Resources of the Sea Floor
Peter A. Rona
Science **299**, 673 (2003);
DOI: 10.1126/science.1080679

GEOLOGY

Resources of the Sea Floor

Peter A. Rona

Plate tectonics is expanding our vision of marine minerals from those eroded from land—metals, gemstones, sand, and gravel—to an entirely new suite produced by dynamic processes in ocean basins. Sea-floor hot springs concentrate metal deposits and energize microbes at the base of vent ecosystems that link inorganic with organic processes, open prospects for living and nonliving resources, and present conservation challenges.

Before the discovery of plate tectonics, ocean basins were regarded as big bathtubs that had served as containers for the oceans since early in Earth history. Marine nonfuel deposits were relegated to minerals derived by erosion of terrestrial rocks and transported to the ocean by rivers in particulate or dissolved form.

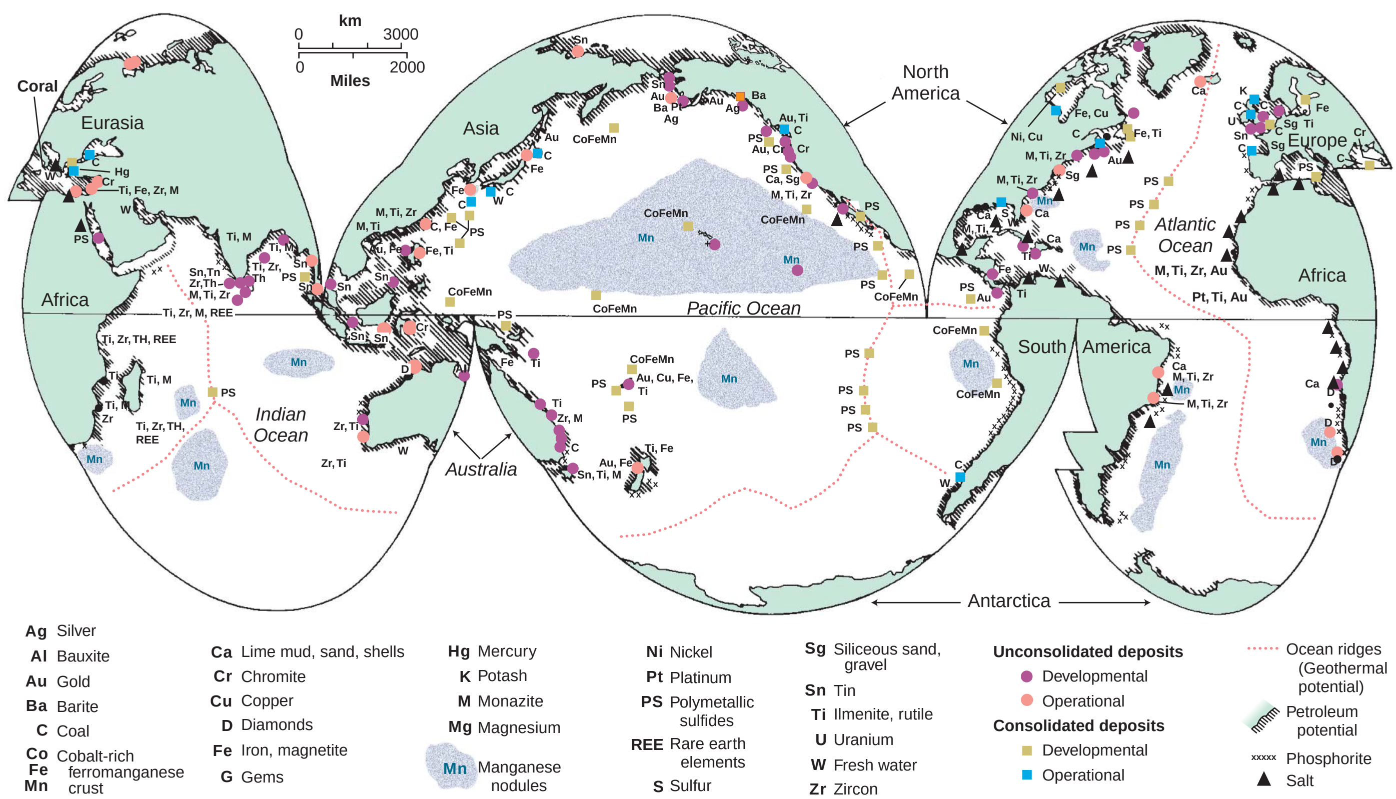
Particles are sorted by water motions as "placer deposits" of dense metallic minerals and gemstones in sediments of continental margins. Hundreds of such sites are known around the world, but few are mined (see the figure) (*1*). The tin mineral cassiterite, eroded from continental granites, is dredged in shallow water offshore Thailand and Indonesia. Gold-bearing sands and gravels in buried fluvial channels have been dredged in shallow water offshore Alaska, New Zealand, and the Philippines.

The largest unexplored potential for metallic mineral placers may exist along the west coast of South America, where rivers may have transported Andean metallic minerals under former wet climates. The biggest current success story is offshore mining for diamonds transported by the ancestral Orange River system to offshore Namibia and South Africa, where they are dredged from water depths to 200 m, with an estimated annual production value of US$ 0.25 billion (*2*). The most widely recovered marine mineral is sand and gravel dredged from beaches and shallow offshore bars for construction materials and beach restoration.

Rivers also carry dissolved elements such as manganese, which is transferred to deep water by biogeochemical cycling to form manganese nodules. Golf to tennis-ball sized, these nodules cover vast areas of the abyssal plains (at depth of 5 to 6 km), which constitute nearly 70% of the sea floor. The manganese and its principal associated metals—cobalt, copper, iron, and nickel—precipitate from seawater over millions of years.

An estimate of the in situ value of these metals, published in 1965 (*3*), incited a "gold rush" mentality that drove negotiation of UNCLOS (United Nations Convention on the Law of the Sea). The marine mineral provision of UNCLOS, which was signed in 1982 and entered into force in 1994, is predicated on sharing of marine mineral resources as the "common heritage of mankind" in an International Area beyond the outer limits of the continental shelf. In 2001, the International Seabed Authority granted exclusive 15-year exploration contracts for tracts of the region of the most prospective manganese nodules (combined Cu, Ni, Co content > 2.5% by weight, abundance > 10 kg/m^2) in the eastern equatorial Pacific to seven groups of "pioneer investors" consisting of national and industrial groups for eventual mining.

Phosphorite deposits also derive largely from the precipitation of dissolved terrestrial material. They form on continental



Global distribution of marine mineral resources known at this early stage of ocean exploration.

The author is at the Institute of Marine and Coastal Sciences and Department of Geological Sciences, Rutgers University, New Brunswick, NJ 08901, USA. E-mail: rona@imcs.rutgers.edu

CREDIT: MODIFIED FROM (*15*)

shelves where easterly trade winds blow offshore, causing upwelling of deep water enriched in phosphorus (between 30°N and 30°S). Present mining of phosphorite, which is mainly used 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.

Plate tectonics showed that the ocean basins are not just passive sinks for material eroded from land, but active sources of mineralization. Hydrothermal deposits are formed at submerged plate boundaries, where heat and chemicals are exchanged between mantle, crust, and oceans. The ocean basins are leaky containers, 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 (*4*). Where the seawater flows near upwelling magma at plate boundaries, it is heated, expands, and rises buoyantly, dissolving and transporting metals from the rocks and magmatic fluids. The metals react with seawater sulfate and precipitate as polymetallic sulfide deposits beneath and on the sea floor. High-temperature (to 400°C) metal- and sulfide-rich hydrothermal solutions discharge, precipitating clouds of metallic mineral particles at "black smoker" vents.

The first hydrothermal mineral deposit was found in the 1960s in the northern Red Sea, where sea-floor spreading separates Africa from the Saudi Arabian peninsula. Hydrothermal solutions discharge as density-stratified, metal-rich brines and precipitate metalliferous sediments in basins along the spreading axis. In 1979, the Saudi-Sudanese Red Sea Commission used hydraulic dredging techniques from a modified offshore oil-drilling vessel to assess the largest of these deposits, the Atlantis II Deep at 2-km water depth. At ~100 million metric tons, this Zn-Cu-Ag-Au deposit is the largest known sea-floor hydrothermal deposit and awaits favorable market conditions for mining (*5*). Salt deposits are related to restricted circulation at an early stage of opening.

As sea-floor spreading continues, a sea like the Red Sea opens into an ocean basin like the Atlantic, where metal-rich deposits formed at the spreading axis move away from the axis and become targets for future exploration. Hydrothermal activity at sites along the spreading axis continues to concentrate deposits. For example, the TAG (Trans-Atlantic Geotraverse) active mound in the rift valley of the Mid-Atlantic Ridge at latitude 26°N (*6*) has been built by internal precipitation and buoyant discharge of hot, metal-rich solutions of seawater salinity over the past 50,000 years. With a diameter of ~200 m and a height of ~40 m, the mound has the size and shape of the Houston Astrodome and is 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. Underneath lies an upflow zone through the volcanic rocks that host the deposit (*7*).

Sea-floor features like chimney-shaped vents can regenerate in weeks to years, but the deposit as a whole requires tens of thousands of years to concentrate economically interesting metals into zones separate from the predominant iron. The deposits are thus not renewable resources. The three-dimensional form of the mound is analogous to that of ancient polymetallic sulfide deposits mined on land since preclassical times. Insights gained from active sea-floor mounds have stimulated a surge of discoveries of such deposits on land in China and elsewhere.

Similar hydrothermal mineralization processes occur at submerged fore-arc volcanoes and in back-arc basins of volcanic island chains associated with subduction at convergent plate boundaries in the western Pacific. The polymetallic sulfide deposits at these sites are economically more promising than those at ocean ridges. They contain higher base and precious metal contents attributed to larger magmatic input (*8*), and lie at intermediate water depths (1 to 2 km) within the 200–nautical mile (370 km) zone of coastal states, as designated by UNCLOS.

In 1997, an Australian company, Nautilus Minerals, leased two active hydrothermal sites in the Bismarck Sea from the Papua New Guinea government to evaluate for mining (*9*). Other sites presently considered promising include active volcanoes. Conical Seamount near the leased sites has a gold content comparable to that of a commercial deposit on the neighboring island of Lihir (*10*), and the Sunrise deposit in the Izu-Ogasawara Arc south of Japan (*11*) is under evaluation by the Japan Metal Mining Agency.

Cobalt-rich ferromanganese deposits precipitate from seawater over millions of years and form crusts on the bare volcanic rock substrate of seamounts. (The metals derive both from chemical erosion of terrestrial rocks and sea-floor hydrothermal discharge.) The crusts are particularly abundant in the 200–nautical mile zones of island states in the western equatorial Pacific. With cobalt consumption at 36,900 tons per year, mainly used in steel, about 700,000 dry tons of crust per year mined from a single seamount could provide 11 to 20% of the need (grade 0.6 to 1.0%) (*12, 13*). However, cost-effective methods to recover the crust from a rocky substrate and refine it remain to be developed.

Active hydrothermal vents host diverse ecosystems. The heat-loving microbes at the base of the food chain supporting these ecosystems (*14*) derive their energy primarily from the oxidation of hydrogen sulfide dissolved in the ore-forming hydrothermal fluids. Commercial applications of these chemosynthetic microbes include use of their enzymes in DNA fingerprinting, detergents, food preservation, and flow enhancement in deep oil wells; of their bioactive compounds for pharmaceuticals; and of the microbes themselves as bioreactors with roles in concentrating and refining metallic mineral ores.

The discovery of vent ecosystems was so unexpected that they fall outside the legal framework of UNCLOS. A regime to manage development of these mineral deposits in an environmentally compatible manner and to protect the vent ecosystems that they host is in deliberation.

Marine minerals derive from sources on land and in ocean basins. We possess only a preliminary knowledge of their diversity and distribution (see the figure). The continental margins of whole continents remain to be explored. Less than 5% of the sea floor is known in sufficient detail to find hydrothermal mineral deposits at and away from plate boundaries. The scientific and economic significance of microbe-based mineral-hosted ecosystems in ocean crust is only starting to emerge. A major class of magmatic deposits including chromite and nickel-, copper-, and platinum-group sulfides known on land remains to be discovered in the mantle underlying the ocean crust.

Sea-floor resources are immense and of great scientific interest and increasing economic value. It is important to remember that mining marine minerals is only economic when the costs of bringing them to market under prevailing conditions are factored in and environmental impacts are evaluated.

References

1. J. P. Lenoble, C. Augris, R. Cambon, P. Saget, *Marine Mineral Occurrences and Deposits of the Economic Exclusive Zones, MARMIN: A Data Base* (Editions IFREMER, Brest, France, 1995), pp. 1–274.
2. R. H. T. Garnett, in *Handbook of Marine Mineral Deposits*, D. S. Cronan, Ed. (CRC Press, Boca Raton, FL, 2000), pp. 103–141.
3. J. L. Mero, *The Mineral Resources of the Sea* (Elsevier, Amsterdam, 1965).
4. C. Meade, R. Jeanloz, *Science* **252**, 68 (1991).
5. Z. Nawab, *Proposed Technologies for Mining Deep-Seabed Polymetallic Nodules* (International Seabed Authority, Kingston, Jamaica, 2001), pp. 26–27.
6. P. A. Rona *et al.*, *Econ. Geol.* **8**, 1989 (1993).
7. S. E. Humphris *et al.*, *Nature* **377**, 713 (1995).
8. K. Yang, S. D. Scott, *Nature* **383**, 420 (1996).
9. W. J. Broad, "First move made to mine mineral riches of seabed," *New York Times*, 21 December 1997, p. A1.
10. P. M. Herzig, M. D. Hannington, in *Handbook of Marine Mineral Deposits*, D. S. Cronan, Ed. (CRC Press, Boca Raton, FL, 2000), pp. 347–368.
11. K. Iizasa, *et al.*, *Science* **283**, 975 (1999).
12. J. R. Hein *et al.*, in *Handbook of Marine Mineral Deposits*, D.S. Cronan, Ed. (CRC Press, Boca Raton, FL, 2000), pp. 239–280.
13. J. R. Hein, personal communication.
14. H. W. Jannasch, *J. Mar. Biotechnol.* **3**, 5 (1995).
15. P. A. Rona, *Episodes* **25**, 2 (2002).