



Deep-Ocean Mineral Deposits: Metal Resources and Windows into Earth Processes

Paul A. J. Lusty¹ and Bramley J. Murton²

1811-5209/18/0014-0301\$2.50 DOI: 10.2138/gselements.14.5.301

Deep-ocean mineral deposits could make a significant contribution to future raw material supply. Growing metal demand and geopolitics are focussing increasing attention on their resource potential and economic importance. However, accurate assessment of the total amounts of metal and its recoverability are very difficult. Deep-ocean mineral deposits also provide valuable windows through which to study the Earth, including the evolution of seawater and insights into the exchange of heat and chemicals between the crust and the oceans. Exploration for, and potential extraction of, deep-ocean mineral deposits poses many geological, technical, environmental and economic challenges, as well as regulatory and philosophical questions. Great uncertainty exists, and the development and stewardship of these deposits requires an incremental approach, encouraging transparency and scientific and civil societal input to balance the interests of all.

KEYWORDS: ocean floor, mineral deposits, ferromanganese nodules, Fe–Mn crusts, sulfides, metals, resources, International Seabed Authority

THE BLUE PLANET: EARTH'S FINAL FRONTIER

The Earth's oceans form a continuous body of saltwater covering more than two thirds of the planet and storing 97% of its water. With an average depth of about 3,700 m (Charette and Smith 2010), the oceans are widely considered to be Earth's final frontier. They control global climate and weather and have provided humanity with many resources for millennia. Extending away from land, the oceans are divisible into three main regions: the continental shelf, where water depths are generally less than 200 m; the continental slope; and the flat or gently sloping abyssal plain, typically occurring at depths greater than 4,000 m (Fig. 1). Although a poorly defined term, the 'deep' ocean may be considered to be seafloor below 200 m where, with little penetration of sunlight, photosynthesis is not possible. The deep seafloor covers about 60% of the Earth's surface and hosts a spectrum of geological settings, geomorphologic features and ecosystems. This diversity, and its long and dynamic history, results in the deep seafloor hosting mineral deposits that are both similar to those found on the continents as well as types unique to the oceans.

Despite its fundamental importance, due to its sheer size, we lack basic information about many aspects of the deep ocean. The challenges of sensing what lies below the water

surface in an alien environment for humans, makes access difficult, costly and reliant on technology. After decades of ocean exploration, only about 10% of the ocean floor has been surveyed by ship-based sonar systems (Becker et al. 2009), and these provide only an average resolution of about 100 metres squared.

A Brief History of Deep-Ocean Mineral Exploration

Oceans have fascinated humans throughout history and the notion of deep-ocean mining goes back to at least 1870 when, in Jules Verne's classic book *20,000 Leagues under the Sea*, Captain Nemo

announced that, "In the depths of the ocean, there are mines of zinc, iron, silver and gold that would be quite easy to exploit." Metal-rich nodules from the deep-ocean floor were described during the HMS *Challenger* expedition (1872–1876) and the potential economic importance of these nodules was acknowledged even at this time. In the 1960s, the oceanographer John L. Mero sparked considerable interest in these deposits when he estimated huge ferromanganese (Fe–Mn)-nodule resources in the Pacific Ocean and predicted an essentially endless supply of metals such as Mn, Cu, Ni, and Co (Mero 1965). The interest in Fe–Mn nodules prompted investigations during the 1980s and 1990s into similar Fe–Mn-rich crusts that can coat rocks on the seafloor.

Major deposits of metalliferous, sulfide-rich sediments were discovered beneath the Red Sea in the mid-1960s, at what is known as the Atlantis II Deep. Although volcanism was long considered a potential source of metals to the marine environment (e.g. Murray and Renard 1891), and seafloor hydrothermal activity had been postulated, direct, visual verification only came with the discovery of metal-bearing 'submarine thermal springs' or 'hydrothermal vents' on the seafloor of the Galapagos Rift in 1977 (Corliss 1979). Further hydrothermal vents and actively forming 'massive ore-grade' sulfide deposits, now known either as seafloor massive sulfide or polymetallic sulfide deposits, were subsequently observed on a mid-ocean ridge called the East Pacific Rise (Francheteau et al. 1979). Recognition that these were the modern analogues of the volcanogenic massive sulfide deposits preserved in ancient oceanic crust on land promoted a flurry of further exploration of the deep seafloor.

1 British Geological Survey
Environmental Science Centre
Keyworth, Nottingham, NG12 5GG, UK
E-mail: plusty@bgs.ac.uk

2 National Oceanography Centre
European Way
Southampton, SO14 3ZH, UK
E-mail: bramley.murton@noc.ac.uk

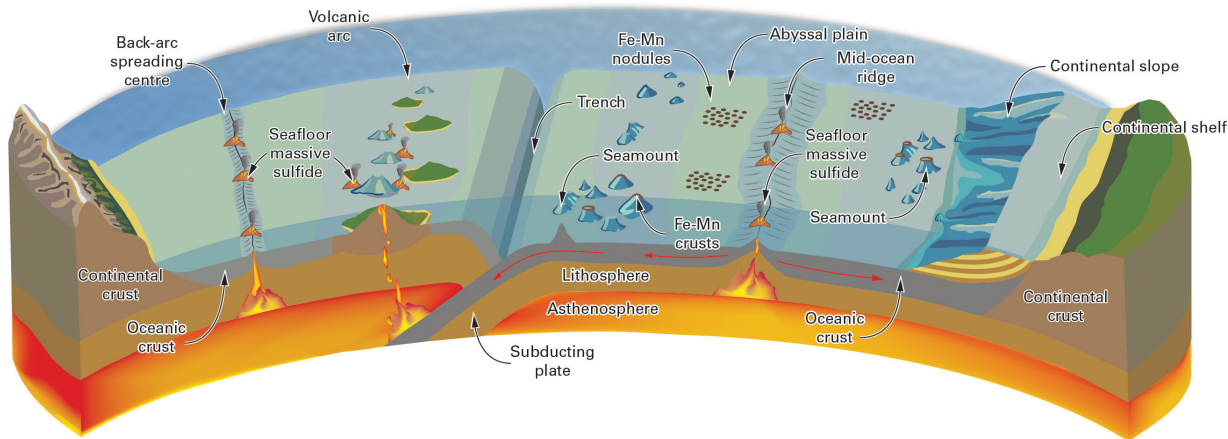


FIGURE 1 A cross-section through the Earth's crust showing the different types of plate boundary, the topography of the ocean floor and the distribution of the major metal-rich deep-ocean mineral deposits. IMAGE: IAN LONGHURST (COPYRIGHT BRITISH GEOLOGICAL SURVEY © UKRI 2018).

METALLOGENY OF THE DEEP OCEAN: AN EVOLVING PERSPECTIVE

A long-held view was that the ocean basins were relatively static features, in which particulate and dissolved matter that had been weathered from the continents accumulated over eons of time. This model adequately explained many near-shore marine mineral deposits that have been exploited for decades. The theory of plate tectonics and the concept of plate boundaries radically transformed this view (Fig. 1). We now understand the importance of magmatic processes on ocean-basin formation – including the flux of heat, fluid and chemicals between the mantle, crust and oceans. This, and the awareness of plate boundaries acting as loci for active mineralization (Figs. 1, 2), has had a huge impact on our appreciation of the geological controls on mineral deposit formation and, hence, on the resource potential of the deep-ocean floor (Rona 2008).

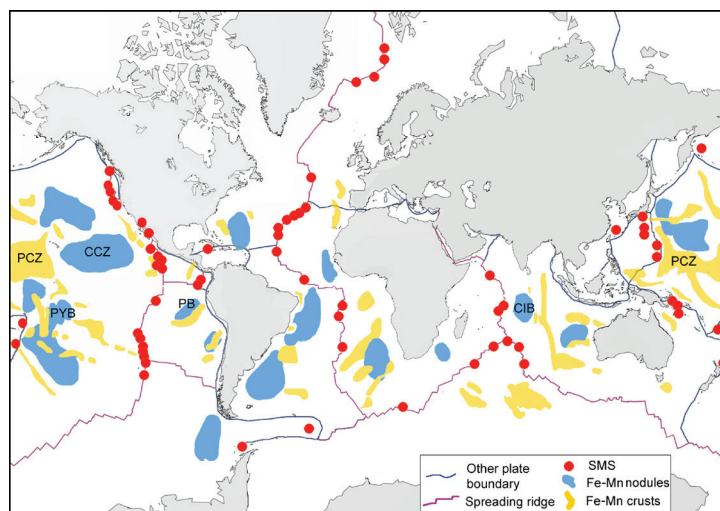


FIGURE 2 Global distribution of the three primary classes of metal-rich deep-ocean mineral deposits: sea floor massive sulfides (SMS); ferromanganese (Fe-Mn) nodules; and ferromanganese (Fe-Mn) crusts. Spreading ridges and other plate boundaries are shown. Abbreviations: CCZ = Clarion-Clipperton Zone; CIB = Central Indian Ocean Basin; PB = Peru Basin; PCZ = Prime Crust Zone; PYB = Penrhyn Basin. Map created using the NOAA National Geophysical Data Center and redrawn from multiple sources, including Murton et al. (2000), Beaulieu et al. (2013), and Hein et al. (2013). COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

Primary Classes of Deep-Ocean Mineral Deposits

Commercial interest, scientific research and regulatory activity is currently focused on three classes of metal-rich deep-ocean mineral deposits, each with distinct geology (i.e. processes of formation and metal tenors), environments of formation, associated ecosystems, specific technological requirements for exploration and extraction, and regulatory challenges.

Ferromanganese Nodules

Ferromanganese (or 'polymetallic') nodules are mineral concretions, composed of Fe oxyhydroxide and Mn oxide. They are variable in shape and size, typically 1–12 cm in maximum dimension. They are most abundant on the ocean's abyssal plains, at water depths of 4,000–6,500 m, where they lie on or immediately below the sediment-covered seafloor (Figs. 1, 2, 3A). Here, Fe and Mn oxide colloids slowly precipitate around a hard nucleus (Figs. 3B, 3C) over millions of years, from ambient seawater (hydrogenetic) and sediment pore waters (diagenetic). Nodule formation is favoured by a range of environmental factors, which are also used as a basis for defining prospective areas for seafloor exploration (Fig. 2). There are five main environmental factors for nodule formation: 1) slow sedimentation rates and bioturbation, which keeps the nodules close to the surface of the seafloor; 2) bottom currents that remove fine sediments and oxygenate the abyssal plain; 3) moderate levels of primary productivity in the surface waters that supply sediment-dwelling bacteria with sufficient organic matter for use in diagenetic reactions that release metals to the pore fluids; 4) semi-liquid sediments that enhance the amount of pore water and diagenetic input to nodule

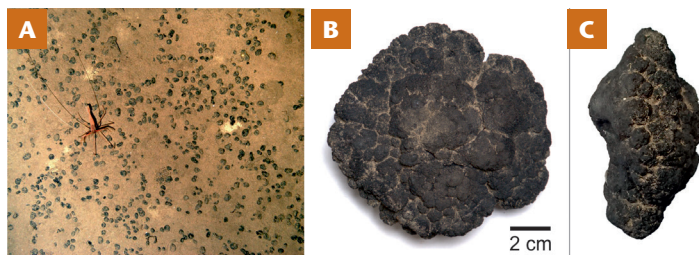


FIGURE 3 Ferromanganese nodules from the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean. (A) Nodules on the sediment-covered abyssal plain in the northeastern 'Area of Particular Environmental Interest' encountered on the RRS *James Cook* cruise JC120 using the autonomous underwater vehicle *Autosub6000*. (B) Upper surface of a large, 11 cm wide nodule. The rough botryoidal surface results from hydrogenetic growth. (C) Side view of the same nodule, showing the flattened shape and smoother base produced by diagenetic growth. COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

growth; and 5) location close to and below the calcite compensation depth (the depth at which calcite dissolves quicker than it can accumulate) (Hein and Koschinsky 2014). The physicochemical properties of the Fe and Mn colloids under oxic conditions make them excellent at scavenging dissolved metals from seawater. Through these processes, nodules are strongly enriched in Ni, Cu, Co, Mo, Zr, Li, Y and rare-earth elements (REEs) relative to the Earth's crust (Hein et al. 2013).

Ferromanganese Crusts

In contrast to Fe–Mn nodules, ferromanganese (Fe–Mn) crusts precipitate on hard surfaces in the ocean, where they are also termed ‘cobalt crusts’, ‘cobalt-rich crusts’ and ‘manganese crusts’ (FIG. 4). They are mineralogically similar to hydrogenetic Fe–Mn nodules and, until the late 1970s, little distinction was made between the two deposit types (Hein and Koschinsky 2014). Their similar physicochemical properties to nodules and their hydro-genetic mechanism of formation means that they also sequester large quantities of metals from ambient seawater. Genetic models for the formation of these deposits are reviewed by Lusty et al. (2018 this issue) who illustrate the importance of local-scale oceanographic processes on crust formation. In addition to their extreme metal enrichments, and therefore, mineral resource potential, they are also important because their stratigraphic layers preserve the isotope composition of seawater at the time of their deposition. This can provide a record of ocean and climatic evolution that might span thousands to tens of millions of years (Koschinsky and Hein 2017). Ferromanganese crusts also influence the concentration of some elements and their redox state in the marine environment (Hein and Koschinsky 2014). A novel example of their scientific application is the use of isotope stratigraphy to date Fe–Mn crusts that coat fossil whale bone: this technique can estimate the time since the whale carcass was deposited and provide temporal constraints on the evolution of the seafloor biotic communities that these carcasses support (Nozaki et al. 2017).

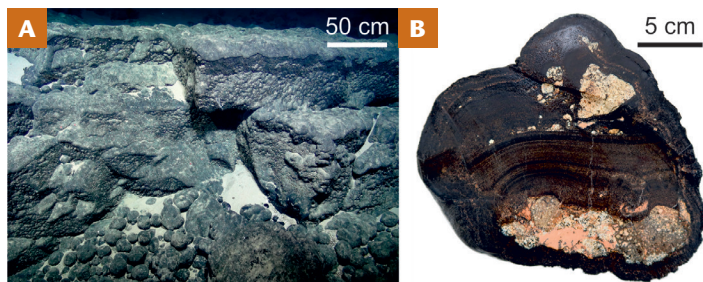


FIGURE 4 Ferromanganese crusts from Tropic Seamount in the northeast Atlantic Ocean encountered during the RSS *James Cook* cruise JC142. (A) Crusts on the flank of the seamount, photographed from the remotely operated vehicle (ROV) *Isis*. (B) Section through a crust sample that shows a complex history of development on fragments of phosphatized sedimentary substrate rock, collected using ROV *Isis*. COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

Seafloor Massive Sulfides

Hydrothermal venting of metal-rich fluids is associated with magmatic activity, typically at the boundaries of tectonic plates. It occurs in all the oceans at depths down to 5,000 m (Beaulieu et al. 2013) (FIGS. 1, 2). This phenomenon is one of the most spectacular examples of geology in action (FIG. 5A). The discovery of hydrothermal vents, including the dense, faunal communities that these sites support (discussed by Jones et al. 2018 this issue), is considered among the most remarkable scientific finds of the 20th century. Many scientists think this is where some of the

earliest life on Earth may have originated (Dodd et al. 2017). Seafloor hydrothermal processes are estimated to circulate the entire volume of the global oceans through the oceanic crust over timescales of about 200,000 years (Johnson and Pruis 2003). The immense scale of this process means it plays a critical role in removing heat from the Earth's crust and controlling the metal budgets of seawater. The characteristics and importance of the related base- and precious metal-rich seafloor massive sulfide deposits (FIGS. 5B, 5C) are explored by Petersen et al. (2018 this issue).

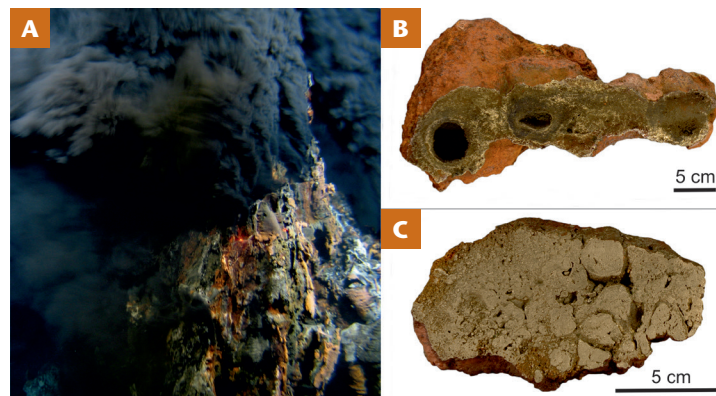


FIGURE 5 Submarine hydrothermal activity and seafloor massive sulfide (SMS) mineralization. (A) The top of vent chimney ‘Balor’, located at a depth of 3,000 m in the ‘Moytirra Vent Field’ at 45°N on the Mid-Atlantic Ridge, photographed from the remotely operated vehicle (ROV) *Holland 1*; courtesy of A. Wheeler, B. Murton and the VENTURE cruise participants, and the Marine Institute, Ireland. (B) Cut section of sulfide chimney from the Trans-Atlantic Geotraverse (TAG) area of the Mid-Atlantic Ridge. (C) Pyrite-rich SMS mineralization from the TAG Field. Samples shown in (B) and (C) were collected using the ROV *HyBis*, during *James Cook* cruise JC138. COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

DEEP-OCEAN EXPLORATION AND MINING

Despite the major technological advances in nodule recovery and the successful pre-pilot mining and metallurgical testing at the Atlantis II Deep site (central Red Sea) during the 1970s and early 1980s when there was great optimism and a widely held belief that deep-ocean mining would commence by the late 20th century, subsequent progress has been slow and unsteady. This was due to adequate supply of metals from land-based mines; to unfavourable economic conditions, including rising energy costs and stable or declining metal prices; to technological challenges; to a growing environmental awareness; and to obligations arising from the United Nations Convention on the Law of the Sea (described by Lodge and Verlaan 2018 this issue). However, with many of these obstacles receding, there is renewed interest in the exploitation of deep-ocean mineral deposits from the private sector, governments, policy makers, regulators, researchers, and non-governmental organizations.

Drivers for Deep-Ocean Minerals Extraction: Why Now?

The mining industry is fond of saying, “If it can’t be grown, it has to be mined.” The Earth’s crust provides almost all of society’s minerals and metals, the vast majority of which are currently derived from mining on land. Global metal demand is increasing, primarily linked to population growth and urbanization, and there are concerns about the security of supply of raw materials due to uneven resource distribution and geopolitics. In recent years, certain metals have been designated as ‘critical’, primarily owing to their economic importance and likelihood of supply shortage.

These factors coupled with the increasing challenges of land-based mining (Calas 2017) are motivating the search for alternative sources of mineral raw materials. Whilst there are many land-based options that can contribute to future mineral supplies, for an industry that accepts significant risk and that has flourished by expanding into new and extreme environments, the deep ocean represents just another frontier.

Present Activity

No commercial-scale deep-ocean mining has yet taken place, but the following developments point to current significant global activity:

- As of February 2018, the International Seabed Authority (ISA) had approved 26 contracts for exploration on the international seabed. The role and activity of the ISA is described by Lodge and Verlaan (2018) in this issue.
- Mineral exploration is also occurring in seabed areas that fall within the jurisdiction of coastal states. For example, the Solwara 1 seafloor massive sulfide project in the Bismarck Sea of Papua New Guinea is at the forefront of the race to become the world's first commercial deep-ocean mine, having already been granted an environmental permit and seabed mining lease.
- There is an increase in government-funded research and resource evaluation programs in numerous countries, including Brazil, China, France, Germany, India, Japan, Korea and Russia. Relevant national legislation is also being updated, which is rapidly enabling a deep-ocean minerals industry, for example the UK Deep Sea Mining Act (2014).
- There is a proliferation of academic research, peer-review publications (e.g. Hein et al. 2013; Petersen et al. 2016) and both popular media and non-governmental organization coverage on the topic.

TECHNICAL CHALLENGES

Determining the Magnitude of the Resource: What We Do and Don't Know

Beyond the first-order assumption that deep-ocean mineral resources are likely to be proportionate to the area of the seafloor (Hannington et al. 2011), we know that specific geodynamic and oceanographic settings control the types of mineral deposits that form and that they influence deposit spatial density, size, form and geochemistry (Figs. 1, 2). Although current estimates of seafloor mineral resources contain significant uncertainties (e.g. Petersen et al. 2018 this issue), recent studies conclude that the deep seabed hosts large quantities of metals, sometimes exceeding land-based mineral 'reserves' i.e. resources that are currently economic to extract (Hein et al. 2013; Cathles 2015).

The composition of Fe–Mn nodules varies at regional to intra-nodule scales (Hein and Koschinsky 2014), but estimates suggest that they may represent one of the most abundant mineral resources on Earth. The metals of greatest economic interest in Fe–Mn nodules are Ni and Co and, to a lesser extent, Cu and Mn. The greatest known concentration of Ni and Cu-rich Fe–Mn nodules occur in the so-called Clarion–Clipperton Zone in the eastern equatorial Pacific Ocean where nodule density can reach a wet weight of 75 kg·m⁻² of seabed (Hein and Koschinsky 2014; Petersen et al. 2016). Additional, important, occurrences are found in the Peru Basin off South America and in the Central Indian Ocean Basin. The most prospective area for cobalt-rich Fe–Mn nodules is the Penrhyn Basin, close to the Cook Islands in the South Pacific (Fig. 2). The

Clarion–Clipperton Zone alone is predicted to contain 21 billion tonnes of nodules, hosting about 280 Mt of Ni (i.e. 3.5 times greater than the total land-based 'reserves'), 220 Mt of Cu, and 40 Mt of Co (i.e. 5.5 times the land-based 'reserves') (Hein and Koschinsky 2014). Although the Clarion–Clipperton Zone is approximately the size of Europe, it only represents a small proportion of the total seafloor that is currently considered prospective for Fe–Mn nodules, which exceeds 51 million km² (i.e. larger than the land area of Asia). There are still vast swathes of the ocean floor yet to be explored and whose mineral potential remains unknown (Petersen et al. 2016). Despite the remarkable concentration of some critical metals in Fe–Mn crusts, Lusty et al. (2018 this issue) urge caution over the reliability of existing resource estimates because of the sampling methods typically employed.

Technology-Driven Science: Drones and Robots

Without a step change in surveying technology, high-resolution mapping of the entire deep-ocean floor is not realistic. Yet, predicting and exploring the most prospective zones is surely a priority. Even this is fraught with uncertainty because current activity naturally focusses on the areas of highest perceived prospectivity based upon historical exploration and existing mineral-deposit models drawn from relatively restricted geographic areas. It can be argued that the deep ocean is so poorly explored that we may not currently even be targeting the optimum zones.

Deep-ocean mineral exploration employs a range of techniques that include ship-based swath sonar bathymetric mapping, geophysical surveying, and the use of autonomous underwater vehicles and remotely operated vehicles to carry a range of sensors (Fig. 6A). Developments in autonomous underwater vehicle technology, including increased autonomy, longer range, improved hovering capabilities and new geophysical and geochemical sensing tools, are key to more efficient seafloor mapping (Wynn et al. 2014). Increased use of swarms of autonomous underwater vehicles that can synchronously map parallel tracts of the seafloor is required. The efficient and rapid interrogation of the huge volume of new data generated will rely on developments in automated image analysis and artificial intelligence. Petersen et al. (2018 this issue) emphasize the importance of seafloor drilling for accurate resource evaluations (Fig. 6B). However, for this to become routine, the technology will have to become more efficient and reliable to reduce the cost of obtaining drill core.

Mining Technology Development and Economics

Technology readiness needs to be considered across the entire lifecycle of operations, from exploration and resource assessment through to mining (Fig. 6C), ore transport, environmental monitoring and management, mineral processing, and metal recovery (Fig. 7).

Ferromanganese crusts are the most technically challenging deep-ocean mineral deposits to recover because they are firmly attached to often steep and uneven rock surfaces (Fig. 4A). Test mining of Fe–Mn nodules and seafloor massive sulfides has already been undertaken. However, full-scale deep-ocean mining systems, including ship-to-ship ore transfer and equipment reliability in ~5,000 m water depths, still require field testing (Fig. 7). Deposit-specific, integrated field tests and pilot mining projects are required to prove the technical feasibility, to assess environmental impacts of mining and to help establish reliable financial and risk models. The costs involved may necessitate a consortium approach, like that successfully employed to reduce risk in the hydrocarbon sector. Another possibility

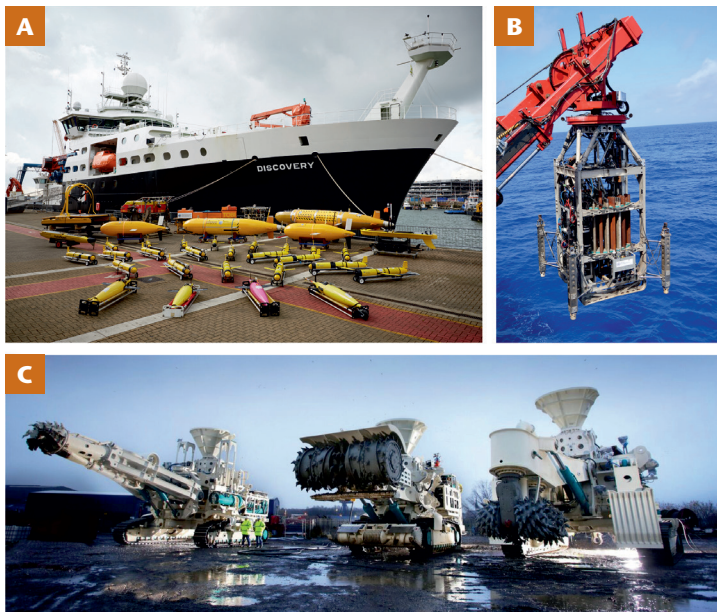


FIGURE 6 Deep-ocean exploration and mining equipment. (A) The UK marine research vessel RRS *Discovery* and an array of equipment, including autonomous underwater vehicles, used for surveying and monitoring the marine environment. (B) Deployment of the British Geological Survey remotely operated sub-sea rock drill (RD2) to acquire drill core from seafloor massive sulfide deposits on the Mid-Atlantic Ridge (RRS *James Cook* cruise JC138). COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018. (C) Deep-sea mining machines manufactured by the UK-based engineering firm SMD (Soil Machine Dynamics Ltd) for Canada-based Nautilus Minerals Inc. PHOTO: SMD, WWW.SMD.CO.UK.

is that national strategic interests and the pursuit of stable supplies of raw materials, with government backing, could result in fast-tracked deep-ocean mining operations. For example, in 2017, Japan, a country heavily dependent on mineral imports, excavated seafloor massive sulfide ore and transported it to the surface in their waters off the coast of Okinawa. However, the long-term development of these resources will be principally based on economic criteria and their ability to compete with land-based mines.

Uncertainties at each stage of the deep-ocean mining value chain, coupled with the potential for future metal price volatility, limit confidence in the profitability of deep-ocean mining. However, the European Commission indicates that marine seabed mining activities could potentially contribute to sustainable economic growth. They estimate that by 2030 as much as 10% of the world's minerals could be derived from the ocean floor (European Commission 2012). Preliminary assessments, based upon numerous assumptions, suggest that the mining of seafloor massive sulfide deposits and nodules could be economically competitive compared with mining some large, low-grade deposits on land (Cathles 2015). The International Seabed Authority consider that deep-ocean mining "appears to be feasible" under certain conditions, namely, deposits having high-grade ores, being proximal to land and occurring in relatively shallow water depths. However, very few sites are currently considered to have sufficient size and grade for potential future mining (International Seabed Authority 2002). The Solwara 1 seafloor massive sulfide deposit (off Papua New Guinea) is relatively small, with an inferred total mineral resource of ~1.4 million tonnes at a grade of ~8% Cu and ~6 g/t Au. By comparison, ancient volcanogenic massive sulfide

deposits on land can contain resources of >150 million tonnes. However, Solwara 1 is one of only a few deep-ocean deposits with a mineral resource estimate that is compliant with international reporting standards. It is high-grade compared to many comparable land-based deposits, lies at a water depth of about 1,600 m, is about 50 km from land and is considered "potentially economically viable" to extract (AMC Consultants 2018).

Extracting ore from the seabed and transporting it to the surface or to land is only the first stage in recovering metals from deep-ocean mineral deposits (Fig. 7). Uncertainty also surrounds the processing of the mined ores and the number of metals that can be economically recovered. The potential for improving the efficiency and reducing the environmental impact of metal extraction from deep-ocean mineral deposits is explored by Zubkov et al. (2018 this issue).

ENVIRONMENTAL IMPACTS AND REGULATORY CHALLENGES

One of the greatest challenges facing the development of deep-ocean mining is gaining the social license to operate: the perception that the potential risks and environmental impacts are too great needs to be overcome. Addressing this will require education, engagement, transparency and, crucially, confidence in the governance framework. Jones et al. (2018 this issue) examine the environmental risks posed by deep-ocean mining, highlighting the need for a first-order understanding of many deep-sea ecosystems that may be affected. This fundamental knowledge is essential to inform development of an evidence-based, robust and socially acceptable regulatory framework for deep-ocean mineral extraction, a complex and emotive topic that is explored by Lodge and Verlaan (2018 this issue). These latter authors provide an overview of the role of the International Seabed Authority in deep-ocean mineral stewardship and the challenges faced in establishing a comprehensive and dynamic regulatory regime for these unique natural resources, which protects the interests of numerous stakeholders.

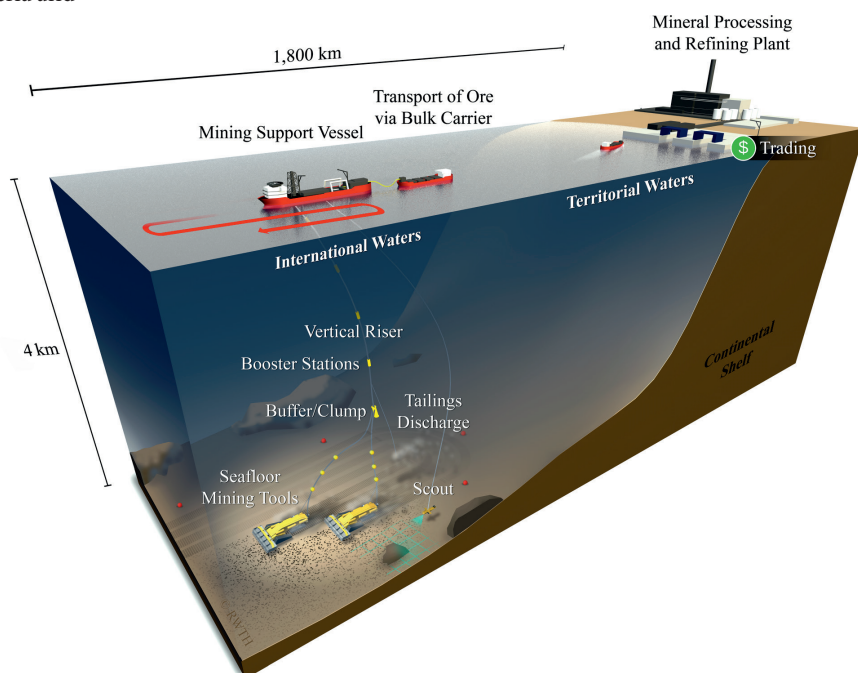


FIGURE 7 Concept for a deep-ocean ferromanganese nodule mining operation. IMAGE: VOLKMAN AND LEHNEN (2017). PUBLISHED WITH LICENSE BY TAYLOR & FRANCIS © 2017.

OUTLOOK

We have sufficient metal resources on land for decades to come. However, as demand grows, the combination of high base- and precious metal grades, and the extreme enrichment of some critical metals in deep-ocean mineral deposits, is likely to result in their eventual extraction. How quickly this happens is highly uncertain, as the development of deep-ocean mining will be influenced by a number of factors that are diverse, dynamic and often interrelated (spanning economics, geopolitics, technology, environment, regulation and societal acceptance).

Extracting these resources will present something of a societal conundrum. Mining will inevitably impact the natural environment, yet many of the metals that these resources contain are the very ones vital to technologies that are integral to society developing a low-carbon future, meeting global sustainable development goals and ensuring the long-term health of the planet. As discussed by Lodge and Verlaan (2018 this issue), automatic opposition to deep-ocean mining is not constructive when its overall environmental impact relative to land-based sources of these metals is uncertain. Currently, we lack the fundamental knowledge about the deep-ocean biosphere to make objective, evidence-based decisions on how best to regulate the sustainable and equitable extraction of these mineral deposits. Furthermore, deep-ocean mineral

deposits can only be considered mineral 'resources' in the broadest sense, as whilst they have anticipated future value commercial-scale economic extraction of metals is largely unproven. It is now, therefore, time to prepare by increasing the rate of seafloor exploration and research to increase our confidence in resource assessments. By these means, we can then determine which resources are most accessible and can be mined with minimum environmental impact if required. The sheer scale of the task appears overwhelming: the exploration areas are typically intercontinental in scale, very remote and in water depths reaching several thousand metres. The key to advancing understanding, to improving the efficiency of exploration and to reducing costs will be international collaboration between different academic disciplines and industry, innovative technology and ensuring that data are openly available.

ACKNOWLEDGMENTS

PL publishes with the permission of the Executive Director, British Geological Survey (UKRI). We thank reviewers Sven Petersen and Stephen Roberts for their thoughtful comments, which helped improve the paper, and we thank Gus Gunn for his input. In addition, the Principal Editor Nancy Ross and Executive Editor Jodi Rosso are thanked for guiding us through the *Elements* publishing process and being the final reviewers for the collection of papers. ■

REFERENCES

- AMC Consultants (2018) Preliminary Economic Assessment of the Solwara Project Bismarck Sea, PNG for Nautilus Minerals Niugini Ltd. Technical Report AMC Project 317045, 274 pp
- Beaulieu SE, Baker ET, German CR, Maffei A (2013) An authoritative global database for active submarine hydrothermal vent fields. *Geochemistry, Geophysics, Geosystems* 14: 4892-4905
- Becker JJ and 18 coauthors (2009) Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy* 32: 355-371
- Calas G (2017) Mineral resources and sustainable development. *Elements* 13: 301-306
- Cathles LM (2015) Future Rx: optimism, preparation, acceptance of risk. In: Jenkins GRT and 5 coeditors (eds) *Ore Deposits in an Evolving Earth*. Geological Society, London, Special Publications 393, pp 303-324
- Charette MA, Smith WHF (2010) The volume of Earth's ocean. *Oceanography* 23: 112-114
- Corliss JB and 10 coauthors (1979) Submarine thermal springs on the Galápagos Rift. *Science* 203: 1073-1083
- Dodd MS and 7 coauthors (2017) Evidence for early life in Earth's oldest hydrothermal vent precipitates. *Nature* 543: 60-64
- European Commission (2012) *Blue Growth: Opportunities for Marine and Maritime Sustainable Growth*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Publications Office of the European Union, Luxembourg, 494 final, 12 pp, doi: 10.2771/43949
- Francheteau J and 14 coauthors (1979) Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise. *Nature* 277: 523-528
- Hannington M, Jamieson J, Monecke T, Petersen S, Beaulieu S (2011) The abundance of seafloor massive sulfide deposits. *Geology* 39: 1155-1158
- Hein JR, Mizell K, Koschinsky A, Conrad TA (2013) Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: comparison with land-based resources. *Ore Geology Reviews* 51: 1-14
- Hein JR, Koschinsky A (2014) Deep ocean ferromanganese crusts and nodules. In: Holland HD, Turekian KK (eds) *Treatise on Geochemistry*, 2nd Edition, volume 13, Elsevier, pp 273-291
- International Seabed Authority (2002) *Polymetallic Massive Sulphides and Cobalt-rich Ferromanganese Crusts: Status and Prospects*. ISA Technical Study no. 2. International Seabed Authority, Kingston, Jamaica, 116 pp
- Johnson HP, Pruis MJ (2003) Fluxes of fluid and heat from the oceanic crustal reservoir. *Earth and Planetary Science Letters* 216: 565-574
- Jones DOB, Amon DJ, Chapman ASA (2018) Mining deep-ocean mineral deposits: what are the ecological risks? *Elements* 14: 325-330
- Koschinsky A, Hein JR (2017) Marine ferromanganese encrustations: archives of changing oceans. *Elements* 13: 177-182
- Lodge MW, Verlaan PA (2018) Deep-sea mining: international regulatory challenges and responses. *Elements* 14: 331-336
- Lusty PAJ, Hein JR, Josso P (2018) Ferromanganese crusts: Earth's storehouse for critical metals. *Elements* 14: 313-318
- Mero JL (1965) *The Mineral Resources of the Sea*. Elsevier, Amsterdam, 312 pp
- Murray J, Renard AF (1891) Origin of the manganese and manganese nodules. Report on Deep-Sea Deposits based on the Specimens Collected during the Voyage of H.M.S. Challenger in the Years 1872 to 1876. In: Thomson CW and Murray J (eds) *Report on the Scientific Results of the Voyage of H.M.S. Challenger during the Years 1873-76: Deep-Sea Deposits*. Her Majesty's Stationary Office, London, pp 372-378
- Murton BJ, Parsons LM, Hunter P, Miles P (2000) *Global Non-Living Resources on the Extended Continental Shelf: Prospects at the Year 2000*. International Seabed Authority, Technical Study No.1, Kingstown, Jamaica, 161 pp
- Nozaki T and 10 coauthors (2017) Depositional age of a fossil whale bone from São Paulo Ridge, South Atlantic Ridge, based on Os isotope stratigraphy of a ferromanganese crust. *Resource Geology*, doi: 10.1111/rge.12138
- Petersen S and 5 coauthors (2016) News from the seabed – geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy* 70: 175-187
- Petersen S, Lehrmann B, Murton BJ (2018) Modern seafloor hydrothermal systems: new perspectives on ancient ore-forming processes. *Elements* 14: 307-312
- Rona PA (2008) The changing vision of marine minerals. *Ore Geology Reviews* 33: 618-666
- Volkman SE, Lehnen F (2017) Production key figures for planning the mining of manganese nodules. *Marine Georesources & Geotechnology* 36: 360-375
- Wynn RB and 13 coauthors (2014) *Autonomous Underwater Vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience*. *Marine Geology* 352: 451-468
- Zubkov MV, Plucinski PK, Dartiguelongue ACY, Lusty PAJ (2018) Metal extraction from deep-ocean mineral deposits. *Elements* 14: 319-324 ■