MARINE METALLIFEROUS SEDIMENTS: A POTENTIAL FUTURE SOURCE OF ESSENTIAL METALS?

INTRODUCTION

Marine metalliferous sediments are widespread geological formations on the ocean floor that may contain significant concentrations of potentially economically valuable metals. These sediments may be enriched in various metals and elemental groups, depending on a combination of sedimentation and seabed chemistry over time, including rare-earth elements (REE).

Geological processes, such as regional hydrothermal activity, sedimentary processes and the slow accumulation of dissolved metals in seawater, influence the formation of marine metalliferous sediments. These deposits are particularly interesting due to their potential as a future source of essential metals for various industries, including electronics and renewable energy technologies.

Researchers and governments are exploring the feasibility of extracting and utilizing marine metalliferous sediments. Their studies contribute to our understanding of Earth's geological processes over time and the processes in the seabed environment.

Where they occur in the Area (defined as the seabed and subsoil beyond the limits of national jurisdiction), marine metalliferous sediments are one of its resources subject to regulation by the International Seabed Authority (ISA) under the United Nations Convention on the Law of the Sea (UNCLOS) and its 1994 Implementing Agreement. However, they are not addressed in the Exploration regulations or the Exploitation regulations currently under negotiation.
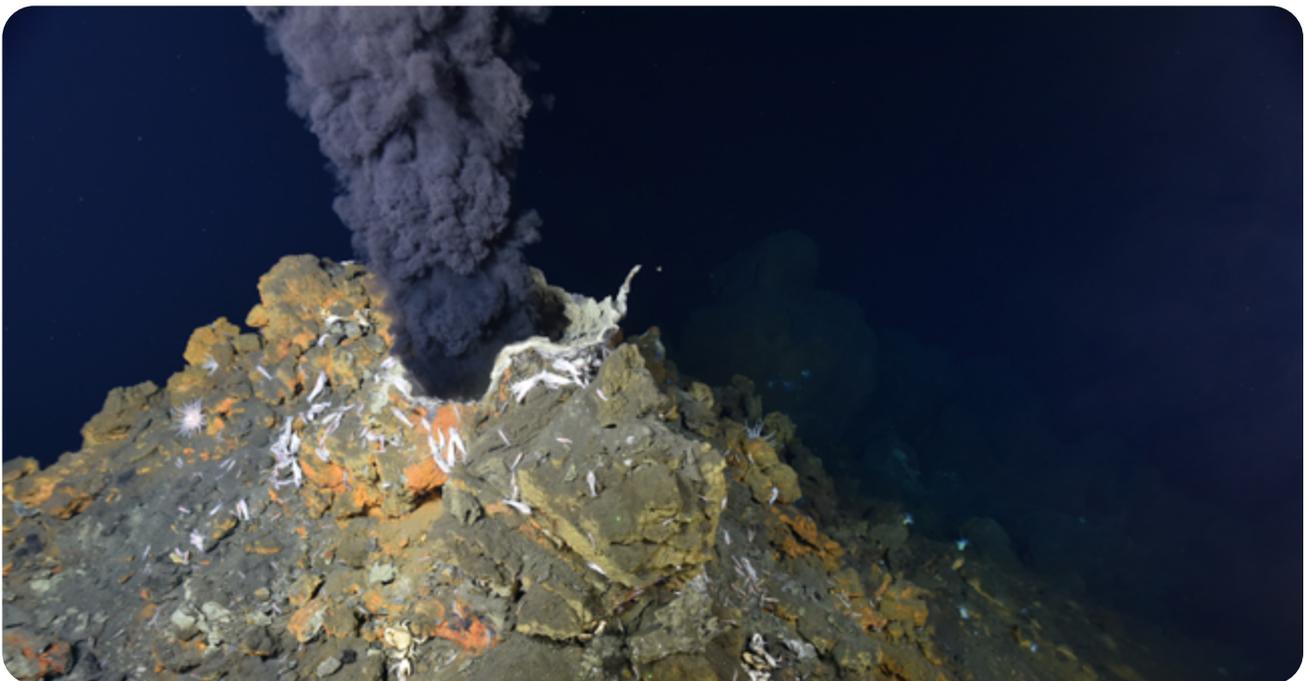
HISTORICAL CONTEXT, GEOLOGICAL DEFINITION AND FORMATION

Marine metalliferous sediments were first identified during the HMS Challenger expedition between 1873 and 1876 (Murray and Renard, 1891). They represent potential metal resources and a tool for exploring hydrothermal vent sites (Gurvich, 2006) and vent districts. Unconsolidated, metal-enriched sedimentary deposits are the modern analogues of lithified and unlithified ancient marine sediment deposits of the Paleo-oceans, often found as extensive exhalite horizons in ophiolite belts such as Oman and Cyprus (Fleet and Robertson, 1980; Robertson and Hudson, 1973) and in older crustal rifting regions (Hoggard et al., 2020). Metalliferous sediments form through plume fall out and mass wasting related to hydrothermal vent activity (James and Elderfield, 1996; Mills and Elderfield, 1995) and/or uptake of dissolved metals from seawater (Boström and Peterson, 1969; Gurvich, 2006) or are related to isolated hot brine pools (Degens and Ross, 1969). Because their formation may be directly linked to the degradation of polymetallic sulphide (PMS) deposits, the metal content of metalliferous sediments is also strongly dependent on the fluid composition at each hydrothermal vent site. In general, metalliferous sediments are enriched in iron and manganese that form oxides and (oxy-) hydroxides, trace amounts of Fe-Cu-Zn-Pb-sulphide minerals (such as pyrite, marcasite, galena, sphalerite, chalcopyrite), silica polymorphs, including quartz and amorphous silica, barite and many more. Transitional metals, such as cobalt, nickel, gold, silver, vanadium, REEs and uranium, can be enriched locally (German et al., 1993; Takaya et al., 2018).

FORMATION

Deep-sea metalliferous sediments generally combine varied modes of formation with components and inputs from multiple sources. They often have multiple formation processes and vary in composition. Most reported occurrences and accumulations are associated with hydrothermal activity along oceanic spreading centres, where hydrothermal fluids discharge (Figure 1, frame A). Once the high-temperature hydrothermal fluids vent and mix with cold near-bottom seawater, very fine-grained particles precipitate as plume fall out (Dymond, 1981). In addition, due to weathering and mass-wasting processes on the seafloor, massive sulphide mounds may form from clastic sulphide debris (Metz et al., 1988; Mills and Elderfield, 1995; Halbach et al., 1998).
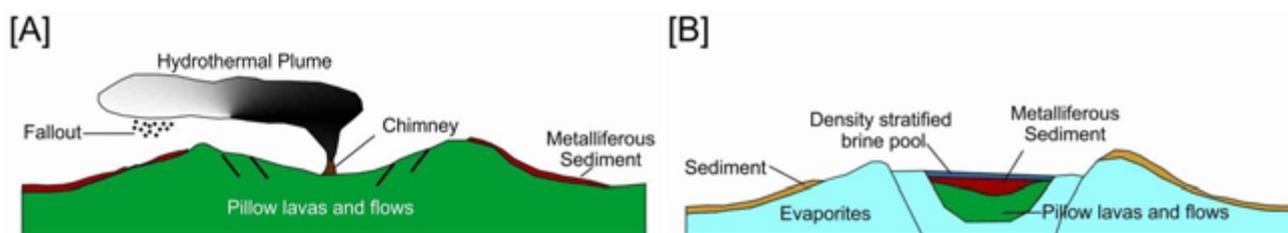
Figure 1. Schematic diagram showing the difference between the formation of metalliferous sediments in mid-ocean ridge settings (A) and the Red Sea (B). Most of these sediments accumulate in small depressions, so-called sediment ponds (Rona et al., 1993), where they form alternating layers of red-brown mud with intercalated layers of carbonate, silicic ooze, or sulphide debris (Figure 2). Low sedimentation rates facilitate metal scavenging from seawater. Metals are either incorporated into or adsorbed onto particles predominantly composed of iron and manganese (oxy-) hydroxides (Boström and Petersen, 1969; Marchig and Erzinger, 1986; Gurvich, 2006; Li and Schoonmaker, 2014), similar to the formation processes of polymetallic manganese nodules (PMN).
Source: Modified from Zierenberg (1990)

In contrast, metalliferous sediments of the Red Sea form from different mechanisms (Figure 1, frame B). Rifted graben structures with submarine brine pools originating from the exhalation of high-salinity brines occur along the central axes of the Red Sea. Sulphides, such as pyrite, sphalerite, galena and chalcopyrite, precipitate from a lower brine layer, whereas iron-(oxy-)-hydroxides and amorphous silica

precipitate from an upper brine layer, with these minerals later forming clay mineral phases by diagenetic processes (Weber-Diefenbach, 1977). The brines' high salinity, elevated temperature and heavy metal concentrations ensure a hostile environment for organisms (Watson and Waterbury, 1969). Thus, bioturbation, sulphate reduction and oxidation processes are inhibited, resulting in undisturbed accumulations that are further protected from weathering by overlying anoxic brines. The overall metalliferous sulphide accumulations cover an area of 60 km2 and can reach a thickness of up to 20 m (Zierenberg, 1990).
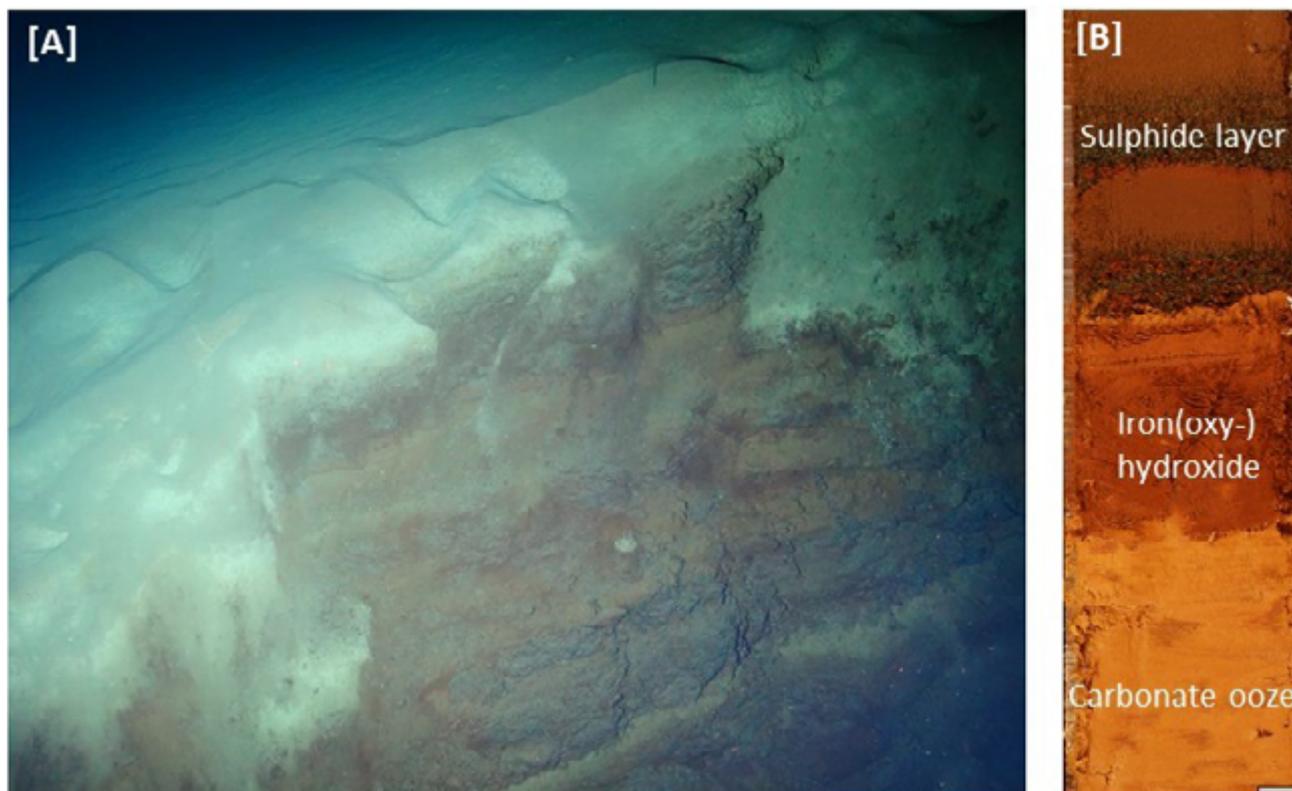
Figure 2. Sediment accumulation from the Transatlantic Geotraverse TAG hydrothermal vent area
Legend: An outcrop of metalliferous sediments at a fault scarp that are is overlain by carbonate ooze (A), sulphide layers in iron-rich hydrothermal sediment that alternates alternate with carbonate ooze (B) Image credit: National Oceanography Centre; ISA, 2021

OCCURRENCES

Significant accumulations of metalliferous sediments are found in mid-ocean ridge settings, where their precipitation is directly linked to hydrothermal activity. They are widely distributed in the Pacific Ocean and occur in the Indian, Atlantic and Arctic oceans (Gurvich, 2006; Dekov, 2008). The largest field of metalliferous sediment accumulation is in the Southeast Pacific, covering approximately 10 million km2. The second-largest fields were identified adjacent to the East Pacific Rise and at the Rodrigues Triple Junction in the Indian Ocean. Small occurrences are found in the vicinity of hydrothermal vent sites, such as Transatlantic Geotraverse, Rainbow and Grimsey, in the Mid-Atlantic Ridge. Many more are found along the mid-ocean ridges in all oceans. Accumulations are also described in back-arc settings, such as the Manus, Lau and North Fiji Basins. The significant potential of REEs plus yttrium enrichments was identified in the abyssal plain of the western North Pacific Ocean (Takaya et al., 2018). Deep-sea clays are highly enriched in REEs plus yttrium through selective adsorption processes. The Red Sea hosts 23 sites of metalliferous sediments, with Atlantis Deep II forming the largest deposit (Figure 3).
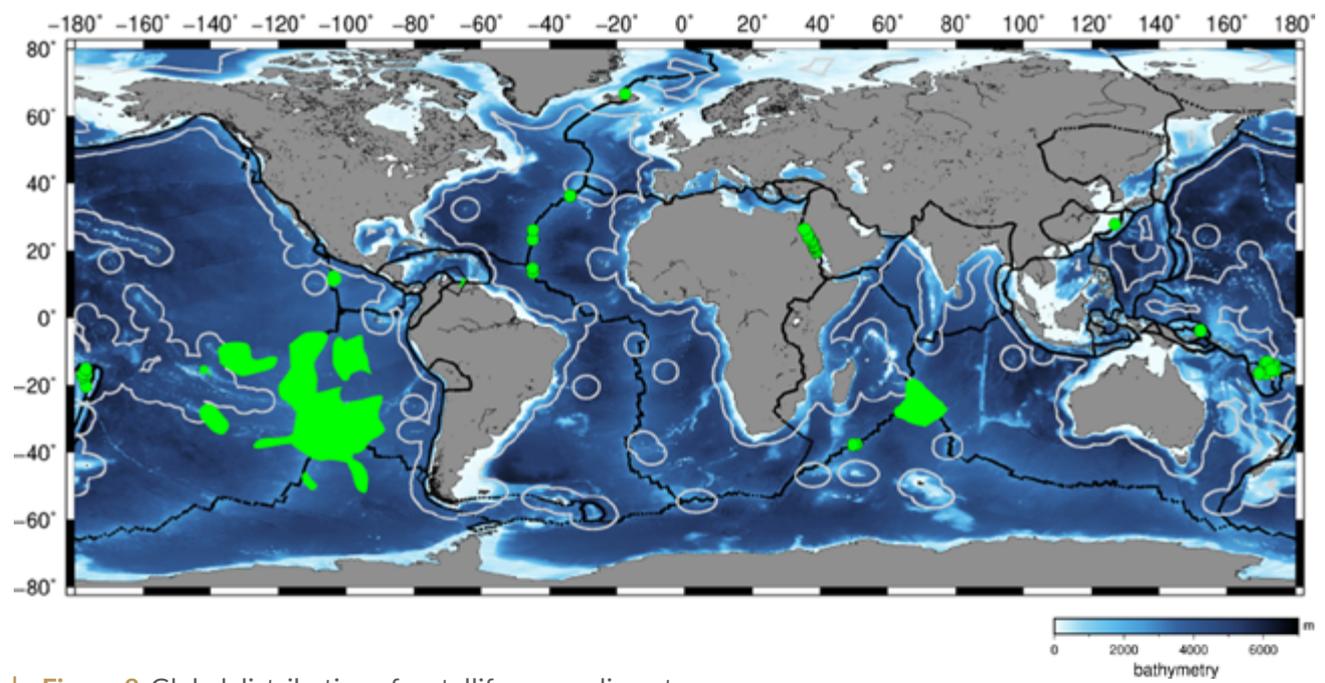
Figure 3. Global distribution of metalliferous sediments
Source: Data compiled from Gurvich (2006) and references therein, and Dekov et al. (2008), Hrisheva & Scott (2007), Hu et al. (2017), Rusakov et al. (2013) and Pan et al. (2018) Note: The distribution of data records does not indicate where metalliferous sediment deposits are absent (ISA, 2021)

RESOURCE POTENTIAL

No resource potential has been estimated for the global occurrence of metalliferous sediments. Takaya et al. (2018) estimate a rare-earth oxide resource potential of 1.2 million tons of rare-earth oxides for red REE-rich clays from the western North Pacific Ocean near Minami-Tori-Shima island. Estimates are based on a limited number of sediment cores from an area of 105 km2, down to a maximum depth of 10 m subseafloor, with extrapolated concentration maps.

The only significant resource potential has been estimated for the Atlantis II Deep basin in the Red Sea. Manafai International reassessed the resource estimate, which comprises approximately 89 million tons of dry salt-free ore, containing 3.75 million tons of zinc, 0.81 million tons of copper, 4 million tons of manganese, 5,000 tons of cobalt, 7,000 tons of silver and 47 tons of gold. The deposit forms in a complex basin adjacent to the median rift, where seafloor spreading has operated during the last 5 Ma. Exhalation of metal-rich hydrothermal brines from rift-related and cross-cutting fracture zones produced up to 25 m of metal-rich sediments over an area exceeding 57 km² (Hamer, 2017).

TECHNOLOGY

Marine metalliferous sediments occur in different areas and geological settings on the seabed. Different conditions of formation, enrichment and occurrence may require different technological approaches for identification, exploration and potential future recovery. Metalliferous sediments associated with marine PMS sites can be identified using similar exploration strategies. Mapping and sonar devices are the primary technologies for identifying depressions that can act like sediment traps. Hydrocast profiles identify geochemical anomalies and venting in the water column and coring. Trench-cutting equipment is used to assess the thickness and subsurface composition of the sediments. Oceanographic and sedimentation processes control the distribution of metalliferous sediments on the abyssal plain and require a dense network of regional-to-local surveys, similar to those used in PMN exploration. It

remains to be tested whether backscatter bathymetric data can serve as a valid exploration tool. Metalliferous muds from the Red Sea would require different approaches during exploration.

Mustaffa and Amann (1978) propose that suction technologies could be used to extract metalliferous sediments. A vibrating/cutting head with a seawater jet system will dilute and liquefy the mud, which a pump system will then transport through pipes and risers to a surface platform/vessel. The extracted sediment-water mixture will be dewatered before transport to land for further processing. No process for extracting REE-rich sediments has been proposed, although an approach similar to that used for land-based clay-hosted REE deposits is likely.

CONCLUSIONS AND RECOMMENDATIONS

Marine metalliferous sediments represent a fascinating and potentially valuable geological resource widely distributed across the ocean floor. These sediments, enriched in economically significant metals, including REEs, cobalt, nickel and others, are shaped by a complex interplay of hydrothermal activity, sedimentary processes and the slow accumulation of dissolved metals from seawater. As global demand for essential metals, driven by the electronics and renewable energy industries, continues to rise, exploration and extraction of marine metalliferous sediments have attracted increased attention from researchers and governments across national jurisdictions. However, they are not covered by any regulations.

The definition and formation of metalliferous sediments indicate that they are polygenetic, often linked to hydrothermal activity along oceanic spreading centres. The diverse composition of these sediments, enriched in iron, manganese, sulphide minerals and transitional metals, underscores their potential as a future resource. Significant accumulations have been documented in various oceanic settings, from mid-ocean ridges to back-arc regions, indicating that they occur globally and have the potential to serve as a resource.

Although not fully quantified globally, the resource potential of marine metalliferous sediments is exemplified by estimates from specific sites, such as the Atlantis II Deep basin in the Red Sea. The prospect of extracting valuable metals from them, including zinc, copper, manganese, cobalt, silver and gold, presents a compelling economic opportunity. However, the feasibility of large-scale extraction and the associated environmental impacts require careful consideration.

It is recommended that technological advancements be encouraged in the field, as marine metalliferous sediments play a crucial role in identifying, exploring and potentially recovering these resources. Various exploration strategies, ranging from mapping and sonar devices to hydrocast profiles and coring, are employed to locate sediment trap structures and assess subsurface composition. The application of trench-cutting equipment and the development of innovative extraction technologies, such as suction systems, demonstrate ongoing efforts to refine extraction processes.

It is also recommended that research on marine metalliferous sediments be broadened, as they hold promise as a future resource. The sustainable exploitation of these deposits necessitates a comprehensive understanding of their geological, environmental and economic implications. International collaboration, regulatory frameworks and ongoing research efforts will be crucial in shaping the responsible development of this emerging resource potential, ensuring its contribution to the global supply chain while minimizing environmental impact. As we navigate the complexities of extracting valuable metals from the depths of our oceans, the careful balance between economic opportunity and environmental stewardship remains paramount.

Consequently, the ISA Council should, in due course, consider a legal regime that accounts for the resource potential of these sources and the interest of Member States in exploring them for metals.

LITERATURE

Boström, K., and Peterson, M. N. A. (1969)1969. The origin of aluminum-poor ferromanganese sediments in areas of high heat flow on the East Pacific Rise. Marine Geology, 7(5), 427–-448. https://doi.org/doi: 10.1016/0025-3227(69)90016-–4.

Degens, E. T. and Ross, D. A. (1969)1969. Hot brines and recent heavy metal deposits in the Red Sea. New York: Springer.

Dekov, V. M., Scholten, J., Garbe-schönberg, D., Botz, R., Cuadros, J., Schmidt, M., and Stoffers, P. (2008)2008. Hydrothermal sediment alteration at a seafloor vent field: Grimsey Graben, Tjᐧrnes Fracture Zone, north of Iceland. Journal of Geophysical Research. Solid Earth, 113, B11101. https://doi.org/doi: 10.1029/2007jb005526.

Dymond, J. (1981)1981. Geochemistry of Nazca plate surface sediments: an evaluation of hydrothermal, biogenic, detrital, and hydrogenous sources. Geological Society of America, 154, 133–173. https://doi.org/doi: 10.1130/MEM154-p133.

Fleet, A. J. and Robertson, A. H. F. (1980)1980. Ocean-ridge metalliferous and pelagic sediments of the Semail Nappe, Oman. Journal of the Geological Society of London, 137, 403–422. https://doi.org/doi: 10.1144/gsjgs.137.4.0403.

German, C. R., Higgs. N. C., Thomson, J., et al. (1993). A geochemical study of metalliferous sediment from the TAG hydrothermal mound, 26_08"N, Mid-Atlantic Ridge. Journal of Geophysical Research, 98(B6), 9683–9692. https://doi.org/doi: 10.1029/92JB01705.

Gurvich, E. G. (2006)2006. Metalliferous sediments of the world ocean: fundamental theory of deep-sea hydrothermal sedimentation. Berlin, Heidelberg: Springer.

Halbach, P., Blum, N., Münch, U., Plüger, W., Garbe-Schönberg, D., and Zimmer, M. (1998)1998. Formation and decay of a modern massive sulfide deposit in the Indian Ocean. Mineralium Deposita, 33, 302–309. https://doi.org/doi: 10.1007/s001260050149.

Hamer, R. D. (2017)2017. The Atlantis II Sea Floor Massive Sulphide Deposit, Red Sea - Current Status and Future Programme. https://one-mine.org/

Hoggard, M.J., Czarnota, K., Richards, F.D. et al. (2020)2020. Global distribution of sediment-hosted metals controlled by craton edge stability. Nat. Geosci. 13, 504–510. https://doi.org/10.1038/s41561-020-0593-2.

Hrischeva, E., and Scott, S. D. (2007). Geochemistry and morphology of metalliferous sediments and oxyhydroxides from the Endeavour segment, Juan de Fuca Ridge. Geochimica Acta et Cosmochimica Acta, 71, 3476–3497. doi https://doi.org/: 10.1016/j.gca.2007.03.024.

Hu, Q., Zhang, X., Jiang, F., Wang, B., Luan, Z., Chen, C., and Yan, J. (2017)2017. Geochemical characteristics of hydrothermal sediments from Iheya North Knoll in the Okinawa Trough. Chinese Journal of Oceanology and Limnology, 35, 947–955. https://doi.org/doi: 10.1007/s00343-017-6035-3.

ISA (2021). Marine mineral resources: scientific and technological advances. ISA Technical study no. 30, 98p.

James, R. H. and Elderfield, H. (1996)1996. Dissolved and particulate trace metals in hydrothermal plumes at the Mid-Atlantic Ridge. Geophysical Research Letters, 23(23), 3499–3502. https://doi.org/doi: 10.1029/96GL01588.

Li, Y. H. and Schoonmaker, J. E. (2014)2014. Chemical composition and mineralogy of marine sediments. In Holland, H. D. and Turekian, K., Eds. Treatise on geochemistry (pp. 1–32). Amsterdam: Elsevier Ltd.

Marchig, V. and Erzinger, J. (1986)1986. Chemical composition of Pacific sediments near 20°S: changes with increasing distance from the East Pacific Rise; and Appendix. In Initial Reports DSDP. Vol. 92 (pp. 371–381). Washington: US Govt Print-Office. https://doi.org/doi: 10.2973/dsdp.proc.92.119.1986.

Metz, S., Trefry, J. H., and Nelsen, T. (1988)1988. History and geochemistry of a metalliferous sediment core from the Mid-Atlantic Ridge. Geochimica et Cosmochimica Acta, 52(10), 2369–2378. https://doi.org/doi: 10.1016/0016-7037(88)90294-310.1016/0016-7037(88)90294–3.

Mills, R. A. and Elderfield, H. (1995)1995. Hydrothermal activity and the geochemistry of metalliferous sediments. In Humphris, S. E., Zierenberg, R. A., Mullineaux, L. S. and Thomson, R. E., Eds. Seafloor hydrothermal systems: Physical, chemical, biological, and geological interactions. Geophysical Monograph. Vol. 91 (pp. 392–407). Washington: American Geophysical Union.

Murray, J. and Renard, A. F. (1891)1891. Deep-sea deposits. Report "Challenger" expedition (1873-1876). London: Eyre and Spottiswoode.

Mustaffa, Z. and Amann, H. (1978)1978. Ocean mining and protection of the marine environment in the Red Sea. Offshore Technology Conference, Houston, Texas, May, 1978. - OTC Paper 3188.

Pan, A., Yang, Q., Zhou, H., Ji, F., Wang, H., and Pancost, R. D. (2018)2018. Geochemical impacts of hydrothermal activity on surface deposits at the Southwest Indian Ridge. Deep Sea Research Part I Oceanographic Research Papers, 139, 1–13. https://doi.org/doi: 10.1016/j.dsr.2018.05.009.

Robertson, A. H. F. and Hudson, J. D. (1973)1973. Cyprus umbers: chemical precipitates on a Tethyan ocean ridge. Earth Planetary Science Letters, 18(1), 93–101. https://doi.org/doi: 10.1016/0012-821X(73)90039-3

Rona, P. A. and Scott, S. D. (1993)1993. A special issue on sea-floor hydrothermal mineralization; new perspectives; preface. Economic Geology, 88(8),1933–1973. https://doi.org/doi: 10.2113/gsecongeo.88.8.1935.

Rusakov, V. Y., Shilov, V. V., Ryzhenko, B. N., Gablina, I. F., Roshchina, I. A., Kuz''mina, T. G., Kononkova, N. N., and Dobretsova, I. G. (2013)2013. Mineralogical and geochemical zoning of sediments at the Semenov cluster of hydrothermal fields, 13°31☐-13°30☐ N, Mid-Atlantic Ridge. Geochemistry International, 51, 646–669. https://doi.org/doi: 10.1134/S0016702913050066.

Takaya, Y., Yasukawa, K., Kawasaki, T., Fujinaga, K., Ohta, J., Usui, Y., Nakamura, K., Kimura, J.-I., Chang, Q., Hamada, M., Dodbiba, G., Nozaki,T., Iijima, K., Morisawa, T., Kuwahara, T., Ishida, Y., Ichimura, Y., Kitazume, M., Fujita, T., and Kato, Y. (2018). The tremendous potential of deepsea mud as a source of rare-earth elements. Scientific Reports, 8, 5763. https://doi.org/doi: 10.1038/s41598-018-23948-5.

Watson, S. W. and Waterbury, J. B. (1969)1969. The sterile hot brines of the Red Sea. In Degens, E. T. and Ross, D. A., Eds. Hot Brines and Recent Heavy Metal Deposits in the Red Sea (pp. 272–281). New York: Springer.

Weber-Diefenbach, K. (1977)1977. Geochemistry and diagenesis of recent heavy metal ore deposits at the Atlantis II deep (Red Sea). In Klemm, D.D. and Schneider, H. J., Eds. Time and stratabound ore deposits (pp. 419–436). New York: Springer.

Zierenberg, R. A. (1990)1990. Deposition of metalliferous sediments beneath a brine pool in the Atlantis II Deep, Red Sea. In McMurray, G. R., Ed. Gorda ridge- a seafloor spreading centre in the United States Exclusive Economic Zone (pp. 131-–142). New York: Springer