National Ocean Exploration Forum

October 20-21, 2016

A Discussion Paper on Marine Minerals

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Ocean Exploration – The Mineral Resources Perspective

Increasing demand for resources and growing challenges of discovery on land are encouraging the search for alternatives in the oceans. China, Japan, Korea, Russia, India, France, and Germany, are all actively exploring for metals in the deep oceans. Other countries (Papua New Guinea, Fiji, Tonga) have leased portions of their EEZs for exploration of seafloor hydrothermal ore deposits. Because the oceans cover more than 70% of the Earth's surface, many expect them to contain vast quantities of mineral resources [1-3]. However, even after three decades of intensive research, there is a continuing lack of knowledge regarding the numbers of deposits and their possible economic significance. Addressing these uncertainties requires new technology and new concepts to better understand the resource potential.

The prospects of deep-sea mining have advanced in "fits and starts", first with the manganese nodule boom in the late 1970s and early 1980s, then the Red Sea pilot mining project, and now the likelihood of mining seafloor polymetallic sulfide deposits. Perceived shortages of metals from land-based mining are a major driver. For some countries, the goals are increased security of supply, as China controls more of the production and or metals are increasingly sourced from high-risk jurisdictions (e.g., cobalt from the Democratic Republic of Congo) [4]. Smaller countries with access to the ocean resources could benefit financially from their exploitation. Other countries have large service sectors for the marine industries that see the opportunity to benefit from demand for new technology.

"Peak Metals"?

When demand for raw materials surged in the first part of this decade, mining companies were encouraged to turn to lower grade ores and deeper deposits [5]. Concerns were raised that certain commodities could no longer be produced to meet the demand, and number of metals were identified as particularly vulnerable to fluctuations in supply [6]. Western industrialized economies dependent on imports of these so-called "critical metals" sought a variety of new sources, including in the oceans. Some even speculated that we had reached "peak metals". However, as was experienced with "peak oil", new technology and new thinking about where resources might be extracted can change everything (in the case of oil and gas turning America into a major exporter). The same will likely happen to "peak metals". But there is still a question about where those new metals will come from?

Many consider that deep-sea mining could add diversity and alleviate supply concerns. Even among skeptics, the resource potential of the deep sea is considered to be huge, but only a tiny fraction of the 360 million km2 of ocean floor has been explored. There are many unsubstantiated assessments of the actual amount of new resources that may be available and, compared to the late 1970s, there is far greater sensitivity to the potential environmental impacts of their exploitation, with increasing calls for internationally binding standards and research-based management to ensure protection of the oceans. Despite these uncertainties, many countries and commercial enterprises are conducting in-depth studies of their technology readiness levels for the emergence of a new industry.

The "Triumvirate" of Deep-Sea Resources: Nodules, Crusts and Sulfides

Deep-sea minerals are part of a wider spectrum of non-fuel marine resources, presently dominated by aggregates and other dredged materials. Aggregate mining is by far the most important segment of the marine mining sector [7], however, diamonds are also being mined off southwest Africa, tin is being mined intermittently in Southeast Asia, gold has been mined off Alaska, and iron-rich sands were recently targeted for development in New Zealand. Marine phosphorites, which have recently been considered as a source of fertilizer (and possibly uranium) occur in abundance on the continental shelf areas of Peru, Chile, Namibia, eastern Australia, New Zealand, Baja, and the Atlantic margin of Morocco [2]. Phosphorite deposits are also locally abundant on submarine plateaus and offshore banks of the southeastern Unite States. Several countries have now imposed a moratorium on offshore phosphate, iron and placer gold mining, most recently on the Chatham Rise of New Zealand and off Namibia. Australia and New Zealand have recently set aside vast tracts of their potentially mineral-rich offshore as marine reserves [8].

All offshore mining today is in shallow water – generally less than 300 m. Targets for deep-sea mining are at far greater depths and limited to just three classes of mineral deposits: manganese nodules, Co-rich ferromanganese crusts, and seafloor massive sulfide (SMS) deposits. They occur in all of the world's oceans, but they are not evenly distributed, being controlled by major geological and oceanographic domains (Figure 1).

Manganese nodules – Nodules are solid concretions of manganese oxide minerals (up to tens of centimeters in size) that grow over millions of years from the metals dissolved in seawater and from porewater in sediments. They occur widely on the sediment-covered abyssal plains at depths of 4000 to 6500 m. The largest concentrations are found in the Clarion-Clipperton Zone (CCZ) between Mexico and Hawaii. Current estimates of the total abundance of nodules in the CCZ are as high as 21 billion tonnes, covering vast areas (about one million tonnes per 100 km^2). The first of the "pioneer" exploration licenses in the CCZ began to expire this year, setting the stage for possible exploitation. The total contained metal in the CCZ nodules is estimated to be 5900 million tonnes Mn, 280 million tonnes Ni, 220 million tonnes Cu, and 40 million tonnes Co [9]. These quantities, if recoverable, would be sufficient to satisfy all current demand for Mn, Ni, Co, and Cu for decades into the future [10]. At the current time only Ni, Co, and Cu are being considered for recovery, although some important rare metals also could be sourced from manganese nodules (e.g., molybdenum, platinum, yttrium) [4]. Much of the technology to mine nodules is already built, but processes for recovery of the metals have not been tested at an industrial scale. Draft regulations for mining are being circulated for comment by the International Seabed Authority, the governing body in "the Area" beyond national jurisdiction, but environmental impact studies are still underway. Outside the CCZ, the global abundance of nodules is far from certain.

One estimate is as high as 2,000 billion tonnes [9], mostly in international water (Figure 1). In August 2015, the Cook Islands opened a tender for 10 exploration blocks of10,000 km^2 each encompassing the nodule occurrences in their EEZ.

Co-rich ferromanganese crusts – Cobalt-rich ferromanganese crusts are layers of manganese and iron oxides, up to 30 centimeters in thickness that precipitate widely on exposed rock surfaces in the deep ocean. They form at water depths from ~500 m to 7000 m, mainly on the upper flanks of volcanic seamounts, ridges, and plateaus that are swept clean of sediment by strong currents. Many of these seamounts are found within the EEZs of Pacific island states. Current estimates of the total amount of crusts in the prime Pacific seamount area are on the order of 7.5 billion tonnes, containing 1700 million tonnes Mn, 32 million tonnes Ni, 7.4 million tonnes Cu, and 50 million tonnes Co [9,10]. The crusts have generally higher grades of Co than manganese nodules, as well as higher concentrations of certain trace metals and metalloids, such as Te, and they cover smaller areas than nodules (on the order of one million tonnes per 20 km^2). However, the thin hard crusts and uneven rocky surfaces are expected to be much more difficult to mine, and no proven technologies have been developed. Four contracts for the exploration of Co-rich ferromanganese crusts in "the Area" (3 in the Pacific and one in the Atlantic) cover 12,000km2, but these represent less than 1% of the potentially favorable areas for crusts (Figure 1). The total global tonnage of crusts is estimated to be about 200 billion metric tons [9], about 30% in international water and 65% in EEZs of western Pacific island states.

Seafloor massive sulfide deposits – Seafloor massive sulfides or SMS are accumulations of metallic sulfide minerals that precipitate from high-temperature, up to 400°C, hydrothermal fluids – so-called black smoker vents – along volcanically active ridges (e.g., mid-ocean ridges and back-arc basins) and on active volcanic seamounts. Individual deposits range in size from only a few thousand tonnes up to several millions of tonnes [11]. Thus, they are much smaller targets than nodules or crust resources, but they are characterized by much higher grades of metals, in particular Cu, Zn, Ag, and Au. They occur at water depths from <500 m to as deep as 4000 m (the maximum depth of exploration for SMS). More than 300 deposits have been identified since the discovery of seafloor hydrothermal vents in 1979 (Figure 1), but significant massive sulfide accumulations have been found at only 165 of these sites. Current estimates of the total amount of massive sulfide in the oceans vary widely, from as little as 500 million tonnes to more than 5000 million tonnes [11]. Some exceptional accumulations of metals from hydrothermal vents have been found, but these are very rare and restricted to geologically unique environments (e.g., Atlantis II Deep of the Red Sea: [12]). Six contracts for exploration of SMS deposits have been approved in "the Area" since 2011, each covering 10,000km^2. 37% of the remaining sites are in international water; 60% are in EEZs.

Some interest was raised recently by a report of high concentrations of rare earth elements (REE) in deep sea clays of the Pacific [13]. Japanese and Korean scientists have tested this idea and, although the processing of the muds is technically feasible, there have been no reports of a meaningful resource potential. Moreover, questions have been raised about what to do with the mud after the REEs have been leached from them. While the occurrence of REE in deep-sea muds is scientifically interesting, it is probably not a realistic opportunity for deep-sea mining.

A "Race to the Seabed"?

Science and popular media have focused on the "race to the seabed" driven by deep-sea mining. But the outcome of that race is still far from clear. Machines for nodule collection have been in existence since the original nodule boom, and test deployments have been completed. But actual mining has not yet taken place, and there are still no examples of operations that could serve as benchmarks for analysis of economic aspects or environmental impacts. Although exploration licenses have been granted for all three types of deep-sea mineral resources, the first and only commercial licenses for actual mining are for seafloor sulfide deposits (in the Manus Basin of Papua New Guinea and in the Atlantis II Deep of the Red Sea), although there are strong domestic interests in SMS deposits in Japan. Some economic assessments have suggested that SMS offer a potentially larger return on investment than nodules, in terms of $/tonne [14].

Long Lead Times

If deep-sea mining has not started yet, why not and when will it happen? Although there will be many challenges for mining in the deep sea (e.g., lifting hard materials from great depths: [15]), there are probably few insurmountable technology barriers. Many of the difficulties of working in the deep sea have already been faced by the oil and gas industry [16], and the skills and expertise from that sector are readily transferrable to deep-sea mining. However, a complete mining system capable of reliable long-term operation has not yet been realized for any of the resources and is unlikely in the short term. Seabed mining will come with relatively high investment costs in comparison to land-based mining; perhaps as much as 10 times higher [14]. Some argue that this high cost is more than offset by the high grades of the deposits, but this conclusion is not supported by available data [17]. One sobering statistic from land-based mining is that the rate of conversion of newly discovered prospects to actual mines is less than 1 in 1000 [18]. By this metric, only a handful of the currently known seafloor deposits would ever advance to the commercial mining stage.

Those with experience in commercial offshore diamond mining point to the steep learning curves in the development of new marine industry [19]. Diamonds were discovered in deep water off Namibia in the 1970s, but it took 15 years to define a resource, owing the difficulties of assessing grade, and the first mining attempts were not made until the 1990s. It was not until the early 2000s that the offshore diamond industry began to look like it does today. The nodule industry, started in the early 1980s, was reinvigorated in the 1990s, peaked again in 2010, and is currently pushing toward pilot mining tests in perhaps another 5-10 years – a development cycle that will have been at least 50 years long. Nautilus Minerals, which is licensed to mine the Solwara 1 massive sulfide deposit in the Manus Basin, first emerged on the TSX in 1994, they announced their first major resource in 2007, and originally planned to begin mining by 2010. Mining will not commence soon, resulting in a total lead time of at least 25 years. Relatively little exploration was required to locate the Solwara 1 deposit because it had already been discovered when the company was formed, so another 10 years might have been required if a full exploration program had been necessary. Japan legislated its activities in 2009 and is working towards its first SMS mining in the Okinawa Trough in 2018; a lead time of less than 10 years. But they too did not have to conduct an exploration program to locate their first resource, and current expenditures aimed at fast-tracking development are eclipsing the efforts of other countries.

Compounding the long lead times for technology development are the major efforts required to evaluate the resources. Contracts for exploration of nodules in the CCZ cover more than 1 million km². A

typical nodule claim of 75,000 km^2 will take years to map, let alone survey in sufficient detail to establish a resource and an environmental baseline. A sulfide claim typically amounts to no more than 10,000 km^2, and so is a more manageable undertaking. However, a typical high-resolution AUV mapping program can cover no more than about 10 km^2 per day for a single vehicle, requiring enormous amounts of bottom time to survey a claim in its entirety. For most prospects there is still a lack of information about grade distribution, depth extent, surface roughness, sediment cover, metallurgy, environmental sensitivity, etc., and a corresponding low confidence in the resource-reserve estimation. Under these conditions, it is hard to imagine that any development, let alone reliable feasibility studies, can proceed quickly. Once mining commences, Mn nodule prospects in the CCZ could have a relatively long mine life – perhaps 30 years and encompassing 1000s of km^2. Massive sulfide mining will target much smaller deposits (e.g., 2 million tonne Solwara 1 prospect) that could be exhausted in just a few years, thus requiring aggressive exploration to ensure a steady pipeline of projects.

Other Technical Challenges

Although the most favorable sites in the CCZ have already been licensed to contractors, manganese nodule resources elsewhere in the oceans have not been extensively researched. Relatively little is known about the abundance of ferromanganese crusts in most areas of the global ocean. And, there is even less certainty about massive sulfide deposits. In the last four decades, about one-third of the total length of global oceanic spreading ridges, back-arc basins, and submarine volcanic arcs, has been surveyed for hydrothermal vents, but only in the narrow neovolcanic zones close to the ridge axes. This is a tiny fraction of the area with potential for SMS (at least 3.2 million km^2 if the flanks of the ridge, 20 km on either side, are also included). Beaulieu et al. [20, 21] used a broadly linear relationship between the frequency of high-temperature venting and spreading rate, to predict that there should be a total of 1300 (±600) hydrothermal sites in the neovolcanic zones. This number is very close to previous estimates of ~1000 sites based on heat budgets [22] and the known spacing of major vents fields [11]. A more recent estimate [23] suggests that venting sites may be far more numerous, by a factor of 3-6, but this includes large numbers of low-temperature diffuse venting (<50 ∘C) that are not expected to form a mineral deposit. The estimates of the number of undiscovered vents are about equal to the total number that have already been discovered, which means that in a few decades we could conceivably find all of the vent fields on the active spreading centers.

A great deal of science still needs to be done on the nature of the deposits themselves, including their mineralogy, chemical compositions, and physical properties of relevance to resource recovery. There is a paucity of measurements on most sample types, and little is known about the controls on the distribution of some potentially valuable trace elements, including the so-called critical elements, as well as trace metals that may be hazardous to the environment if released [9, 24, 25]. A particularly difficult challenge is the measurement of the physical properties of seawater-saturated samples under hyperbaric conditions. In situ measurements are essential to understanding the geotechnical properties and mechanical responses of the materials to be mined. Whereas nodule mining is expected to be relatively easy, from an engineering standpoint, several important breakthroughs are still required for crust mining, in particular measurement of crust thicknesses and techniques for separation of crusts from the rock substrate [4,9]. Cutting properties of seafloor massive sulfides also have not been tested at a mine scale.

For SMS deposits, the greatest challenge is understanding their 3rd dimension. With the exception of a few deposits that have been drilled scientifically through the Ocean Drilling Program or by commercial

projects, little is known about the interiors of most SMS deposits. Reliable estimates of resource potential are therefore very rare because drilling is needed to infer the tonnage and metal contents. In most cases, the sizes of deposits are estimated only from visual observations of the surface area on the seafloor, with large inherent uncertainties. Some geophysical tools are being developed to improve those estimates (e.g., controlled-source EM), but these are not widely available.

For Science, Time to Get it Right?

The good news is that there is still time to do many of the things that science has to do before a global industry emerges. Early predictions of an economic boom from deep-sea mining have eased because of technological and environmental challenges but also in terms of metal demand – there is no pressing need to recover metals from the deep sea (e.g., [26]). Past economic forecasts for the recovery of metals from the oceans and uncertainties regarding the legal framework in which deep-sea mining might take place have repeatedly shown that it is premature to judge the potential future economic significance of deep-sea mineral deposits [27]. However, another picture is emerging that deep-sea mining could proceed other than as a strictly commercial activity. Major consuming nations with no domestic mining have a strong interest in the potential for mineral supplies from the seabed (especially in Europe, Japan, and Korea). Some countries with no need of minerals from the seabed nevertheless have significant maritime interests that would be strengthened by developing seabed mines – regardless of whether they make money. Others advocate a slower pace with increasing dialogue and training and a focus on research, recognizing that it makes sense to consider all of the risks and opportunities in parallel and in a more coordinated way while there is time to do so.

Where Are the Frontiers for Marine Minerals?

A more detailed consideration of seafloor massive sulfide deposits highlights how little we know about the resource potential of the oceans. Two recent estimates of the total contained metal in seafloor massive sulfide deposits by different methods arrived at essentially the same number – between 10 and 30 million tonnes of Cu + Zn metal [11, 28]. For comparison, the last USGS National Mineral Resource Assessment estimated that the amount of metal remaining to be discovered in massive sulfide deposits on land in the United States was at least 90 Mt (Zn+Cu+Pb). Thus, the metal resources in SMS deposits of the global neovolcanic zones seem rather small. However, this only includes the deposits in volcanically active areas close to the ridge axes; it does not include far greater resources that may be expected off axis. So far, explorers have not strayed more than 10 km from the ridge, even in the most prospective areas. The number of deposits away from the spreading centers could be at least an order of magnitude higher, although many (or most) will be buried by sediment.

Size Matters

Some SMS deposits are significantly larger than others. This is important because in land-based mining just a few of the largest deposits typically contain the vast majority of the metals. For Cu-Zn deposits – the fossil analogs of modern black smokers – 80% of the produced metal has come from fewer than 25% of the deposits, all larger than 10 million tonnes [17]. It is clear that one large deposit can change the resource outlook, but where are those deposit to be found? Detailed mapping, and in some cases drilling, indicates that a number of deposits contain individually 1 to 5 million tonnes of massive sulfide (e.g., TAG hydrothermal field on the Mid-Atlantic Ridge) and can occur in clusters of more than 10

million tonnes. Four deep drill holes that penetrated the Bent Hill and ODP mounds at Middle Valley (ODP Legs 139 and 169) indicated a combined tonnage of between 10 and 15 million tonnes [29 and references therein], making them the largest accumulation of sulfides on the sea floor. Both are old, off-axis deposits, partly buried by sediment. One "giant" deposit of 90 million tonnes has already been found in the Atlantis II Deep of the Red Sea [12], but the next largest deposits are an order of magnitude smaller. Where is the next giant?

Slower is Better?

Until 1984, it was widely accepted that hydrothermal activity on slow-spreading ridges would be limited because of the lack of near sea-floor magmatic heat. However, following the discovery of the TAG hydrothermal field on the Mid-Atlantic Ridge [30], it became apparent that the slow-spreading ridges may host some of the largest hydrothermal systems. A strong tectonic control on fluid flow has since been recognized that contributes to the formation of unusually large deposits on the slow and ultraslow-spreading ridges where few deposits were expected at all [31]. Deeply penetrating faults in these settings allow circulation of seawater to considerable depths and, in some cases, at some distance off axis. This concept is supported by recent discoveries on the ultra-slow spreading Southwest Indian Ridge, the Knipovich and Gakkel ridges in the north Atlantic, and the Mid-Cayman Rise [21]. Our long-standing view of the relationship between hydrothermal activity and spreading rate is being challenged, and our understanding of the mid-ocean ridges still falls short of what is needed to launch an effective exploration program for large SMS deposits.

Under the Cover of Sediment

Where large hydrothermal systems are active in sedimented rifts, massive sulfides may be accumulating mostly by subseafloor replacement within permeable sedimentary layers. This may be where the giants are hidden. The sediment has an insulating effect, preserving the high heat flow associated with rifting, preventing the loss of metals to black smoker plumes, and enhancing the preservation of the contained sulfide deposits. About 5% of the world's active spreading centers are covered by sediment from nearby continental margins in places like the northern Juan de Fuca Ridge (Middle Valley) and the Gulf of California (Guaymas Basin). The highest rates of burial, typically associated with clastic sedimentation from major rivers, are on the order of 10 to 100 cm/1,000 yr, compared to open ocean pelagic sedimentation of 1 cm/1,000 yr. During the Pleistocene low stand of sea level in the northeast Pacific, an abundant supply of terrigenous sediment buried the southern Gorda Ridge beneath 200 to >1,000 m of turbidite, mostly from a single glacial outburst and catastrophic flooding that originated in the Columbia River system [32]. In the Arctic Basin, the ultraslow-spreading Gakkel Ridge is propagating into continental crust beneath the Laptev Sea, directly under the Lena River Delta. All are prospective sites for buried hydrothermal activity and large sulfide deposits; many are the very same basins currently being explored for hydrocarbon deposits. Finding these deposits will require specialized search tools to identify high heat flow, sub-seafloor structures, and chemical indicators of leaking hydrothermal fluids – many of the same tools used in petroleum exploration. A major development in this search will be increasing accuracy of the global marine gravity data (e.g.,[33, 34]), which is already revealing deeply buried, extinct spreading centers beneath the sediments of the Gulf of Mexico and off the coast of Brazil.

Where Arcs and Continents Collide

By analogy with ancient deposits, the most productive seafloor hydrothermal systems are likely to be found in volcanic arc environments, where the oceanic plates are converging. Formation and rifting of arc crust, oblique collisions, opposing subduction zones, and microplate tectonics that characterize the Western Pacific margin today were all likely important aspects for the formation and preservation of ancient ore deposits mined on land today [29]. Although there has been considerable attention on the active magmatic fronts of the arcs, where spectacular explosive volcanism and degassing are common (e.g., "Ring of Fire" expeditions: [35], large-scale hydrothermal convection necessary to form the largest deposits is mainly restricted to large and deep calderas or where the arc crust is actively rifting. Rifted continental crust, which is characterized by high crustal heat flow, kilometer-scale pre- and synvolcanic extensional faulting, and thick sedimentary cover is perhaps the most favorable setting for such large deposits, as seen in the present-day Okinawa Trough – a probable modern analog for some of the largest base metal mining districts in the world (e.g., Bathurst, New Brunswick, Iberian Pyrite Belt: [29, 36]. But many of these highly prospective settings are off-limits to exploration for science because they are in economic exclusion zones that are intensely contested by neighboring countries (e.g., the Andaman Trough north of Sumatra, the eastern edge of the Sea of Okhotsk behind the Kurile arc, the Bering Sea adjacent to Kamchatka).

Beyond the Known Plate Boundaries

Because submarine hydrothermal activity is so closely associated with spreading ridges and convergent margins, establishing the full extent of the resource potential has depended on a rigorous accounting of the plate boundaries. Hydrothermal venting has been found along the boundaries of 46 of the 52 recognized tectonic plates [21]. However, the recent advances in satellite altimetry and gravity modelling are bringing microplate mosaics into much better focus, with the discovery of new and smaller plates in complex geodynamic settings that may harbor previously unrecognized styles of seafloor mineralization. New research is revealing a much greater diversity of deposit types in these settings, including the first submarine gold vein mineralization in eastern Papua New Guinea and porphyry or epithermal-style copper-gold mineralization off New Zealand and the Japanese islands [29,36]. These findings are changing current thinking about the "metallogeny" of the oceans and also drawing attention to the potential of subsea resources on the continental shelves.

Beneath the Continental Shelf

Nearly 1/4 of the area of the global ocean basins is underlain by continental crust. Geologically, much of the continental shelf and slope are merely the submerged portions of the continental landmasses. In some cases, such as the Arctic basin, continental bedrock underlies almost 50% of the offshore area. This region is normally buried under several kilometers of sediment, so its extent and makeup is largely unknown. One reason for this is that offshore drilling (almost exclusively for hydrocarbons) generally stops at the basement. McKelvey [37] recognized that theoretically, any mineral resource mined on the continents could also occur in the offshore continental basement. If one considers the area of the continental shelf, then the resource potential, if accessible, is staggering. Some of the most richly-endowed mineral districts on Earth border the oceans (e.g., ancient terranes in Canada, Southern Greenland, West Africa, India, North China, and parts of Brazil), and the favourable geology does not stop at the shoreline. To access some of these deposits, more than 100 subsea underground mines have sunk shafts from land (or from artificial islands) to exploit coal, iron ore, nickel, tin, gold, copper, and

even mercury off the coasts of Australia, Canada, Chile, Finland, France, Greece, Japan, Poland, Spain, Taiwan, Turkey, the United Kingdom, and the United States [37]. While many of these are historical mines, one of the largest gold discoveries in China was recently made by drilling 2 km below the Yellow Sea along strike from the giant Jiaodong gold district [38]. Somewhere along the continental margins of the Atlantic basin, there is likely mineralization preserved from the opening of the Atlantic 70-80 my ago; somewhere in the Arctic, in the Kara Sea or the Laptev Sea, there may be extensions of the Permian flood basalts that host the giant Norilsk Ni deposits; somewhere in the Gulf of Mexico or the Mediterranean there are probably Mississippi Valley Type Pb-Zn deposits forming in offshore karsts associated with salt domes and oil and gas seeps. The list is long and someday could change the currently understood spectrum of offshore mineral resources.

Outlook

It Starts with a Geological Map

The global ocean assessment of mineral resources is hampered by our limited knowledge of the geology of the deep sea and its marginal basins. The most recent OECD report, *The Future of the Ocean Economy in 2030*, pointed out that governments charged with this assessment "… lack even basic tools such as a geological map of the seafloor – which is at the center of every land based minerals regulatory system …" [39]. A geological map is fundamental to resource exploration because the depicted features (rock type, age, composition, structure) correspond to the diagnostic elements in genetic models of the different mineral deposit types (e.g., metal sources, transport pathways, and depositional traps), exactly as in petroleum systems. The locations and quality of resources can be readily assessed with the right geological maps. Our geological maps of the oceans are rudimentary and mostly limited to the sedimentary cover and the (paleomagnetic) ages of the oceanic crust. Increasing application of multiparameter geophysics (magnetics, electromagnetics, gravity) is needed to advance the state-of-the-art from just high-resolution bathymetry to something approaching a geological map. A lack of seismic data (in part because of limited instrument pools), even at passive margins where seismicity is thought to be limited, has hindered advances in understanding the underlying lithospheric structure, which fundamentally determines where resources will be found. And, a step change is required in the density of sampling. Spatial and temporal variability in the composition of the crust in many prospective geodynamic settings is significant, sometimes at a very fine scale, yet samples that are needed to identify rock types are often collected 10s or even 100s of kilometers apart.

Where to Look, How to Look?

A major revision of the current mineral resources outlook for the oceans will likely result from expanding that search in two different directions: 1) onto older oceanic crust, and 2) onto and below the continental margins. The mineral resources of the oceans, as we know them, are strictly 2D – nodules, crusts, and massive sulfides on an essentially flat seafloor. Any short-term exploitation of those resources will also be 2D. If we imposed the same limitation on land deposits (i.e., mined only at the surface) we would have run out of metals to mine a century ago. Eventually, our assessment of marine mineral resources will require a 3D (and 4D) approach, similar to what the petroleum industry does routinely when modeling sedimentary basins. Numerical models constrained by geological sections and high-resolution plate histories can be a powerful tool in the search for mineral resources in the oceans.

Use of geophysical tools that can penetrate the sedimentary cover and detect signals from depth will be essential to test these models, just as they have on land.

Trans-Atlantic Geotraverse Revisited

We cannot map the entire ocean floor, but we can parse it into a number of achievable transects that focus on specific geodynamic settings of significance for global ocean resources. The transect approach is analogous to that of major geosurveys on land (Lithoprobe, AuScope, EarthScope) that involve intensive and coordinated geological mapping and geophysical surveys in key areas, typically with deep crustal seismic sections to characterize the fundamental architecture of the continents and with detailed sampling and geochronology. More than 40 years ago, and over a period of more than 10 years, long before the discovery of black smokers at the East Pacific Rise, Peter Rona led one of the first major regional geoscientific transects of the global mid-ocean ridge system, leading to the discovery of the Trans-Atlantic Geotraverse (TAG) site [40-44]. He defied conventional wisdom that slow-spreading ridges would be barren of hydrothermal activity and eventually made the first submersible observations of the only known active submarine hydrothermal field on a slow-spreading oceanic ridge. That project highlighted the effort required to make significant new discoveries in an immense ocean. Within individual countries, there is scope for such initiatives through interagency cooperation. However, there is no "Global Geological Survey of the Oceans" that can provide comprehensive information far beyond the areas of national jurisdiction. Such an initiative today would require a coordinated international effort at an unprecedented scale.

Note:

The views and interpretations expressed in this Discussion Paper are entirely those of the authors and do not represent any official stance by the University of Ottawa, GEOMAR Helmholtz Center for Ocean Research Kiel, or any other parties.

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Figure 1. A) and B) Areas with high Mn nodule potential and high ferromanganese crust potential, respectively, based on seafloor morphology, age of the crust, and metal input as defined by [4]. C) Location of high-temperature seafloor hydrothermal systems and associated mineral deposits. Red symbols indicate high metal concentrations (average of >5 wt% Cu, >15 wt% Zn, or >5 ppm Au in grab samples); large symbols indicate deposits with sizes estimated to be at least 1 million tonnes. Light blue areas delineate the Exclusive Economic Zones. Abbreviations: CCZ Clarion-Clipperton Zone, PB Peru Basin, PEN Penrhyn Basin, PCZ Prime Crust Zone. Modified from [25].