New Perspectives on Deep Ocean Exploration

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Abstract

Our vision of marine mineral resources is expanding with present and potential scientific and economic benefits as our understanding of the Earth advances. The introduction of the theory of plate tectonics opened new prospects for exploration in the deep ocean within and beyond the 200 nautical mile-wide Exclusive Economic Zone (EEZ) offshore coastal states. This paper presents the expanding perspective of non-living and living resources of the deep seafloor and is accompanied by the first film to clearly illuminate hydrothermal vents and their ecosystems in the deep ocean.

Marine Minerals from Continental Sources

Prior to the introduction of the theory of plate tectonics in the 1960's, ocean basins were regarded as big bathtubs that served as containers for the oceans since early in Earth history (Rona, 2003). The prospect of marine metal and non-metal non-fuel deposits under this scheme was limited to those minerals derived by erosion of continental rocks and transported to the ocean by rivers in solid (particulate) or dissolved phases (Lenoble et al., 1995). The particles were sorted by water motions and concentrated as placer deposits of dense metallic minerals and gemstones in sediments of continental margins (Garnett, 2000). Dissolved phosphorous and manganese were precipitated as phosphorites on continental margins (useful as fertilizers) within the EEZ, and contributed to the precipitation of manganese nodules on abyssal plains beyond the EEZ..

River input is an adequate source of those dissolved elements transferred to deep water by biogeochemical cycling that form phosphorite deposits and manganese nodules (Edmond et al., 1979). Phosphorite is precipitated on continental shelves where easterly trade winds blow offshore causing upwelling of deep water enriched in phosphorous (0^o to 30^o North and South latitudes). Present mining of phosphorite for principal use as fertilizer is from land deposits that formed during past higher sea levels, but extensive untapped deposits exist on continental shelves of agricultural developing nations like India. Golf- to tennis-ball sized manganese nodules cover vast areas of the abyssal plains (water depth to 6 km), Earth's largest physiographic province constituting nearly 70 percent of the seafloor. The nodules contain manganese with principal associated metals (cobalt, copper, iron, nickel), which precipitate from seawater over millions of years (Cronan, 2000). Estimate of the *in situ* value of these metals (Mero*,* 1965) incited a "gold rush" mentality, which drove negotiation of the United Nations Convention on the Law of the Sea (UNCLOS), an international “constitution” for use of the oceans. The marine mineral provision of UNCLOS, which was signed in 1982 and entered into force in 1994, is predicated on sharing of mineral resources as the "common heritage of mankind” in an International Area beyond the EEZ. The International Area is managed by the International Seabed Authority, an agency created by UNCLOS, in distinction to the EEZ under the sovereignty of adjacent coastal states. The International Seabed Authority has granted exclusive exploration contracts for tracts of the region of the most prospective manganese nodules (combined Cu, Ni, Co content >2.5 weight percent; abundance > 10 kg m^{-2}) in the eastern equatorial Pacific to “registered pioneer investors” consisting of seven national and industrial groups for eventual mining (Glasby, 2000).

Marine Non-living and Living Resources from Sources in the Deep Ocean

Plate tectonics expanded our vision of the ocean basins from passive sinks for material eroded from land to active sources of mineralization and opened new prospects. Focus expanded to processes at submerged plate boundaries (divergent and convergent), as the loci of a global system of exchange of heat and chemicals between the Earth's mantle, crust and oceans. The ocean basins are now known to be leaky containers of the oceans because volcanic rocks of ocean crust are fractured. Cold, dense, seawater flows kilometers downward and a mass approaching that of the ocean is assimilated into the underlying mantle over geologic time (Meade andJeanloz, 1991). Where the seawater flows near magma upwelling at plate boundaries, it is heated, expands, and buoyantly rises dissolving and transporting metals from the rocks and magmatic fluids. The metals link with sulfur primarily from seawater sulfate to precipitate as polymetallic sulfide deposits beneath and on the seafloor. Remaining high-temperature (to 400^o C) metal-and sulfide-rich hydrothermal solutions discharge, precipitating clouds of metallic mineral particles from "black smoker" vents that settle out of the water column as metalliferous sediments.

The first hydrothermal deposit was found at a submerged plate boundary in the 1960’s in the northern Red Sea, an early stage in the opening of an ocean basin where seafloor spreading at a divergent plate boundary has been separating Africa from the Saudi Arabian peninsula for the past 10×10^6 years. Hydrothermal solutions flowing by salt layers inter-bedded with volcanic rocks discharge and pond as density-stratified metal-rich brines and precipitate metalliferous sediments in several basins situated along the spreading axis. A pre-pilot mining test arranged by the Saudi-Sudanese Red Sea Commission in 1979 used hydraulic dredging techniques from a modified offshore oil drilling vessel to assess the largest of these deposits at 2 km water depth in the Atlantis II Deep. This Zn-Cu-Ag-Au deposit with a dry weight of 100 x 10^6 tonnes is the largest seafloor hydrothermal deposit known and awaits favorable market conditions for mining (Nawab, 2001).

As seafloor spreading continues, a sea like the Red Sea opens into an ocean basin like the Atlantic and metalliferous deposits formed at the spreading axis move off-axis as targets for future exploration. Like the Red Sea, hydrothermal activity occurs at sites along the spreading axis and concentrates deposits exemplified by the TAG (Trans-Atlantic Geotraverse) actively growing sulfide mound in the rift valley of the Mid-Atlantic Ridge at latitude 26^o N (Rona et al., 1993). There hot solutions of normal seawater salinity buoyantly discharge and have episodically built a mound the size and shape of the Houston Astrodome (200 m diameter by 35 m high) over the past 50,000 years composed primarily of polymetallic sulfides (Cu, Fe, Zn, Ag, Au). Drilling by the Ocean Drilling Program revealed a lens-shaped ore body beneath the mound, in turn, underlain by an upflow zone through the volcanic rocks that host the deposit (Humphris et al., 1995). Although seafloor features like chimney-shaped vents can regenerate quickly (weeks to years), the deposit as a whole "cooks" for tens of thousands of years to concentrate interesting metals into zones separate from the predominant iron, so that these deposits are not renewable resources. The 3-D form of the mound is generic for an economically important class of ancient Volcanogenic Massive Sulfide (VMS) deposits mined on land since pre-classical times. Insights gained from the active seafloor analogs have stimulated a surge of discoveries of these deposits where they have been uplifted onto land in the geological past in P.R. China and elsewhere (Rona and Hou, 1999).

Similar hydrothermal mineralization processes occur at submerged fore-arc volcanoes and spreading axes in back-arc basins of volcanic island arcs associated with subduction zones at convergent plate boundaries in the western Pacific. The polymetallic sulfide deposits at these settings are more prospective than those at divergent plate boundaries because they contain higher base and precious metal contents attributed to a larger magmatic input (Yang and Scott, 1996), and lie at intermediate water depths (1-2 km) within the EEZ, sometimes overlapping, of coastal states. In 1997 a lead article in the *New York Times* (Broad, 1997) announced that an Australian company, Nautilus Minerals, had leased from the Papua New Guinea government two active hydrothermal sites in the Manus basin of the Bismarck Sea to evaluate for mining. Other sites presently considered prospective include the craters and calderas of active volcanoes: These include Conical Seamount, also in the Bismarck Sea, with gold content comparable to that of a commercial deposit on the neighboring island (Lihir; Herzig and Hannington, 2000), and the Sunrise deposit in the Izu-Ogasawara Arc south of Japan *(*Iizsa et al., 1999) under evaluation by the Japan Metal Mining Agency.

Cobalt-rich ferromanganese deposits precipitate from seawater over millions of years like manganese nodules, but form crusts on the bare volcanic rock substrate of seamounts. Cobalt is the prospective metal of a suite co-derived from chemical erosion of terrestrial rocks and seafloor hydrothermal discharge. The crusts are particularly abundant within the EEZ of island states of the western equatorial Pacific. With global cobalt consumption at 26,000 tons yr^{-1} principally for making steel, an estimated 700,000 dry tons of crust mined per $year^1$from a single seamount would provide 10 to 25% of the need depending on grade (Hein, 2000). Cost-effective methods to recover the crust from a rocky substrate and to refine it remain to be developed.

The most widely distributed marine mineral is water, which has accumulated in ocean basins through Earth history by output from the Earth's interior by volcanic activity at plate boundaries and input to our atmosphere by comets. The need for a reliable and adequate source of fresh water in light of depletion by population growth, industrialization, and climate change is a pressing environmental problem. The oceans are the largest reservoir of water on Earth. Cost effective desalination is needed to tap this source.

Heat-loving chemosynthetic microbes lie at the base of the food chain that supports seafloor vent ecosystems (Jannasch, 1995. The microbes are energized by the ore-forming fluids that concentrate polymetallic sulfide deposits and are hosted in the deposits. These microbes utilize chemical energy derived primarily by oxidation of hydrogen sulfide dissolved in the hydrothermal solutions to manufacture carbohydrates from seawater constituents as their nutrients (Jannasch, 1995). The genomes of certain of these microbes exhibit characteristics at the base of the tree of life and their study may elucidate the origin of life. Commercial applications of their enzymes include DNA fingerprinting (polymerase chain reaction), food preservation, laundry detergents, flow enhancement in deep oil wells, and bioactive compounds for pharmaceuticals including those compounds that have promise for cancer treatment. The discovery of these microbes and their vent ecosystems was so unexpected that they fall outside the legal framework of UNCLOS. Environmental guidelines to sustain harvesting of deep ocean minerals and microbes are being developed by the UN and the ISA.

Conclusions

Mineral resources of the deep ocean are the product of both terrestrial and sub-sea processes. We presently possess only a preliminary knowledge of their diversity and distribution (Figure 1). The continental margins of whole continents remain to be explored. Less than 5 % of the seafloor has been explored in sufficient detail to find hydrothermal mineral deposits at submerged plate boundaries and virtually none of the seafloor away from plate boundaries or at depth beneath the seafloor. The scientific and economic significance of microbe-based mineral-hosted hydrothermal ecosystems in ocean crust is only beginning to emerge. A showing of the current film, *Volcanoes of the Deep Sea* (copyright The Stephen Low Company) illuminates these ecosystems in the deep Pacific and Atlantic oceans more clearly than ever before. A major class of deposits concentrated by magmatic processes including chromite and nickel- and platinum-group element-rich sulfide mineral phases known on land remains to be discovered in the mantle underlying the ocean crust. A lesson learned from the early “gold rich” for manganese nodules is that marine minerals are only economic when their market value exceeds the costs of bringing them to market under prevailing conditions. The most critical of all marine minerals is water because it is vital for life and depletion exceeds replenishment on land.

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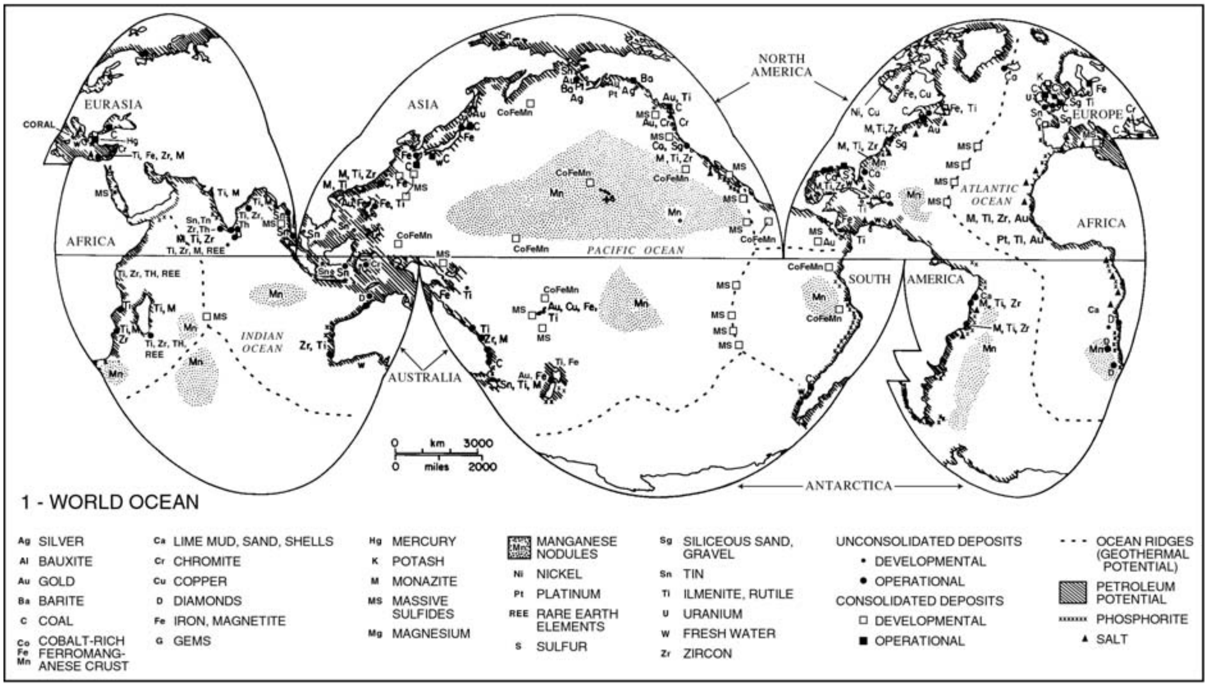

Figure 1. Global distribution of marine mineral resources (modified from Rona, 2003).