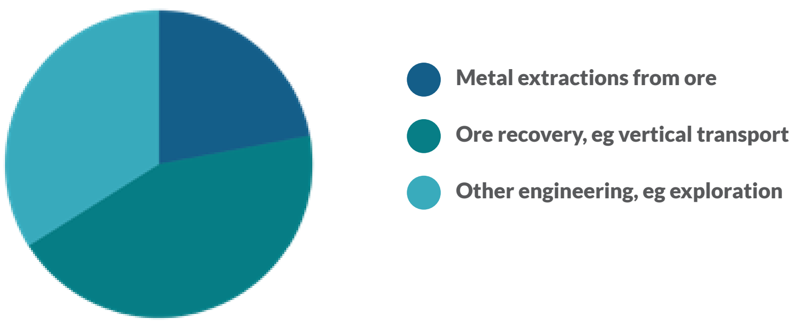


Figure 14. Percentage of publications across the engineering research disciplines

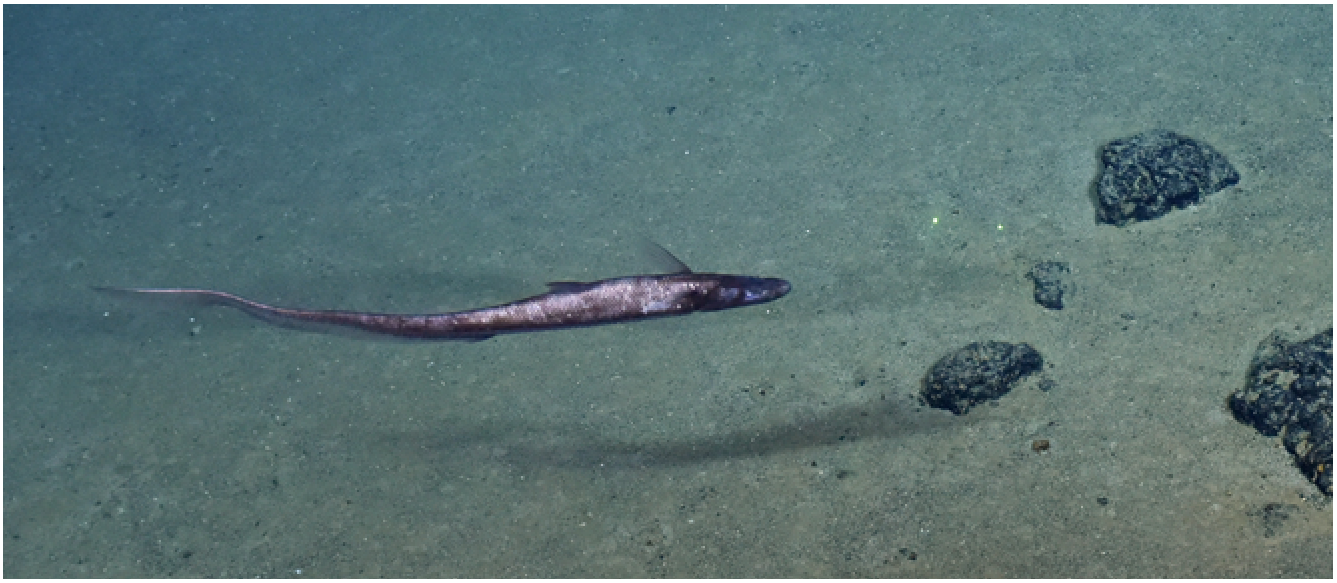
In the selected subset of scientific studies, six categories of metallurgical processes were identified, all aimed at optimizing metal yields and minimizing waste in the recovery of Co, Ni, Cu and Mn from PMNs.

3.5.2.1. Acid and ammonia-based leaching processes

Recovery of Co, Ni, Cu and Mn from PMNs can be achieved using either ammonia-based or sulfuric acid-based leaching methods (Sheik et al., 2022). Both approaches generate effluents from which acids and alkalis are recovered via electrochemical salt splitting using anion- and cation-exchange membranes.

The Council of Scientific and Industrial Research, Institute of Minerals and Materials Technology, in India, incorporates both acid- and ammonia-based routes for the recovery of Mn, Cu, Ni and Co. The process involves the reuse of solid residues and effluents, thereby improving the product portfolio. Key steps include ammoniacal-SO2 leaching, reductive acid leaching, demanganization, iron removal, smelting, bulk sulfide precipitation, mixed sulfide dissolution, solvent extraction, electrodeposition, precipitation and electrochemical salt splitting (Aishvarya et al., 2022).

Electrodeposition of high-purity electrolytic manganese dioxide, used in lithium batteries, has been successfully performed on ammoniacal-leached PMNs (Marandi et al., 2022). Additionally, the use of non-



ionic surfactants can enhance the leaching of Fe, Co, Ni and Cu from PMNs, while simultaneously enriching Mn content in the leached residue by retarding its dissolution during leaching (Mukherjee et al., 2021).

3.5.2.2. Bioleaching and glycerol-assisted leaching

Bioleaching utilizing heterotrophic Mn-reducing microorganisms, coupled with washing, can recover approximately 55 per cent Mn, 36 per cent Ni, 15 per cent Co, 27 per cent Zn and 38 per cent Cu when pulp density is increased to 10 per cent (w/v) (Štyriaková et al., 2022). Achieving complete recovery of Mn, Cu, Zn, Co and Ni requires intermittent bioleaching with about 25 cycles, during which around 60 per cent of the medium is replaced each time.

Glycerol, a non-toxic, biomass-derived reductant, has been tested for reductive acid leaching of manganese nodules, resulting in over 95 per cent Ni extraction and over 98 per cent extraction of Cu, Co and Mn within one hour (Venkataseetharaman et al., 2021).

3.5.2.3. Gaseous reduction and smelting

Recovery of Cu, Ni, Co and Mn from PMN can also employ gaseous reduction-and-smelting routes (Sarangi et al., 2022). In this process, hydrometallurgical methods based on acid or ammonia leaching often produce significant amounts of Mn- and Fe-containing residues during the recovery of Cu, Ni and Co. In the gaseous reduction process, nodule pellets are exposed to natural gas to reduce their mineral content. The reduced pellets are then melted to form an alloy containing Cu, Ni and Co. The residual slag, mainly composed of oxides of Mn, Fe and Si, is processed separately. For example, Mn can be recovered as silicomanganese alloy during this step.

3.5.2.4. Reduction roasting and magnetic separation

High recovery rates were achieved by reducing the ore at 1150°C for 2 hours in the presence of CaF2, SiO2, pyrite and anthracite, followed by magnetic separation at 160 kA/m (Xiaoxing et al., 2020).

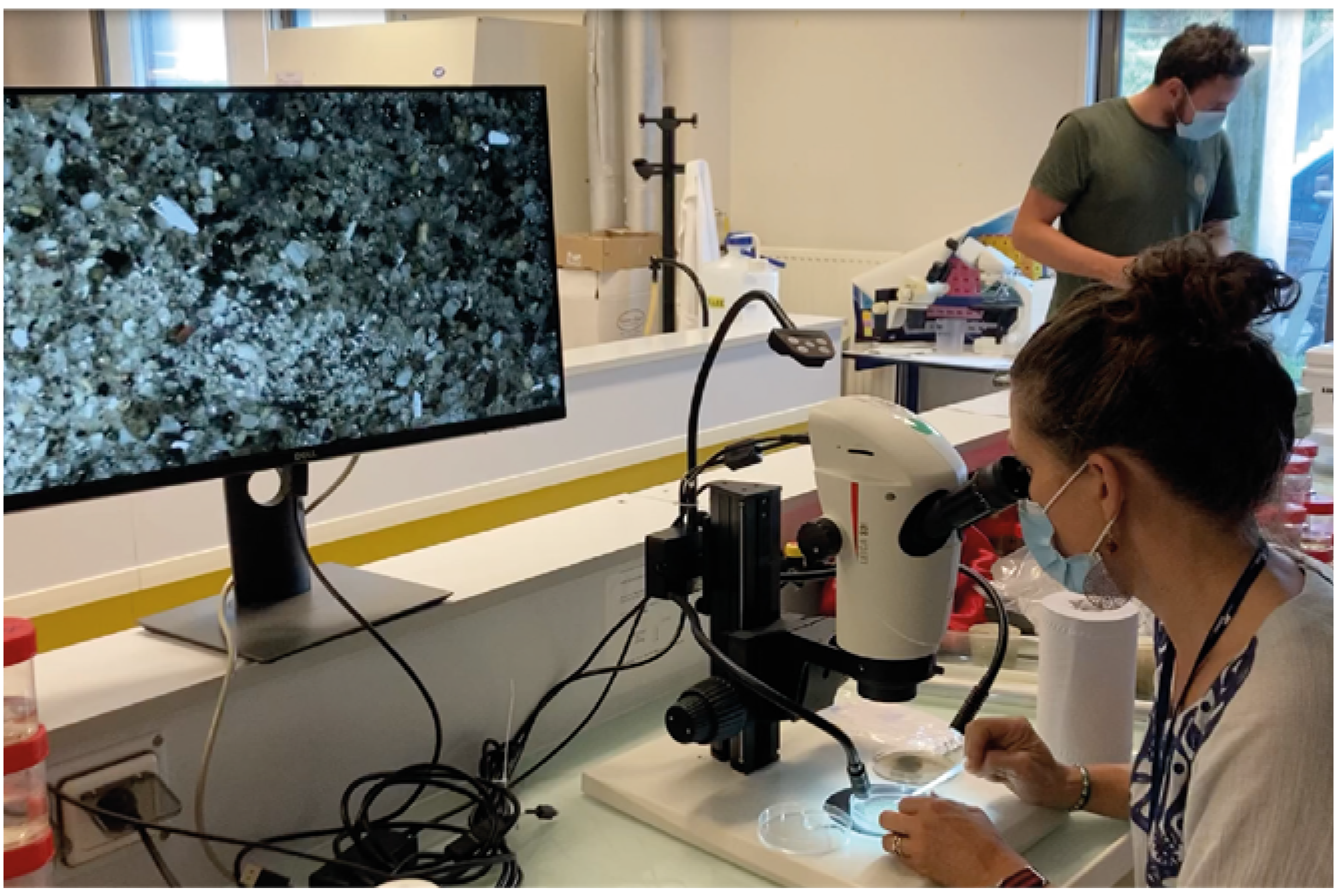
3.5.2.5. Combined pyro- and a hydrometallurgical route

The Metal Mining Agency of Japan (now known as the Japan Organization for Metals and Energy Security) has adopted the smelting and chlorine-leaching process, which combines pyrometallurgical and hydrometallurgical treatments (Nishi et al., 2023). Deep Ocean Resources Development is exploring the smelting and chlorine-leaching process flow to reduce capital and operating costs. Slow cooling of the matte from the nodules is suggested to facilitate phase separation and potentially decrease the load on subsequent hydrometallurgical steps. This process has been the subject of multiple international patent applications, initially filed and granted in France and Japan in 1977 and is now in the public domain.

3.5.2.6. Hydrometallurgical treatment of FeNiCuCo alloys

A hydrometallurgical process for treating FeNiCuCo alloys has been proposed by the German Federal Institute for Geoscience and Natural Resources. The method involves pressurized sulfuric acid leaching with hydrogen gas suppression, followed by precipitation and solvent extraction to recover the metals (Keber et al., 2020).

The deep-sea mining industry continues to focus on improving the efficiency of extracting a wide range of minerals from polymetallic ores. This involves multiple, often integrated, processing steps that present technical challenges, particularly in relation to leachate management, effluent recovery and energy consumption.



4. GENDER REPRESENTATION ACROSS THE RESEARCH DISCIPLINES

Figure 15 shows that the analysis of first authors' gender revealed that gender parity appears to have been reached only in the study areas of oceanography and biology, with women accounting for 49 per cent and 52 per cent of first authors, respectively. A persistent gender gap was observed across all mineral geology publications. However, PMN publications performed slightly better, with 40 per cent of first authors female, followed by CFC at 29 per cent and PMS at 18 per cent. In engineering publications, 30 per cent of first authors were women.

These trends confirm ongoing gender gaps in these fields. As context for these observations, science, technology, engineering and mathematics disciplines continue to have lower enrolment of female students (Merayo & Ayuso, 2022). Additionally, pursuing a career in deep-sea science is not straightforward for women, as long offshore research cruises can take a toll on family life and can present (perceived or real) additional safety risks, as documented in the knowledge output of the S.H.E Community "Gender guidelines to promote inclusive and equitable opportunities in deep-sea research expeditions" available on the S.H.E website. In response, the S.H.E. programme is developing gender guidelines to facilitate women's participation on offshore research cruises.

While gender-based analysis helps understand women's participation across different subject areas, it is also important to consider that certain disciplines, such as biology and chemistry, have traditionally been preferred by female candidates. In contrast, subjects such as geology and engineering are relatively more preferred by male candidates. According to the S.H.E. community, this may indicate personal choices and systemic factors rather than discrimination alone.

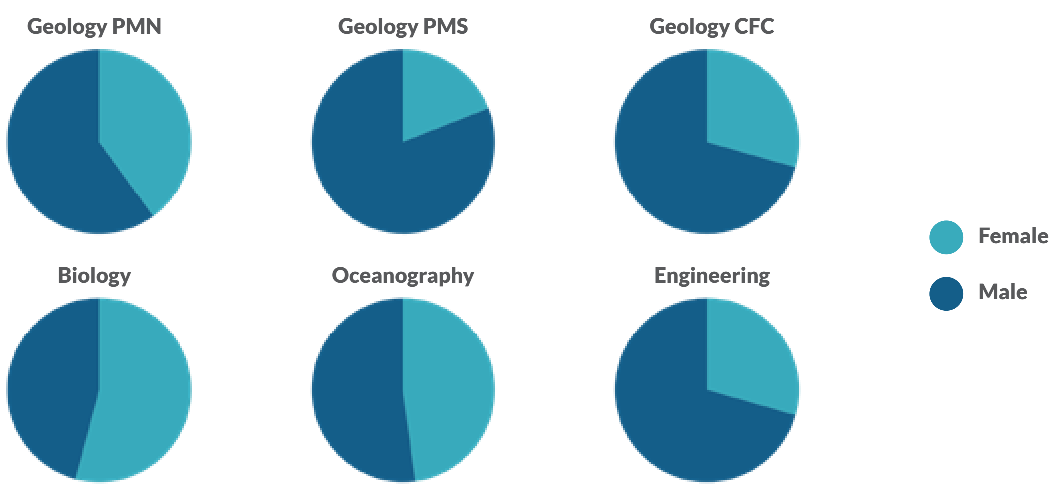


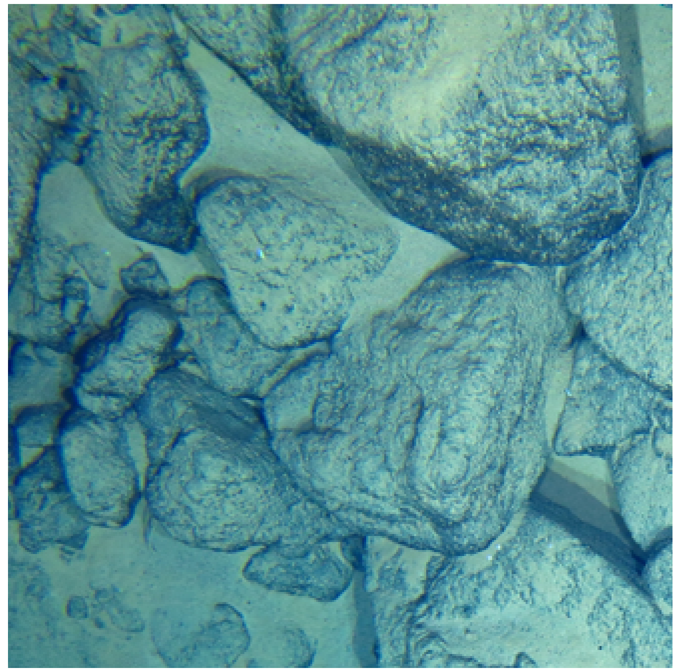
Figure 15. Gender balance across research disciplines (percentage)

5. GEOGRAPHICAL DISTRIBUTION OF LEADING INSTITUTES AND COUNTRIES

Before evaluating the geographical distribution of publications for different mineral types, it is important to highlight the distribution of contractors and their sponsoring States across the world's regions. A more detailed overview of the status of exploration activities in the Area is available online.

In the context of deep-sea exploration contracts established under the ISA, sponsoring States are distributed across the established ISA regional groups. Exploration activities within the Western European and Others Group are supported by States including Belgium, France, Germany and Poland. The Eastern European Group features sponsoring States such as the Russian Federation, a major entity that holds several exploration contracts. This group also includes the States comprising the Interoceanmetal Joint Organization, a consortium constituted by Bulgaria, the Czech Republic, Poland (which is also categorized under the Western European and Others Group) and the Slovak Republic. Within the Asian Group, sponsoring States with active exploration contracts for diverse minerals encompass China, India, Japan, the Republic of Korea and Singapore. Furthermore, this group is unique in its inclusion of small island developing States from the Asia-Pacific region, such as Nauru, the Cook Islands, Kiribati and Tonga, all of which function as sponsoring States with currently active exploration contracts. The Group of Latin American and Caribbean Countries includes Jamaica and Cuba (the latter being a participating member of the IOM consortium) among its sponsoring States. Notably, the African Group currently has no States holding exploration contracts within the Area.

5.1. Geology



Two general trends are observed. First, cooperation between countries in Europe is frequent, while such cross-country collaborations are not reflected in publications from Asia. However, within each Asian country, several institutes (typically 2-5) often collaborate on a single publication, indicating strong national-level cooperation. Overall, most publications reflect a collaborative effort among institutions, either within a single country or across multiple countries.

Figure 16 shows that the first authors of 44 PMN geology papers analysed were affiliated with institutions in 14 countries. More than half of these publications originated from Germany, Poland and China. The only transcontinental partnerships identified were with the USA (Germany-USA, Poland-USA, Korea-USA). Interestingly, while the USA is not an ISA Member state, such collaborations indicate an overarching interest in MSR collaboration irrespective of the researcher's affiliation across continents. This suggests that partnerships are driven primarily by expertise, rather than by the host countries' status within the ISA (Figure 15).

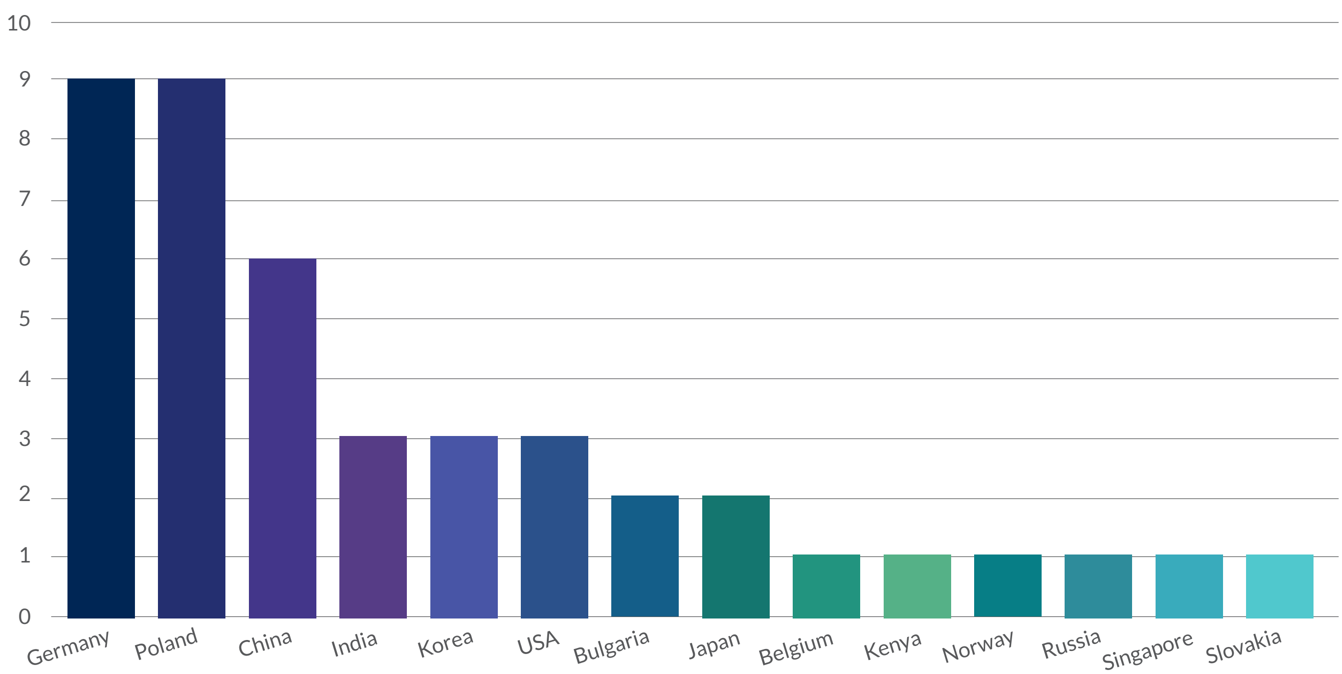


Figure 16. Countries of first author affiliation for selected PMN publications (2020-2023)

Figure 17 shows that the first authors of 96 PMS geology publications analysed were affiliated with institutions in eight countries. China led this subset, accounting for 60 per cent of publications, followed by the Russian Federation (18 per cent) and India (7 per cent) (Figure 16).

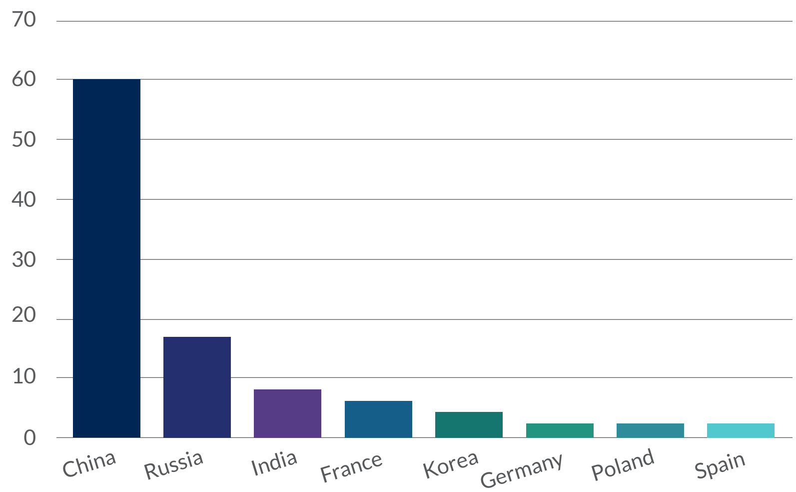


Figure 17. Countries of first author affiliation for selected PMS publications (2020-2023)

Figure 18 shows that the first authors of 45 CFC publications analysed were affiliated with institutions in nine countries (Figure 17). The top three contributors were Brazil (28 per cent), which at the time of writing still held an ISA exploration contract in the South Atlantic, followed by Japan (20 per cent) and the Russian Federation (13 per cent).

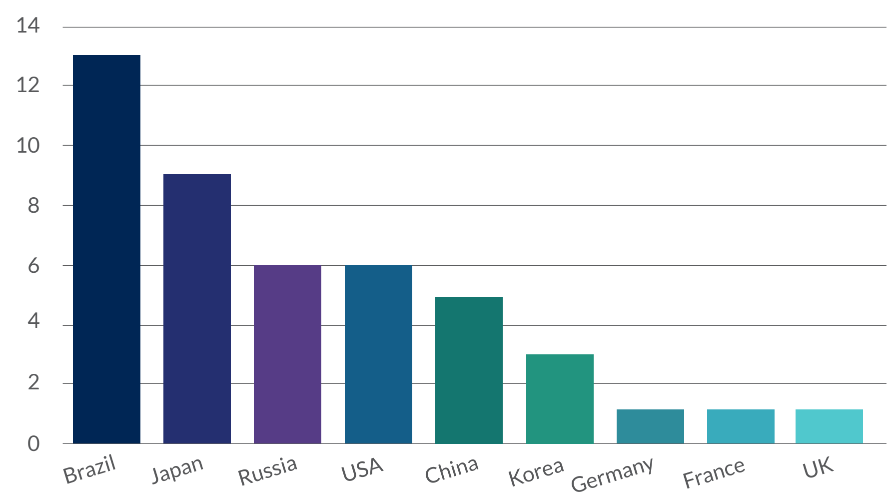


Figure 18. Countries of first author affiliation for selected CFC publications (2020-2023)

5.2. Biology

Figure 19 shows the deep-sea biodiversity research has been driven by a relatively small group of countries and institutions, often corresponding to those with ISA exploration licences or well-developed deep-sea programmes. While the total number of affiliations of authors in the biology subset came from 20 countries, institutes in three countries accounted for 38 per cent of the studies. Germany (sponsoring State) stands out in PMN research, with the largest number of PMN-focused papers. This reflects Germany's historical investment (the Disturbance and recolonization experiment in a manganese nodule area of the deep South Pacific and the Peru Basin project experiment) and leadership in the JPI Oceans projects related to MiningImpact. German institutions (GEOMAR Helmholtz Centre for Ocean Research Kiel, Federal Institute for Geosciences and Natural Resources (ISA contractor), Senckenberg) have extensively studied CCZ ecology and even pioneered techniques for impact monitoring. China is the second-largest contributor to the analysed biological studies (12 per cent). China's Second Institute of Oceanography has intensely explored the SWIR vents and Northwest Pacific seamounts, contributing new species and environmental data. France is the third-largest contributor (8 per cent), with publications from the French Research Institute for Exploitation of the Sea and the University of Brest, France, among others.

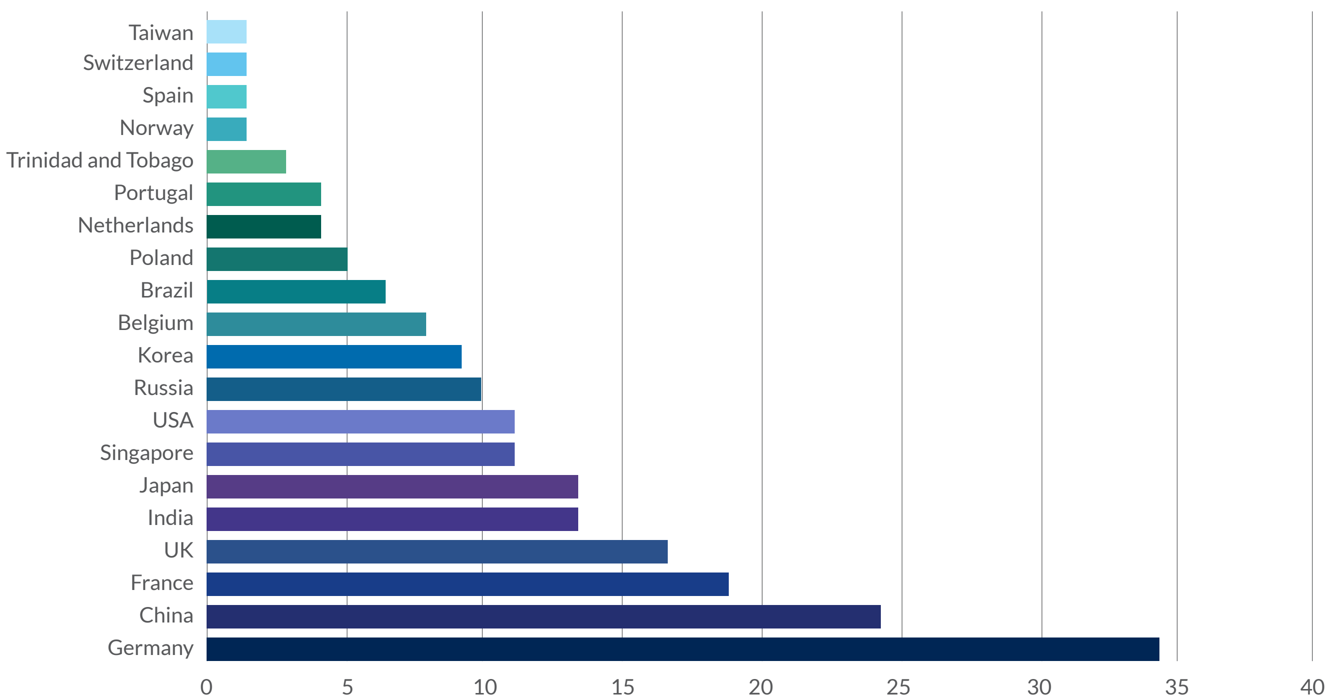


Figure 19. Countries of first author affiliation for selected biology publications (2020-2023)

5.3. Oceanography

Figure 20 shows that the first authors of oceanographic publications analysed came from 11 countries, with China, the United States of America and the Russian Federation as the top three contributors, together accounting for over half of the total publications. Key contributing institutions include the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry and the Shirshov Institute of Oceanology in the Russian Federation, the University of Hawai'i, Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology in the United States of America and the Second Institute of Oceanology and the South China Sea Institute of Oceanology in China.

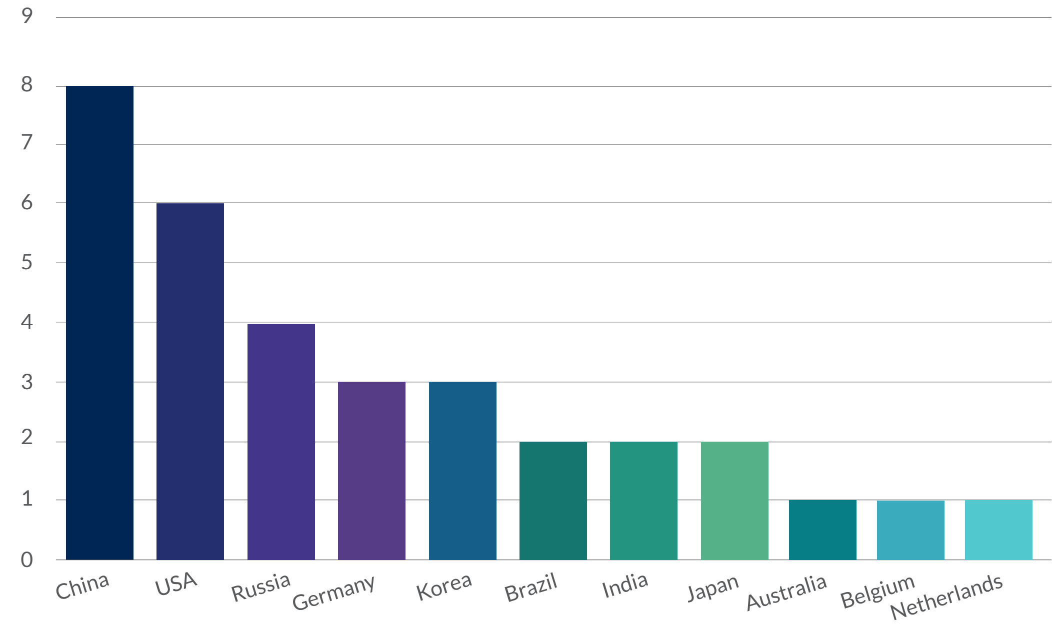


Figure 20. Countries of first author affiliation for selected oceanography publications (2020-2023)

5.4. Engineering

Figure 21 shows that 13 countries contributed to engineering-related publications, with three Asian countries accounting for 40 per cent of the total (India, China and Japan). Several Chinese institutes were involved, with the majority of contributions coming from the Beijing General Research Institute of Mining and Metallurgy and the School of Mechanical and Electrical Engineering at Central South University. Key Indian contributors included the CSIR-Institute of Minerals and Materials Technology and the National Institute of Ocean Technology, while for Japan, the primary contributor was the University of Tokyo.

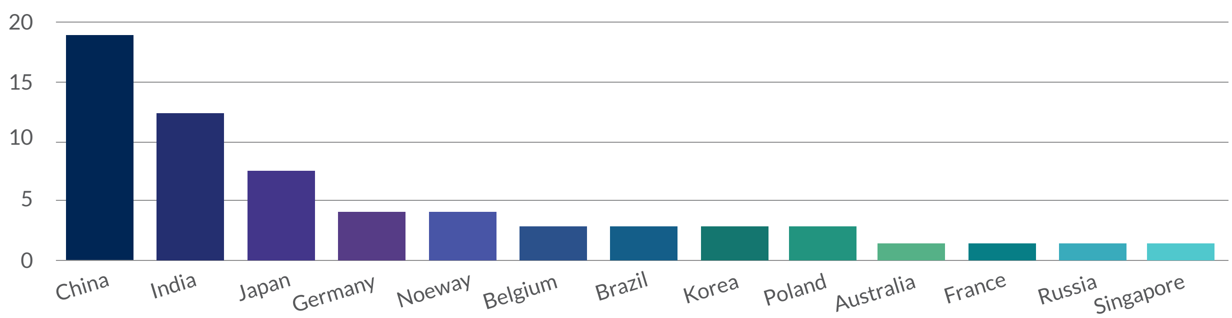


Figure 21. Countries of first author affiliation for selected engineering publications (2020-2023)

6. CONCLUSION AND RECOMMENDATIONS

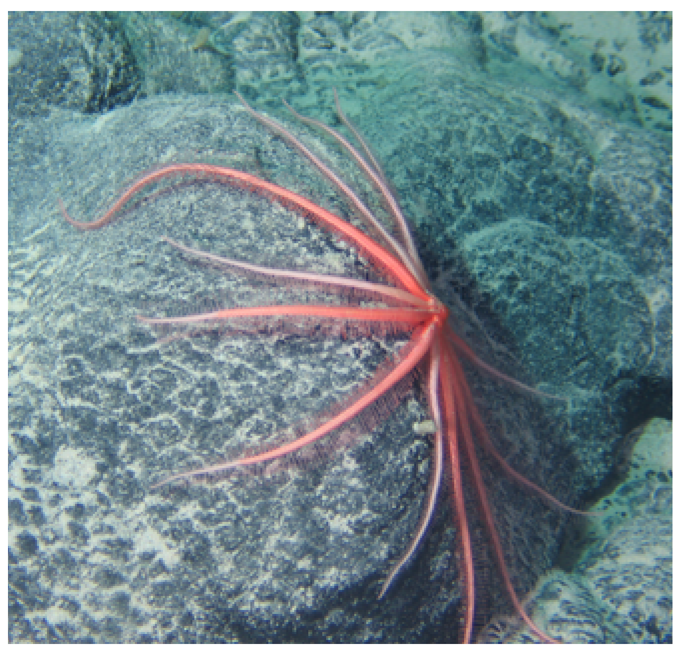
This section concludes with a summary of the findings from the analysis conducted by the mentees and mentors, a recommendation by the mentees and mentors on reporting standards for annual reports and an assessment of the effectiveness of the S.H.E. Mentoring Programme.

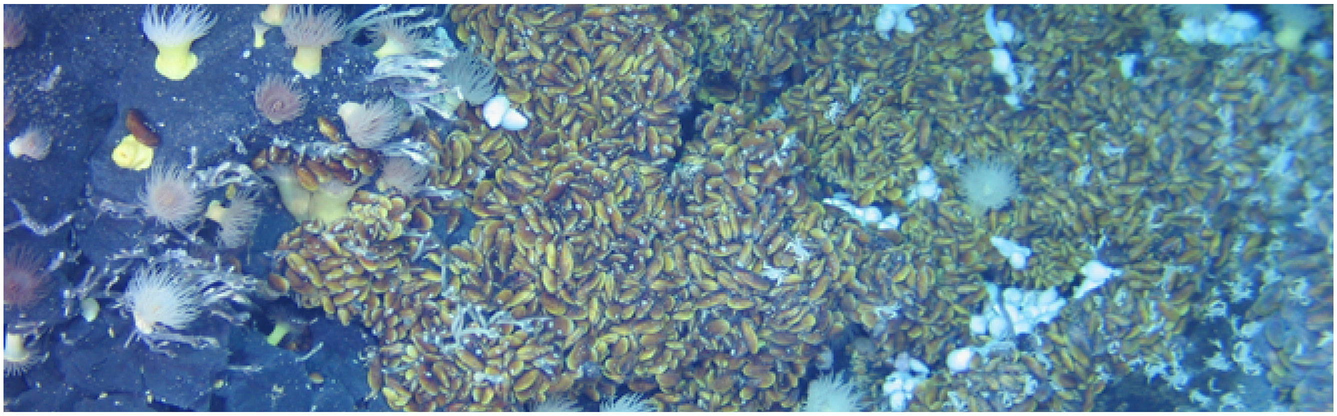
The quantity and breadth of scientific publications over four years confirm that exploration activities under contracts with the ISA have advanced fundamental and applied sciences in deep-sea exploration, including valuable contributions from the broader scientific community.

Across the disciplines analysed, it is evident that research in the CCZ is more advanced than in other areas, largely due to its long-standing role as a focus of exploration. Since the adoption of the first exploration regulations in 2000, 17 out of 31 exploration contracts have been granted for PMNs in the CCZ, seven for PMS and five for CFC. The CCZ is also the only region with a regional environmental management plan, which is up for review in 2025.

The biological publications from the CCZ include regional biogeographic syntheses that integrate baseline data sets across faunal groups to support environmental management, as well as research aimed at strengthening the science-policy interface within the ISA's regulatory framework for environmental protection. It was found that analyses primarily focused on benthic invertebrates, with megafauna being the most frequently targeted faunal group. Moreover, more than half of the publications addressed biodiversity and taxonomy. Notably, every major taxon has yielded new species, with up to 48 identified across the entire repository.

The geological papers address a range of topics, including tectonics, structural geology, geochemistry (including trace-metal analysis), and mineralogy. Resource assessment is a key focus across all mineral types, including the use of novel technologies such as artificial neural network models. The PMS research has focused on identifying new hydrothermal vent sites, conducting geochemical studies, characterizing deposits and assessing their resource potential. Another prominent topic is the environmental and technological implications of the extraction technologies used across the different minerals. The CFC research has focused on the mineralogical and geochemical characteristics of Fe-Mn crust distribution on seamounts, as well as on more fundamental topics such as tectonics, geological history, magmatism and volca-





nism in regions like the Rio Grande Rise, which are inherently linked to the formation of seamounts and, subsequently, to the development of ferromanganese crusts.

The analysis of publications with an engineering component revealed a strategic focus on metallurgical processes for mineral extraction from PMN, with at least six identified pathways aimed at optimizing metal yields and minimizing waste during recovery, including innovative approaches using microorganisms for bioleaching.

The oceanographic publications covered modelling, as well as physical and chemical oceanography, with the interaction among oceanographic processes, geology and deep-sea ecosystems emerging as the most prominent theme.

The analysis revealed that scientists often put forward future research priorities. In oceanography, examples include advancing turbulence models for hydrothermal systems and studying the variability of ocean surface currents at smaller scales and their influence on deep-ocean current dynamics to mitigate the potential impacts of deep-sea mining on benthic ecosystems. In biology, formal taxonomy must continue to be prioritized, expanding beyond sediment invertebrates to include pelagic and midwater ecosystems. Key processes such as plume dynamics, carbon cycling and larval dispersal also require further study. Additionally, emerging topics such as automation and artificial intelligence approaches in geology and biology are gaining traction in deep-sea research. Another growing topic of interest in geology is the resource assessment of REY in deep-sea sediments, which may lead to feasibility studies evaluating their potential for future mining. Additionally, research on the composition of nodule fines to assess the impact of return-water tailings on geochemical cycling has gained traction.

The analysis of gender representation across disciplines revealed that, except in oceanographic and biological studies, women are less frequently listed as first authors, with significantly lower representation in geology and engineering.

Generally, publications coming from Asia show stronger national-level cooperation than international ones. Institutes from countries with exploration contracts have a strong publication record in deep-sea research, except for American institutes, which often serve as subcontractors to ISA contractors. Across the research disciplines analysed, the deep-sea research has been driven by a relatively small group of countries, with three accounting for at least 40 per cent of publications in each research area. The front-runners include China, Germany, France, India, Japan, the Russian Federation and the USA. Except for the USA, which is not an ISA Member State, all are among the top 20 financial contributors to the ISA.

Conducting horizon-scanning exercises through systematic literature reviews, including patents, to take stock of progress and track research priorities identified by researchers, could inspire future programmes or feasibility studies within the ISA's mandate to promote MSR. Future analyses should include more comprehensive literature reviews rather than focusing only on the scientific publications reported by contractors in their annual reports. Continuing to promote women's empowerment initiatives in the deep sea should remain a priority for ISA, and it should expand its portfolio to include deep-sea ocean literacy initiatives aimed at inspiring young adults, with a particular focus on encouraging women to pursue careers in deep-sea ocean sciences and technology.

The S.H.E. Mentoring Programme contributed to supporting women's career development and leadership in MSR while identifying areas for improvement to enhance future cohorts.

Areas for improvement identified include:

- In-person exchanges and training sessions: Incorporating in-person components would increase the benefits and maintain motivation for mentees and mentors. The current pilot cohort offered only remote-based activities, which proved challenging.
- Collective knowledge outputs: Working towards shared outputs has increased cross-disciplinary collaboration and motivation to contribute, but has also presented challenges.
- Programme duration and scope: Defining a clear scope at the onset would allow for faster delivery. The current two-year duration is time-intensive. With a focused scope, a one-year timeline could be feasible.
    - Integration into existing programmes should be the way forward: Anchoring the S.H.E. Mentoring Programme within existing ISA MSR initiatives would support sustainability and effectiveness.
- Expansion to other disciplines: Expanding the programme to other areas, such as a legal mentorship programme, would add value and meet broader capacity-building needs.

A key bottleneck remains funding. The current programme has been run entirely on ISA programmatic funds, with additional donor support from France and volunteered contribution. Securing sustainable funding will be essential to continue and expand the S.H.E. Mentoring Programme.

TABLES AND FIGURES

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ANNEX 1.
MEET THE S.H.E. MENTORING PROGRAMME COMMUNITY

Mentees

Mpho Sehlabo
PhD Student, Energy and Mining Law
University of Cape Town
South Africa

Mpho Lydia Sehlabo has a multidisciplinary educational background, including a BSc in Marine Biology and Ocean and Atmosphere Sciences, a BSc Honours in Oceanography and a Master's in Mining and Mineral Law from the University of Cape Town, South Africa. She is currently a doctoral researcher and a research and teaching assistant in the Department of Private Law at the University of Cape Town, specializing in Mining and Energy Law.

Mpho demonstrates a passion for science and law for ocean conservation and sustainability. She has previously been involved in an at-sea training programme during which she gained practical knowledge on PMNs and CFC. She has served in various leadership roles throughout her academic journey and has shown entrepreneurial acumen. Mpho's employment history includes various roles at the University of Cape Town. Outside of her academic and professional pursuits, Mpho enjoys poetry, literature and volunteering at non-profit organizations. Mpho is the founder and CEO of the Mpho Sehlabo Foundation, which donates essentials to marginalized and underprivileged communities and students.

Ms. Oluyemisi Oluwadare
Geochemist and Economic Geologist; Assistant Director
Nigerian Geological Survey Agency (NGSA)
Nigeria

Oluyemisi Oluwadare is a geochemist and economic geologist with over 20 years of experience in research and fieldwork. Currently serving as Assistant Director at the Nigerian Geological Survey Agency in Abuja, Nigeria, Oluyemisi specializes in identifying deposits in construction materials and assessing their suitability for various applications such as concrete aggregates. She is adept at interpreting research data, preparing geological reports, maps and diagrams and developing operational methods related to geology, geochemistry and mineral exploration. Her role also involves coordinating fieldwork activities.

Oluyemisi holds a Master of Science (Hons) in Mineral Exploration and Mining Geology from the University of Jos, Nigeria and a postgraduate diploma in Mineral Exploration from the Nigerian Institute of Mining and Geosciences. She is currently pursuing her postgraduate diploma in Mineral Exploration from the University of Jos.

Lucy Njue
Senior Geologist
Geothermal Development Company
Kenya

Lucy Njue is a geoscientist with over 16 years of expertise in the geothermal and mining industries. She holds an honours degree from the University of Nairobi and has contributed to regional geothermal training and consultancies. Lucy is proficient in field and borehole geology. As a Senior Geologist at the Geothermal Development Company since 2009, Lucy has played a key role in the Menengai geothermal project, leading the geology section and contributing to strategic development initiatives. Lucy's consultancy work extends to United Republic of Tanzania and Rwanda, where she has led geological assessments and well-targeting efforts in the Menengai geothermal field. She has chaired the Geothermal Development Company Technical Exchange Forum and served as Treasurer of the Geology Society of Kenya, demonstrating her leadership in the geosciences community. Lucy has previously served on various committees at Geothermal Development Company, advocating for gender mainstreaming and disability inclusion.

Randa Mejri
Assistant Professor
University of Sfax
Tunisia

Dr. Randa Mejri blends rigorous evolutionary science with hands-on coastal stewardship to power a more resilient Mediterranean. Currently an Assistant Professor of Marine Biology and Ecology at the University of Sfax, Tunisia, with extensive experience in marine biology, functional ecology, biogeography and sustainable development. Randa's educational background includes a PhD thesis that produced the first comprehensive checklist of Tunisian Gobiidae and analysed the morphometric and genetic structure of Mediterranean populations of Pomatoschistus species, work which still guides regional conservation genetics. She also holds a Master's degree in biodiversity and the evolution of coastal ecosystems and a Bachelor's degree in biological sciences, both of which anchor her integrative research approach. Throughout her career, Randa has contributed significantly to scientific research, publishing numerous papers on marine biodiversity, genetic architecture and coastal dynamics while coordinating high-impact projects such as CLIMED (Interreg Initiative) and CLEAR Med (Ocean Decade Initiative).Randa is a driving force in professional networks and civil society initiatives, having founded the Tunisian Association of Doctors and PhD

Students in Sciences, cofounded Early Career Ocean Professional Programme in Tunisia, a part of the African Network of Deep-Water Researchers and serving as Vice-President of nongovernmental organization Kantara Save Earth from Kerkennah Archipelago alliances through which she channels her research into tangible, community-led ocean solutions.

Ijeoma Eunice Orji

Hydrographer; Staff Officer Grade Three (SO3), Maritime Safety Information
National Hydrographic Agency of Nigeria
Nigeria

Ijeoma Eunice Orji has a diverse background in naval operations, geology and hydrography. She has a B.Sc. (Hons) in Geology and Exploration Geophysics from Ebonyi State University in 2016 and has completed the basic training course at the Nigerian Naval College. Her sea experience includes serving as a watchkeeping officer aboard Nigerian Navy ships, where she was responsible for navigation and watchkeeping duties. Transitioning to shore-based roles, Orji has worked at the Nigerian Navy Hydrographic Office since December 2022 as a Staff Officer III Survey Operation/Maritime Safety Information Officer. In this capacity, she manages survey data, oversees data-processing and quality control, drafts notices to mariners and prepares survey reports. Beyond her professional pursuits, Orji engages in extracurricular activities such as reading, travelling, cooking and music.

Nezha Mejjad, PhD

Researcher
National Center for Energy, Sciences and Nuclear Techniques (CNESTEN), Rabat
Morocco

Nezha Mejjad is a Research Scientist in Geochemistry and Environment at the National Center for Energy, Sciences and Nuclear Techniques in Rabat, Morocco. She completed her Ph.D. in Geochemistry and Environment at Hassan II University in 2018, focusing on marine pollution, including heavy metals and radionuclides. She holds a Master's in Sustainable Blue Growth from the University of Trieste and the National Institute of Oceanography, obtained in 2019 and another Master's in Open Innovation and Youth Entrepreneurship from CIHEAM Bari, Italy and the University of Bari, Italy, completed in 2021.

Dr. Mejjad leads a blue carbon sequestration project at Centre National de l'Energie, des Sciences et des Techniques Nucléaires (National Centre for Energy, Science and Nuclear Techniques), using nuclear techniques to assess carbon storage in Moroccan lagoon ecosystems. In 2019, she was awarded an EU Deep Blue project fellowship under the BlueMed Initiative for her thesis at Hassan II University. Her research includes 42 international journal papers and 10 book chapters, focusing on pollution and human-environment interactions. She recently joined the editorial board of Communications Earth & Environment (Nature), serves as an Academic Editor for PLOS ONE and is editing a forthcoming book on nuclear-based marine pollution assessment, scheduled for publication in 2024-2025 with Springer, in its "Environmental Science and Engineering" series.

Mentors

Joshua Tiwangye Tuhumwire

Chief Executive Officer, Gondwana Geoscience Consulting Ltd;
Member, ISA Legal and Technical Commission
Gondwana Geoscience Consulting Ltd
Uganda

Mr. Joshua Tuhumwire (Uganda) is a geologist and graduate of Makerere University, Uganda and Vrije Universiteit Brussel, Belgium. He joined Uganda's civil service as a junior geologist at the Department of Geological Survey and Mines in 1980. He spent the next 30 years at the same institution until his retirement in 2010.

Mr. Tuhumwire undertook various geological mapping and mineral exploration work at the start of his career. Later, he joined senior management, planning and supervising projects, and eventually served as the institution's head for 10 years. He had a stint consulting in mineral exploration and serving the corporate world in Uganda's nascent oil and gas sector. From 2007 to 2020, Mr. Tuhumwire was involved in all three rouneds of the United Nations World Ocean Assessments as a member of the group of experts. He has been a member of the ISA Legal and Technical Commission since 2017.

Professor Dr. Pedro Madureira

Professor
University of Évora
Portugal

Dr. Pedro Madureira is an Associate Professor at the University of Évora, Portugal. Between November 2012 and March 2024, he served as the deputy head of the Task Group for the Extension of the Portuguese Continental Shelf and as the scientific and technical coordinator of the Continental Shelf Project. Dr. Madureira was the principal investigator of several oceanographic campaigns in the North Atlantic throughout his career. From 2012 to 2022, Dr. Madureira served as a member of the ISA Legal and Technical Commission. His main academic interests include the evolution of volcanic islands, the formation and distribution of deep-sea mineral resources, the marine environment and deep-seabed exploration.

Dr. Marzia Rovere
Senior Researcher, Marine Geology
Institute of Marine Sciences, National Research Council of Italy (CNR)
Italy

Dr. Marzia Rovere holds a PhD in Earth Sciences and is a senior researcher at the National Research Council of Italy, Institute of Marine Sciences. Her scientific interests are broad and include seafloor and sub-seafloor mapping, submarine landslides and their potential to trigger tsunamis, sediment transport in coastal and slope areas, marine geo-resources, including aggregates on continental shelves, and geo-biodiversity habitats such as cold seeps and hydrothermal sites.

Dr. Rovere participates in several EU projects, including EMODnet Bathymetry, where she coordinates the Central Mediterranean Digital Terrain Model contribution. She was Vice-Chair of the joint IOC-IHO GEBCO Guiding Committee (2021-2024) and a member of the ISA Legal and Technical Commission (2015-2016).

François Charlet
Exploration Manager
Global Sea Mineral Resources (GSR)
France

François Charlet, currently exploration manager at Global Sea Mineral Resources NV, oversees offshore campaigns for resource definition and environmental baseline studies. After studying marine geology and sedimentology in France, where he earned his Master's degree from the University of Lille I, François began his professional career as a research assistant at the Renard Centre of Marine Geology, Ghent University, Belgium. In 2005, he joined the DEME Group as a marine geologist and worked mainly on soil investigations worldwide, as part of foreign dredging and environmental projects. In 2013, he joined Global Sea Mineral Resources NV as an exploration manager, leading exploration and research expeditions at sea. Until now, he has led and participated in 11 offshore campaigns in the CCZ, the Pacific Ocean and the Cook Islands.

Dr. Ann Vanreusel
Professor
Ghent University
Belgium

Dr. Ann Vanreusel studied biology at Hasselt University, Belgium and completed her licentiate studies at the University of Ghent, Belgium. She joined a marine biology research group and started a PhD on the ecology of meiofauna in coastal environments. As a postdoctoral researcher at the University of Ghent, she focused on deep-sea research, particularly within various European projects.

Dr. Vanreusel has more than 250 scientific publications in this field and has served as a principal scientist during various research campaigns on the European margins, from Portugal to Ireland. Dr. Vanreusel is a professor at the University of Ghent, where she teaches and co-organizes the inter-university course in marine and lacustrine sciences and management. She supervised more than 20 PhD students in her career.

Dr. Annemiek Vink

Lead, Polymetallic Nodule Exploration
German Federal Institute for Geosciences and Natural Resources (BGR)
Germany

Dr. Annemiek Vink is a marine geobiologist working as a manager of a project to explore PMNs in the German Federal Institute for Geosciences and Natural Resources contract area in the CCZ. Her focus is on collecting adequate environmental baseline data and analysing the potential impacts of nodule exploitation on faunal communities and ecosystems (due to nodule removal, sediment plume dispersion and settling). Dr. Vink has participated in several research and exploration cruises into the CCZ since 2013. One of the major aims of the project is to work closely with renowned scientific institutions in Germany and abroad to guarantee professional, scientific input to the exploration project and to provide sampling and data-sharing opportunities to the stakeholder community. This creates effective synergies and focused outputs that are valuable from a scientific perspective and would also help inform policy and the development of robust regulations related to deep-sea mining and environmental management.

Support team

Dr. Noémie Wouters

Programme Coordinator, Marine Scientific Research
International Seabed Authority (ISA)
Jamaica

Currently, Dr. Noémie Wouters is proud to contribute to the ISA as Programme Coordinator for Marine Scientific Research, furthering the ISA Marine Scientific Action Plan. Noémie is a dedicated marine scientist with a strong academic and managerial background. She has a Master of Business Administration with a focus on green hydrogen initiatives, a Master's in Marine and Lacustrine Sciences from Ghent University, Belgium and a PhD from the University of Lisbon, Portugal, focusing on marine resilience assessment tools. Her work included collaboration with a biomimicry consulting firm and influencing marine policy through the European Marine Board.

Noémie participated in BlueInvest sessions by the European Commission and served in an EU expert group. Returning to Ghent University in 2015, she initiated Blue Growth projects and launched the UGent Blue Growth summer school. In 2018, she became CEO of Bluebridge, the Blue Economy innovation centre at Ghent University, where she organized a strategic think tank on critical minerals.

Tanesha Dixon-Gayle

Support Consultant
Jamaica

Ms Tanesha Dixon-Gayle is a Senior Foreign Policy and Diplomacy Services Officer with Global Affairs Canada, based in Kingston, Jamaica. She supports organisations in shaping and executing media and communication strategies across international relations, public diplomacy, partnership development, gender equality communication, and development cooperation. Her portfolio covers strategic communication, coordination, speech writing, digital engagement and design. She has collaborated with governments, multilateral partners and civil society to advance initiatives that strengthen leadership, visibility and engagement.

Pierre-Jean Valayer

Consultant–Researcher, Energy, Biosphere, Emissions, Time-Series
PJV Energy
France

Currently, a clean energy and oceans consultant based in Dunkirk, France, Mr. Pierre Jean Valayer began his career as a graduate engineer in 1961, working extensively within a major US-based oil and gas company across Europe and the United States of America. During his corporate tenure, he gained geostrategic oil and gas experience, including weathering the 1973 oil crisis, enhancing the evaluation skills of corporate researchers, managing executive roles in the mobility sector, strategizing technology assets and patent litigation.

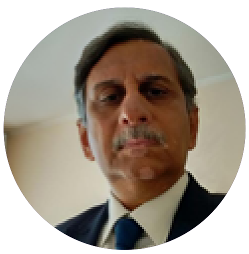
Over the past 15 years, Jean shifted focus to academia and entrepreneurship, co-supervising a PhD thesis in ocean biology and co-founding a sustainability think tank and a small business. He has been instrumental in developing EU project funding strategies, environmental time series capabilities and providing strategic intelligence in ocean biology and energy sectors, emphasizing innovation and sustainability.

John A. Mataro

Senior Geologist; Inspector of Mines and Environment
Mining Commission of Tanzania
Tanzania

Mr. John Astony Mataro is a Senior Geologist and Inspector of Mines and Environment at the Ministry of Minerals of the United Republic of Tanzania. He has over a decade of professional experience in geology, marine science and ocean governance. He is an active member of the Geological Society of the United Republic of Tanzania.

In 2022, Mr. Mataro was selected to join the Africa Deep Seabed Resources group, an initiative established by the ISA that comprises experts from African States deployed to support the work of the ISA Secretariat. Mr. Mataro holds a B.Sc. in geology and a Master's in Environmental Studies (Science).



Dr. Rahul Sharma

Author and Freelance Consultant, Deep-Sea Mining
India

Dr. Rahul Sharma is a former chief scientist of the National Institute of Oceanography, Goa, India. With almost 40 years of experience in the exploration and exploitation of deep-sea minerals, he is currently a freelance consultant in deep-sea mining. His academic career includes more than 65 papers and articles in international scientific journals and books, including the Oxford Encyclopedia, presenting papers at about 60 conferences around the world and serving as an editor for three special issues of international journals and five books on deep-sea mining by Springer.

Dr. Sharma's professional assignments include engagements as a visiting scientist in Japan, a visiting professor in Saudi Arabia, a member of the United Nations Industrial Development Organization mission to assess the status of deep-sea mining technologies in Europe, the USA Japan a consultant to the ISA. In addition to his research career, he has been involved in several activities related to science communication and outreach, as well as training programmes for international participants, professionals and students.

Dr. Samantha Smith

Environmental Management and Social Performance Professional
Global Sea Mineral Resources (GSR)
Canada

Dr Samantha Smith is recognized marine ecology and environmental management expert with two decades' experience conducting environmental assessments in four continents and has over 15 years' experience working with the ocean minerals sector. Dr Smith has a BSc (Hons) from McMaster University (Canada) and a PhD from the University of Bristol (UK) and is an author of a wide range of media products related to environmental management of ocean resources, including peer-reviewed journal articles.

Dr Smith is Director of the environmental consultancy Blue Globe Solutions, an Executive Board Member (Past President) of the International Marine Minerals Society (USA), a Fellow of AusIMM (Australia), and is an International Advisory Board Member of the Lyell Centre for Earth and Marine Science (UK) as well as the JPI Oceans Deep-Sea Mining International Engagement Hub (EU).

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