REPORT

New Mineral Exploitation Frontiers within the 'Blue Planet'

An outstanding feature of the past few decades has been the number of major technological advances, for example in the fields of electronics and metallurgy. All of these utilise metals such as copper, manganese, cobalt and nickel, but there is growing demand for lesser-known commodities, including the rare earth elements (REE), that are present in very small amounts in various minerals (*Mercian Geologist, v.19, p.102-105, 2017*). Traditionally mined on land, attention is now turning to the possibility of obtaining all of these materials from the planet's deep ocean basins.

A comprehensive review of offshore mineral resources by K. Papavasileiou (*2014: 1st European Rare Earth Resources Conference, Milos*) notes that the sandy, shallower waters of continental shelves are already established sources of placer deposits for diamonds and gold, as well as minerals containing tin, titanium, thorium, uranium, zirconium and the 'light heavy minerals' rich in REE, such as monazite and allanite. Mining the deep ocean basins will be more challenging but attractive in that it opens up vast multi-element prospects, many in areas that lie beyond the limits of national jurisdiction. It is not a complete free-for-all, however: licensing and general control of activities, including protection of the seabed environment, is exercised through the auspices of the International Seabed Authority. Based in Jamaica, this is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea.

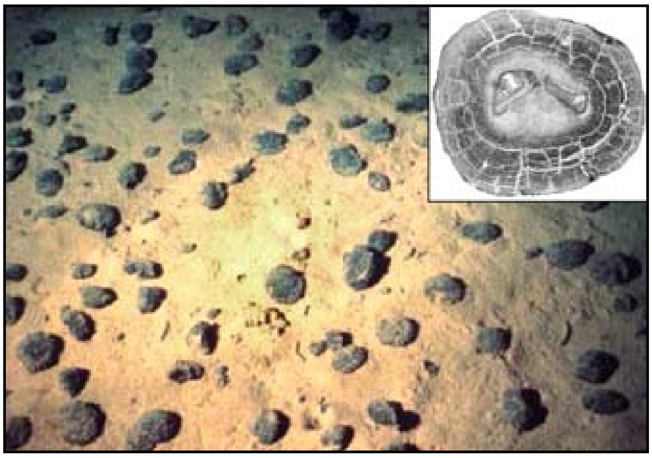
Scientific exploration of the oceanic basins began in earnest during the 1960s, when their pivotal role in the formation and dispersal of tectonic plates was first realised. Detailed seismic, bathymetric and magnetometer surveys were conducted to constrain oceanic topography and rates of seafloor spreading, and rock and sediment samples either drilled or dredged from the ocean floors were studied. Building upon earlier surveys, researchers became attracted to the mineral potential of these seafloor samples, although at that time there seemed little call for new supplies of commodities such as the rare earths. As for the commoner elements known to be present, such as manganese and copper, these could always be obtained much more cheaply on land.

A number of factors explain why the oceans are now an important exploration priority, but two stand out. Firstly, the exponentially increasing demand for the 'technology minerals' required for 'green' products such as wind turbines, solar panels, advanced batteries and fuel-efficient power units, has brought with it the realisation that terrestrial supplies could eventually be exhausted (*Financial Times, August 2017*). The second factor concerns geopolitics, global market forces and strategic technology issues, and is exemplified by the recent furore over the supply of REE. China currently produces 95% of the world's rare earths and its rich natural resources, plus a beneficial combination of state subsidy, lax environmental laws, and cheap labour costs, has allowed it to dominate the market. This was demonstrated in 2010, when China briefly embargoed rare earth exports to Japan, Europe and the USA. Although this stimulated exploration, China's response was then to over-produce, driving down REE prices and by 2015 forcing into bankruptcy various exploration initiatives and also the re-opened Mountain Pass mine in California. Companies currently seeking to buy out this 'failure' include one with alleged affiliates in China, a manoeuvre that has been brought to the attention of President Trump (*Bloomberg Politics, July 2017*). Arising from all this, a new urgency to obtain secure supplies of these strategic commodities has triggered a 'technomineral rush' to the oceans by competing companies and research organisations. Most of these are either sponsored or financially backed by governments, who see this as a potentially lucrative investment. For example, in March 2013 the Prime Minister said that deep-sea mining alone could be worth £40bn to Britain over the next 30 years.

The Royal Society's 'Future of the Oceans' evidence pack (2017) highlights three main types of deep-sea mineral setting of potential economic importance. Polymetallic nodules are perhaps the best known type of deposit, but planning is now well advanced to mine polymetallic sulphides emitted by hydrothermal vents; and the feasibility of mining cobalt-ferromanganese crusts is also under consideration. A new resource that is currently in the early exploration stage comprises REE-yttrium muds.

Polymetallic nodules

These nodules are found embedded in the surficial parts of muddy ocean floors at depths between 4000 and 6000 metres. First discovered in 1868 in the Kara Sea, off Novaya Zemlya in the Arctic Ocean, they were



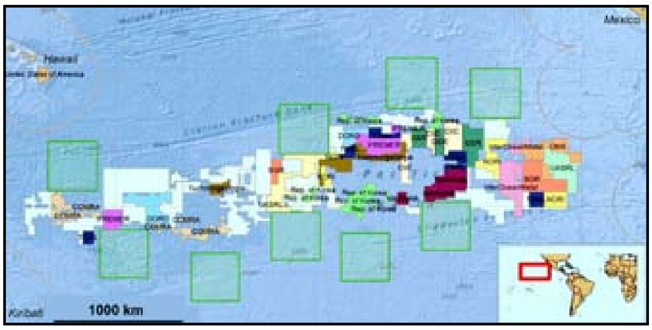
Polymetallic nodules on the ocean floor in the Clarion-Clipperton Fracture Zone; the inset shows concentric mineral growth within a single nodule (source: ISA).

recovered and analysed from other deep sea basins of the world during the scientific expeditions of *HMS Challenger* (1872–76). The expedition report (*Murray & Renard, 1891*) referred to them as 'manganese nodules', and the possibility that they could actually be mined was enlarged upon in J. L. Mero's book '*The Mineral Resources Of The Sea'* (1965), which suggested that in addition to manganese they could yield vast quantities of other elements.

Nodule formation depends upon a number of interrelated processes, summarised in a paper by the Seabed Authority (*www.isa.org.jm/polymetallic-nodules*). A hydrogenous process, in which concretions are formed by slow precipitation of the metallic components from seawater, is thought to produce nodules rich in the clay mineral vernadite, with similar iron and manganese content and relatively high grades of nickel, copper and cobalt. A diagenetic process, in which manganese is remobilized in the sediment column and precipitated at the sediment/water interface, produces the manganese oxide minerals todorokite and birnessite in nodules that are relatively poorer in iron, nickel, copper and cobalt. Other mechanisms include: a hydrothermal process, resulting from hot springs rich in metals, particularly manganese, associated with volcanic activity; a halmyrolitic process, in which the metallic components come from the decomposition of basaltic debris by seawater; and a biogenic process, in which the activity of microorganisms catalyzes the precipitation of metal hydroxides. A more direct biogenic involvement is suggested by concentrations of elements such as copper and nickel in plankton: when these organisms die the organic matter that falls to the sea bottom is a probable source for at least some of the metals incorporated into the nodules.

Whichever process is operative, most researchers conclude that nodule growth is one of the slowest of all geological phenomena, estimated to be of the order of a centimetre over several million years. Nodule formation also requires either a low rate of sedimentation or alternatively the operation of some process, for example bioturbation, that would constantly remove sediment and allow growth of the concretions to continue at or near to the ocean floor.

Typical abundances of the target elements quoted by the Seabed Authority are 29% manganese, 1.4% nickel, 1.3% copper and 0.25% cobalt. However, there is also a potentially valuable range of minor elements, such as molybdenum, rare earth elements, lithium, tellurium, platinum and yttrium; the latter is a transition metal nearly always occurring in association with elements of the heavy REE grouping (HREE). Papavasileiou (*op. cit.)* notes that the content of the particularly valuable HREE is higher in seabed deposits than it is in the largest land-based REE mines. For example, ores from the Bayan Obo (China) and Mountain Pass (USA) mines contain less than 1% HREE (expressed as a percentage of total REE content), whereas polymetallic nodules in the Clarion-Clipperton Fracture Zone (see below) have rare earths of which up to 26% are HREE. However, these minor components of REE would only become economically viable as by-products following processing for the target elements.



Licence areas in the Clarion-Clipperton Fracture Zone of the eastern Pacific Ocean; the green squares outline areas of particular environmental interest (see the ISA website).

Some 80% of polymetallic nodules are found in the deeper parts of the oceans, and are thus difficult to exploit. Moreover the distribution and mineral grade of nodules varies considerably, both locally in response to factors such as topography, as well as from region to region. The Clarion-Clipperton Fracture Zone in the central Pacific Ocean has a high mean abundance of nodules, of around 7 kg/m^2, and exploration licences have (to date) been issued by the Seabed Authority to 17 contractors sponsored by 14 nations. According to the World Ocean Review (*No. 3, 2014)*, the total mass of polymetallic nodules there is 21 billion tonnes. REE contents vary considerably throughout that zone's nodule prospects, but in general, whereas land-based deposits are higher in grade they are lower in total ore actual tonnages (*Papavasileiou, op. cit.*).

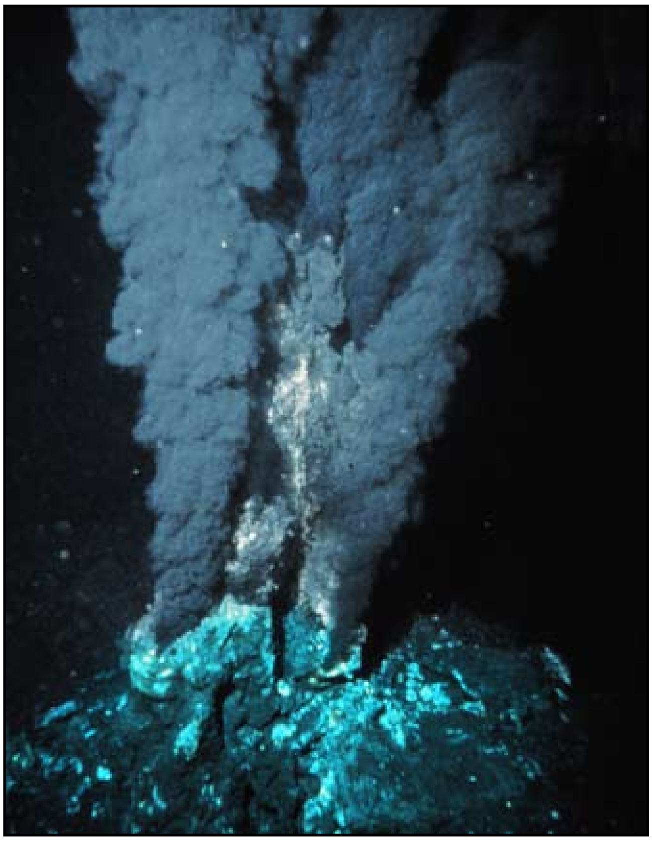
Early pilot projects to exploit polymetallic nodules in the Pacific by nations that include France, Germany and the USA involved prototype underwater machines similar to potato harvesters. By 1982, these projects had concluded that mining in such a challenging environment was not viable and this, combined with depressed metal prices at that time, led to the virtual abandonment of nodule mining. As the Clarion-Clipperton licence map shows, however, there has been a major renewal of interest. A number of mining technologies are being considered (*ISA, op.cit.*), and the necessary equipment is already at an advanced stage of design and possibly trial implementation. For example, DeepGreen Resources of Canada has linked up with Maersk, which will provide a number of vessels for five marine campaigns in the zone over the next couple of years. These projects will allow the company to complete its exploration work and also the final environmental baseline studies that are required by the Seabed Authority; Glencore is poised to take 50% of the copper and nickel from one of the sites, should mining be approved (*Timeline, 2nd August, 2017*). The British government's involvement includes sponsorship of UK Seabed Resources Ltd., which has signed contracts for two licence areas in the Clarion-Clipperton zone.

Polymetallic sulphides

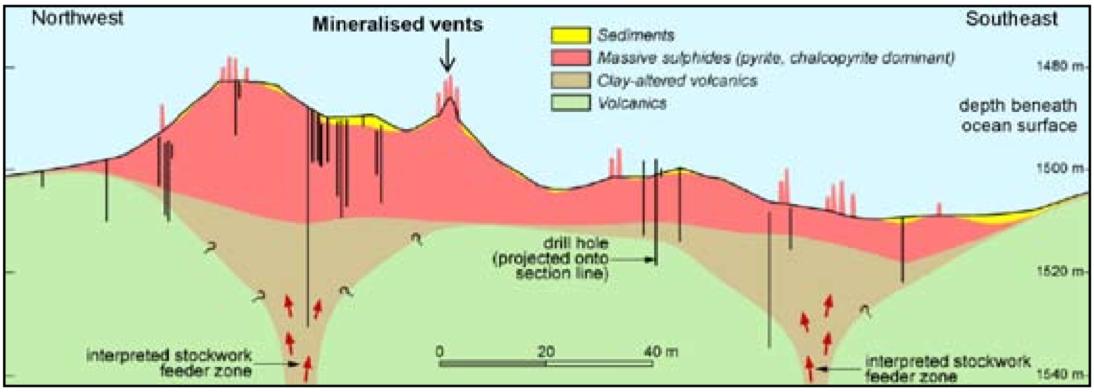
Also known as seafloor massive sulphides, these polymetallic sulphides will most probably be the first type of deep-sea mineral ore to be exploited on a truly commercial scale. Unlike other types of submarine mineral resource, their genesis and three-dimensional architecture is relatively well understood through studies of their equivalents exposed on land. They occur in plate collision zones where fragments of ocean floor have been tectonically emplaced onto forelands above major thrust planes (obduction). Cyprus-type volcanogenic massive sulphide deposits are associated with tectonic segments of basaltic oceanic floor, whereas Kuroko-type deposits are hosted in up-thrusted intermediate-to-felsic volcanic sequences representing the crust of back-arc extensional systems formed above subduction zones. Both types of ore deposit were formed by high-temperature fluids that had been generated when seawater percolated down into the oceanic crust to depths of up to 2000 metres, where it was heated by magma. The rising hot brines leach metals and sulphur from the rocks before being vented onto the ocean floor, commonly constructing the sulphide chimneys known as black smokers.

In modern oceans, the most intensively studied polymetallic sulphide occurrence is the Solwara 1 deposit, which lies off the island of New Britain, within the Bismarck Sea, off the western Pacific Ocean. One of a cluster of 20 such occurrences located close to a spreading ridge within the Manus back-arc extensional basin, it was first discovered in 1996 by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). Plans to mine this prospect are at an advanced stage (see below), following its most recent evaluation involving bathymetric and geophysical surveys and the drilling of more than 100 boreholes, some up to 30 m in length. The results are summarised in a report by I. Lipton of Golder Associates (2012) submitted to the operator, Nautilus Minerals of Canada (*Mineral Resource Estimate, Solwara Project, Bismarck Sea, PNG*).

Solwara 1 is best compared with the Kuroko type of massive sulphide deposit, being developed on the flanks of a submarine volcanic edifice dominated by andesitic and dacitic lavas. Beneath a 2–6 m thick, impersistent carapace of volcaniclastic sedimentary rocks, a layer of mineralised sedimentary rocks passes down into massive sulphides at least 29 m thick in places. In this basal layer the dominant minerals are pyrite and chalcopyrite, hosted within anhydrite or barite gangue. According to Nautilus Minerals, the prospect could yield 72,500 tonnes of copper from ores with an average grade 8% copper, as well as more than 4.5 tonnes of gold (*Scientific American, August 11, 2016*). There are also useful amounts of silver, recorded at 34 g/t (ppm), and zinc (0.9%). Extinct, sulphide-rich vent-chimneys up to 15 m high were encountered in several discrete zones, and these show significantly elevated ore grades; a mean value of 14.9 g/t for gold and 151 g/t for silver was reported by Golder Associates. One possible process accounting for high gold concentrations in hydrothermal chimneys is its precipitation as colloids from boiling fluids (*Geology, 2017, doi.org/10.1130/G39492*). No mention has been made of REE contents at Solwara 1, but they will doubtless be sought as by-products of mineral processing.



Hydrothermal chimney rich in sulphides, that can be exploited when no longer active, as at Solwara 1.



Schematic profile of the prospect at Solwara 1 prospect (after Golder Associates, 2012).

A dark cobalt-ferromanganese crust revealed in a cut section (source: CoRMC-H, Auki).

Cobalt-ferromanganese crusts

The potential value of cobalt-rich ferromanganese crusts is in part due to the vast extent of ocean floor that they cover; one estimate suggests that they may hold a total of one billion tonnes of cobalt (*ISA, 2008: Cobalt-rich crusts pdf*). In addition, they contain REE at concentrations about three times higher than found in polymetallic nodules. Some of the deposits in the Clarion-Clipperton nodule field have similar concentrations to land-based ores in Southern China, according to Hein (*ISA briefing paper, 02/12)*.

The crusts are deposited directly from seawater onto hard-rock substrates, generally at depths of 1000–3000 metres. Mainly composed of the minerals vernadite (manganese oxide) and feroxyhyte (iron oxide), they form encrustations on the sea floor up to 250 mm thick. Convenient for exploration purposes, these are differentiated from surrounding non-mineralised hard rock substrates by their high gamma-ray response. The crusts grow slowly, at rates of 1 to 5 mm/Myr over tens of millions of years, and as they are mostly found on the upper flanks of seamounts many prospects will lie in the exclusive economic zones of island states. Like polymetallic nodules, they contain significant iron and manganese (circa 20%), as well as cobalt and nickel (*Royal Society 2017, op. cit.).* They also contain a great diversity of minor elements, including titanium, cerium, nickel, platinum, manganese, phosphorus, thallium, tellurium, zirconium, tungsten, bismuth and molybdenum (*ISA 2008, op.cit.*).

The Seabed Authority notes that the variable thickness of the crusts, their being attached to a hard rock substrate, and the topographic variability of seamounts, will make their removal potentially more challenging and environmentally disruptive than the mining of polymetallic nodules. Five exploration contracts have so far been let in the western Pacific, where Japanese researchers are carrying out surveys for several island states. Robotic, bottom-crawling vehicles with articulated cutters could fragment the crusts while minimizing the amount of substrate rock collected. Other suggestions include water-jet stripping of crusts from the rock, chemical leaching of the crusts while they are still on the seamounts, and sonic separation of crusts.

REY muds with REE and yttrium

A new style of mineralisation was first reported by Kato *et al*. as REY muds (*2011, Nature Geoscience, doi.10.1038/ngeo1*185). Found at depths of 3500–6000 metres across the central, north and southeastern Pacific Ocean, the ore zones have average thicknesses between 8 and 24 metres. Their total REY oxide (REO) content is around 0.2% by weight, but REE contents are somewhat variable, ranging 600–2250 ppm on the Pacific Ocean floor. According to Nakamura *et al*. (*2015, doi.org/10.1016/B978-0-444-63260-9.00268-6*), these deposits constitute a highly promising resource due to their extremely wide distribution, high REY concentrations and significant enrichment of the less common but increasingly more required HREEs; these include terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. One of the richest deposits yet found lies close to the Minami-Torishima atoll in the western Pacific, and lies within Japan's exclusive economic zone (*Yamazaki et al., 2017, doi.10.1115/OMAE2017-61383*). It is variously claimed to have a maximum REY content of 6500 ppm and REO content of up to 0.5%.

A BBC News article in 2011 reported early claims that in some of these deposits the concentration of rare earths in just one square kilometre would be sufficient to supply one fifth of the current global annual consumption, while the total REO stored in the muds amounts to a possible resource 10 to 1000 times greater than the world's current land reserves. There is also a political dimension, since it is thought that the levels of the economically important HREEs in the Minami-Torishima deposits are much higher than in Chinese ores. Mayer Brown suggests that this could enable Japan to break China's monopoly on REE production (*2014, Three Dimensional Thinking: Rare Earth Elements*).

A major study by Yasukawa *et al*. (*Nature Scientific Reports, 2016, doi.10.1038/srep29603*) used a

Sample of the carbonate-fluorite mineral bastnaesite that contains rare earth elements; at the laboratory of Yasuhiro Kato, Tokyo University (photo: Reuters, Yuriko Nakao, 2011).

statistical approach to assess the REY mineralisation and depositional ages of 3968 bulk sediment samples from 82 sites in the Pacific Ocean and 19 sites in the Indian Ocean. They found that bulk REY enrichment patterns are almost the same as those found in biogenic Ca-phosphate, suggesting a strong biogenic control over mineralisation. One possibility is that REY elements in seawater are 'fixed' by constituents in ocean floor sediments such as Fe-Mn-oxyhydroxides, phosphatic pellets, other organic debris and the zeolite mineral phillipsite. Favourable conditions would be a low sedimentation rate with a concomitant high concentration of Ca-phosphates, enabling the sea-floor muds to become REE-enriched either by direct contact with the oceanic water column or through bioturbation in their uppermost parts. A potentially important finding by Yasukawa *et al*. (*op. cit.*) is that early during the diagenetic stage of mineral growth geochemical interchanges between REY muds and embedded polymetallic nodules feature elements such as Co, Ni, Cu, and Zn. This partially explains why there is geographical overlap between the two types of mineral occurrence, and it raises the possibility that in the future both could be mined from essentially the same operation.

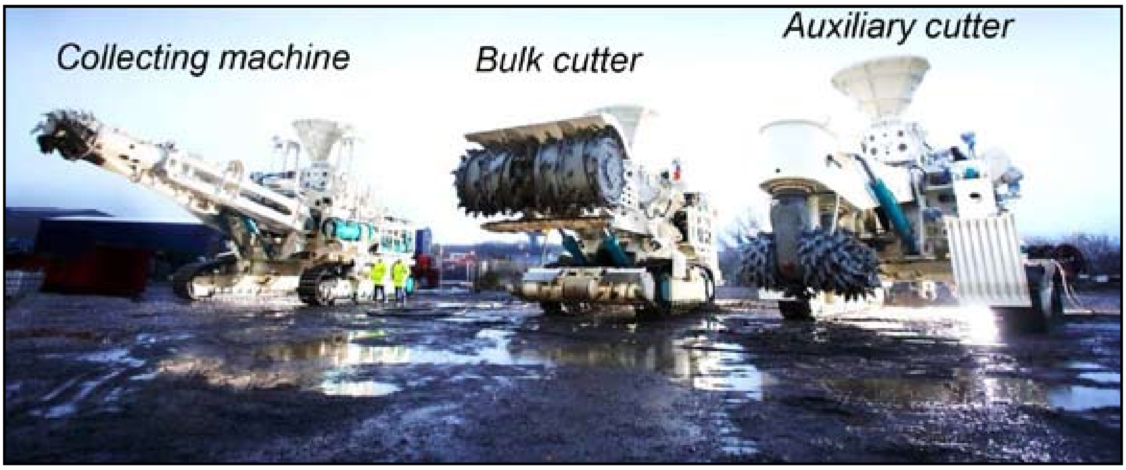
Although Papavasileiou *(2014, op. cit.*) notes that REY-rich muds may constitute a highly promising source of rare earth elements, but only in the long-term, the intensive exploration and beneficiation work currently being conducted by Japanese researchers suggests that exploitation, at least on a pilot basis, could occur sooner rather than later. Advantages are that REY muds constitute a stratiform resource allowing for relatively simple and cost-effective exploitation; they are relatively easy to extract by acid leaching; and they have very low concentrations of radioactive elements such as Th and U, making waste disposal less hazardous and consequently less costly. Experimental processing is well underway, with Takaya *et al*. (*Scientific Reports 2018, doi:10.1038/s41598-018-23948-5*) reporting that, by using a hydrocyclone separator, they were able to concentrate an enormous potential resource comprising biogenic calcium phosphate grains with REY contents up to 22,000 ppm.

Commercial seabed mining to start in 2019?

The research summarised above suggests that the ocean floors do offer a number of attractive prospects for mineral production. The economic review by Papavasileiou (*2014, op. cit.*) notes that the then-current 'basket values' of strategically valuable REE from Clarion-Clipperton Zone polymetallic nodules are significantly higher than those of even the largest terrestrial deposits, due to their relatively greater proportions of neodymium, praseodymium and HREE. A further plus is that ocean floor mineralisation is multi-element in nature, so that a slump in market prices for one product could be offset by continuing buoyancy in others.

The challenges come from the remoteness of deep ocean mineral deposits, the vulnerability of operations to weather conditions, and the consequent high cost of the technologies involved in their exploration, mining, transport to onshore facilities and processing. Market volatility will be introduced via competition with new terrestrial prospects (*see Mercian Geologist, 2017, op. cit.*), and prices can also be affected by the state manipulation of strategic mineral assets, as recently demonstrated for the REE by China. All these factors introduce a significant amount of risk, so it is not surprising to find that the world's first serious attempt to exploit these resources on a commercial basis is heavily backed by a global economic superpower. The lure of the Solwara 1 polymetallic sulphide prospect is seemingly not related to REE contents, which have not yet been declared, but is more likely due to the high grades of copper combined with the significant amounts of valuable minor elements such as gold and silver.

The extent of financial capital already invested in the Solwara 1 project was underlined in March 2018, when the Chinese state-owned Fujian Mawei shipbuilding yard launched the impressive mother ship. The vessel will be capable of carrying 45,000 tonnes of ore and can stay at sea for more than five years at a time (*The Times, August 26, 2017*). A technological breakthrough, it is equipped with umbilically-linked deep-sea robotic diggers that will be operated by the contractor, Nautilus Minerals (*Greg Walters, www.seeker.com, March 2017*).



Deep-sea mining machines, designed and built by the British company Soil Machine Dynamics for the ocean-floor mining operations by Nautilus Minerals at their Solwara 1 polymetallic sulphide project (photo: SMD).

The mining robots have been successfully tested underwater (*Nautilus Minerals Press Release, 2018-05*), although possibly not at the depths they are intended for. Designed to operate in near-freezing temperatures, under pressures 150 times greater than at sea level, they consist of three machines. The auxiliary cutter will carve a level path to make way for the bulk cutter. The latter is equipped with a wide, powerful cutting drum and will produce a mineral-rich slurry to be collected by a third robot, the collecting machine, which will send the slurry to the surface via pump-driven riser system. On the ship, the water is filtered, and solids larger than eight microns are removed before it is returned back into the ocean. The cargo of mineral is then transferred to a transport vessel and sent directly to customers in China. It is likely that the Chinese state-owned Tongling Nonferrous Metals Group will be the first buyer of the extracted copper.

Nautilus Minerals envision that mining operations at Solwara 1 should start in the third quarter of 2019 after a 15-month ramp-up period, but there are still hurdles to overcome. Despite the considerable expenditures already made on machinery, uncertainties have been identified by detractors, as well as by the Company in a series of disclaimers in its forward-looking statement (*Nautilus Minerals Press Release, 2018-11*). Issues include securing the remaining funds necessary to commence mining operations, which will in part depend upon a successful feasibility study to demonstrate whether or not the venture will be commercially viable. Thus the Company's preliminary economic assessment of the prospect notes that the mineral resource estimates are at present only 'inferred', and so cannot be categorized as mineral reserves. There are also objections from local communities pressurising the Papua New Guinea government, which is a 15% partner and in whose territory the deposit lies (*www.marinelink.com, April, 2018*).

Environmental concerns

In its introduction to the 'Future of the Oceans' evidence pack, the Royal Society (*2017, op. cit.*) cautioned that the oceans actually host two important types of natural resource. Marine biodiversity has the potential to yield biological materials useful for medical and genetic studies, whereas the mineral diversity of the deep oceans could be crucial for continuing industrial and technological development. The two are environmentally linked, and while the exploitation of genetic information is likely to have minimal environmental impact, mining may have substantial consequences in that respect and could even compromise the biomedical resources. With rapid advances in technology and forthcoming clarification of international law, it should soon be possible to exploit both types of resource on a larger scale.

The potential for ocean-floor mining to disturb sediments that have been accumulating for millions of years, plus the general lack of detailed knowledge about species distribution and ecosystem recovery times in our oceans, are major concerns for environmentalists. The main risk is that mining operations could generate plumes of toxic sediment drifting on currents through large areas of ocean. This could choke any marine life that feeds by ingesting water and filtering out its food sources, which in turn has potential to adversely affect migration, feeding and breeding activities of higher marine organisms. The consequences could include local species extinction and loss of income to fishery industries, although, given the vast extent of the oceanic environment, a global-scale disaster seems less probable.

The concern shown by marine scientists and conservationists was touched upon in an interview between David Shukman and Stephen Ball, chief executive officer of Lockheed Martin UK, owner of UK Seabed Resources *(www.BBC.com, March 2013*). The latter's position was that forthcoming exploration would establish whether a system to vacuum up polymetallic nodules in the Clarion-Clipperton Zone could be designed to cause minimal impact, but it was accepted that '… until we've demonstrated that, there will be a debate…" There could be more than just a 'debate', however, since the Seabed Authority has an *'... overarching obligation…to prevent, reduce and control pollution of the marine environment from any source, to monitor the risks or effects of pollution and to assess the potential effects of activities under States parties jurisdiction and control that may cause substantial pollution of or significant and harmful changes to the marine environment.*' The Authority's plan for mining at sites such as the Clarion-Clipperton Zone is that adjacent licence areas would not be harvested together, allowing the preservation of untouched areas from which the harvested sites can be recolonized. Good intentions, although Ed Conway (*Comment, The Times, March 17, 2018*) noted that the rules governing deep-sea mining are currently being developed in private meetings of the International Seabed Authority, presumably without representatives from the environmental lobby, and will probably be rubber-stamped by its membership.

In an interview posted on the Seeker website, Michael Johnston, CEO of Nautilus Minerals, said that the company's machines at Solwara 1 are designed to minimize possible undersea pollution clouds through the collection procedure itself, which involves suction rather than blowing. The company is 'quite confident' that the impact from mining activities will be significantly less than some conservation groups are claiming. However, given the increasing public awareness of the oceanic environment and its fragility, prompted also by recent TV programmes such as David Attenborough's 'Blue Planet' series, there seems little doubt that this view will be challenged when deep-sea mining activities commence in the near future.

John Carney