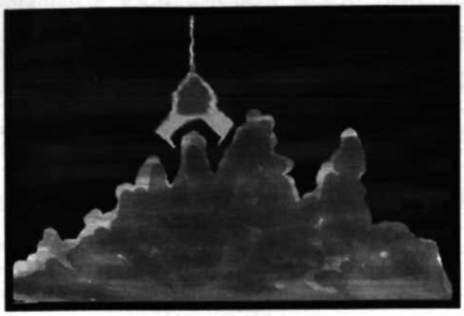

Deep Ocean Mining

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> ***... in the ocean depths, there exist mines of zinc, iron, silver and gold which would be quite easy to exploit***
>
> Jules Verne, 1870
> *Twenty Thousand Leagues Under the Sea*

SUMMARY

Earth's deep ocean beyond the continental rises at depths greater than approximately 1000 m constitutes about half of the surface area of the planet and hosts several mineral resources that have been or are soon to be investigated for commercial recovery. These include manganese nodules (copper, nickel, cobalt), manganese crusts (cobalt, platinum group elements), and polymetallic sulphides (copper, zinc, lead, silver, gold, barium). Polymetallic sulphides, formed by hydrothermal venting on the sea floor, are widespread in a variety of geological settings, including off Canada's west coast. Some deposits, such as the Atlantis II Deep in the Red Sea that contains 94 million metric tons, rival the size of analogous "giant" ore bodies on land although most marine deposits are very much smaller. Two entrepreneurial companies have taken aim at recovering these deposits and one, Nautilus Minerals, holds an exploration licence over large areas offshore of Papua New Guinea. The environmental consequences of mining the polymetallic sulphides are not well known but there is evidence that ocean mining may actually be less deleterious to the planet than land mining. Canadians are in a good position to play a major role in this new industry.

RÉSUMÉ

Les profondeurs marines qui s'étendent au delà des talus continentaux et qui forment plus de la moitié de la surface de la planète, renferment nombres de ressources minérales qui ont déjà été explorées ou le seront prochainement dans une optique d'exploitation commerciale. Ces ressources minérales comprennent des nodules de manganèse (cuivre, nickel, cobalt), des croûtes de manganèse (cobalt, éléments du groupe du platine), ainsi que des concentrations de sulfures polymétalliques (cuivre, zinc plomb, argent, or, baryum). Les sulfures polymétalliques formés par des exhalations hydrothermales sur fond marin sont communs et présents dans une variété de contextes géologiques différents, dont la bordure marine de la côte ouest canadienne. Bien que certains gîtes, tel le gîte *Atlantis II Deep* de la mer Rouge qui renferme 94 millions de tonnes métriques de minerai se compare aux gîtes continentaux géants, la plupart sont beaucoup plus petits. Deux sociétés entreprenantes entendent exploiter ces gisements, et l'une d'elles, *Nautilus Minerals* détient un permis d'exploration couvrant de grandes portions de l'offshore de la Nouvelle-Guinée. Les effets environnementaux de l'exploitation minière de gîtes de sulfures polymétalliques ne sont pas bien connus, mais il y a raison de croire que l'exploitation minière en milieu marin serait moins néfaste que sa contrepartie sur terre. Les Canadiens sont bien placés pour jouer un rôle majeur dans cette nouvelle industrie.

INTRODUCTION

Oceans and seas cover 71% of Earth, an area almost equal in size to two Moons plus two Mars-sized planets (Vogt and Tucholke, 1986). About 55% of this vast territory is deep ocean basins beyond the continental slope at water depths typically well in excess of 1000 m (Kennish, 1994). The surface area of the Pacific Ocean alone is twice that of all the continents. Both the shallow continental margins and the deep ocean basins harbour mineral resources, the economic potential of many of which, especially those in the deep basins, we are only beginning to appreciate (Cronan, 1999).

Ocean mining is not a new venture. Throughout much of the past century and even earlier, there has been placer mining of heavy minerals (gold, tin, titanium, zirconium, rare earths, and others) and diamonds and aggregates from beaches and from contiguous shallow waters. Present-day recovery of gem-quality diamonds from the seabed off the Atlantic coast of southern Africa (Namibia and South Africa) to water depths of about 100 m, with exploration extending to 250 m, represents a potential half-trillion dollar industry using advanced marine technologies.

Although it is not mining in the traditional sense, the oil industry led the way into the offshore in the mid-20th century. Critics of the day questioned the need for recovering this oil when there was plenty on land, and industry lacked the technology. In 1999, 30% of world petroleum production, or about 20 million barrels per day, came from this source (*Oil & Gas Journal,* 18 December 2000), and is growing as technology allows for increasingly deeper installations (Michaels, 2000; Sea Technology Staff, 2000). Wells are producing from depths of 1500 m offshore Brazil. In the Gulf of Mexico, drilling is taking place at depths of 2500 m and a lease at a depth of 3379 m was issued in 2000 (U.S. Mineral Management Service; http://www.mms.gov). Off Canada's east coast, oil exploration leases extend to 4000 m (B. Taylor, Jacques Witford Environmental, personal communication, 2000). In addition, solid gas (methane) hydrates found on many (and maybe all) continental margins at relatively shallow water depth represent an enormous energy source of about two times that of all remaining fossil fuels.

In the deep ocean basins, the main potential mineral resources are manganese nodules, manganese crusts, and polymetallic sulphides. Manganese nodules are centimetre- to decimetre-size lumps of manganese and iron oxides that litter much of the ocean floor at depths of about 5500 m (Figs. 1, 2). In places, these are in sufficient quantities, particularly in the Clarion-Clipperton Zone of the central-eastern Pacific southeast of Hawaii, to be considered potentially economic. The better deposits, perhaps representing

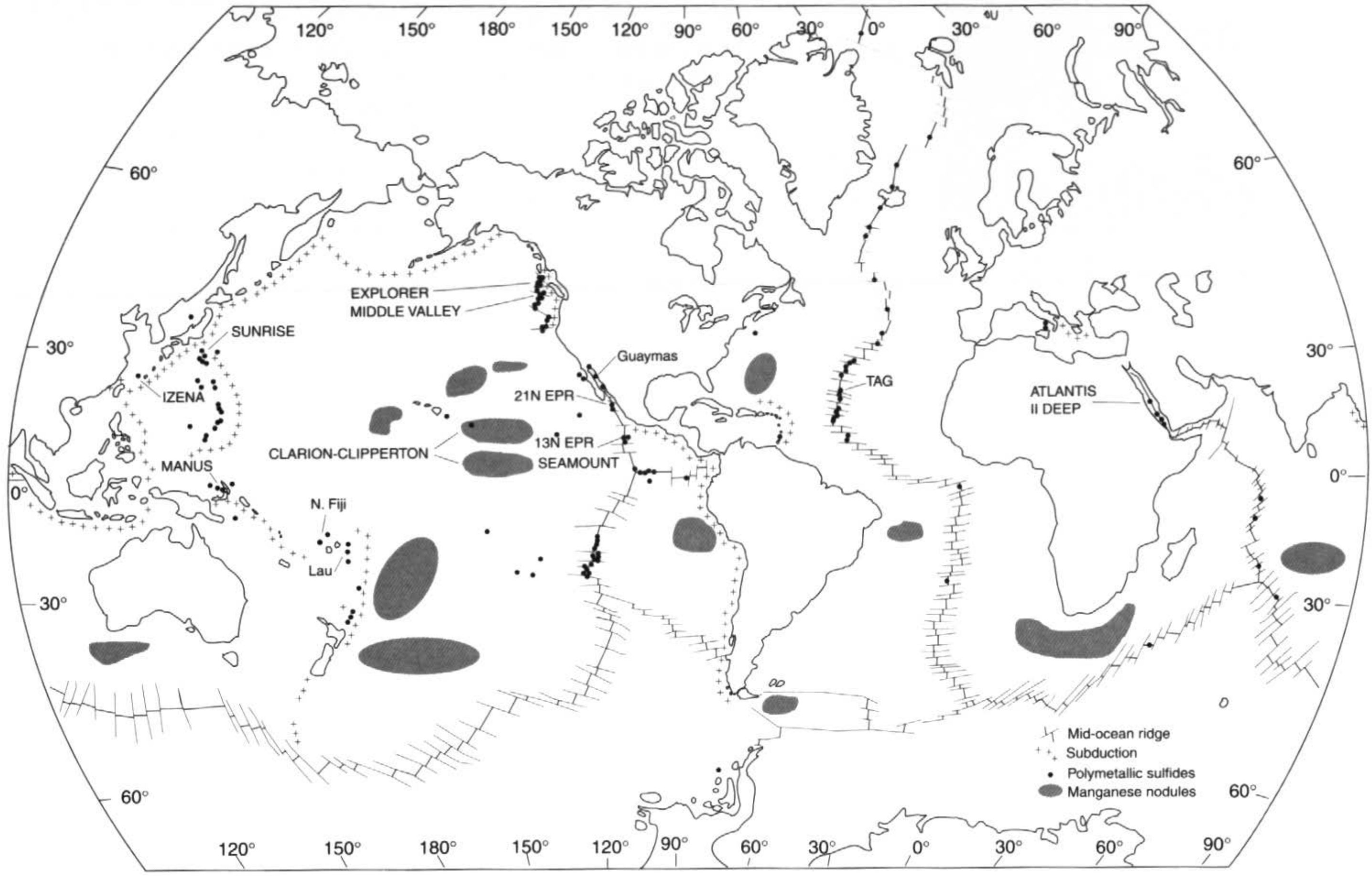

Figure 1 Manganese nodule fields and polymetallic sulphide sites (Rona and Scott, 1993, with additions) on the sea floor. Named deposits are discussed in the text.

10% of the total area of nodule accumulation, average about 2.4% Cu + Ni + Co, a grade similar to that of terrestrial sulphide Ni-Cu ores such as at Sudbury, Ontario (Exon *et al.,* 1992). Seafloor nodules as a copper resource are about 10% of that of known land reserves. Manganese, an essential element in steel making that is also finding other industrial uses, constitutes 20-25% of the higher-grade nodules and may someday itself become economic to recover, as land mines wane. Manganese crusts (Figs. 3, 4) form centimetre- to decimetre-thick pavements of manganese and iron oxides, typically over a calcium phosphate substrate, on the flanks of seamounts at water depths of 1000-2500 m. They contain on the order of 1% Co and minor platinum group elements. Polymetallic sulphides of Cu, Zn, Ag, Au and, in back-arcs, Pb are produced by seafloor hotsprings in a variety of geological settings at water depths from very shallow

Figure 2 Manganese nodules on the Pacific Ocean floor. Note the sediment cloud produced by contact of the photograph trigger (outer diameter of 15 cm) with the sea floor. Photograph courtesy of the United States Geological Survey.

(few tens of metres) to 3500 m (see compilations by Rona and Scott, 1993; Hannington *et al.*, 1994; Fouquet, 1997). These are discussed in more detail below.

Between 1974 and 1982, a consortium of private companies spent $US650 million in a failed venture to mine manganese nodules. The failure was due to a combination of unrealistic expectations brought about by inflated evaluations of the potential resource, high costs of metallurgical extraction, political interference, and collapsing metal prices. A renewed effort is underway today. In international waters, this is under the jurisdiction of the United Nations Law of the Sea Treaty that came into effect in November 1994. Regulations on prospecting and exploration for nodules were approved by the Assembly of the United Nations International Seabed Authority in July 2000 and additional regulations for manganese crusts, polymetallic sulfides, gas hydrates, and other commodities are being formulated.

The main players this time in manganese nodules are government-funded agencies in China (China Ocean Mineral Resources Research and Development Association, COMRA), Korea (Ministry of Maritime Affairs and Fisheries, MOMAF) and Japan (Metal Mining Agency of Japan, MMAJ). All three countries are in need of the strategic metals contained in nodules. COMRA has had three ships providing continuous surveillance of its nodule claim near Hawaii and has a co-operative agreement for logistics with the State of Hawaii. MOMAF has an approved budget of $US100 million for the 10-year period 2000-2010, leading to commercial nodule mining by 2013. At present, a Korea Ocean Research and Development Institute (KORDI) ship is surveying and sampling Korea's nodule claims in the Clarion-Clipperton Zone. KORDI also has research and development programs for mining manganese crusts and polymetallic sulphides in the Pacific Ocean. For several years the MMAJ has had an active exploration program for nodules, crusts, and polymetallic sulphides in the Pacific, and is developing a hydraulic multipurpose machine for recovering marine minerals. In addition to these three, India has a modest program in the Indian Ocean and is developing an ocean mining crawler. A consortium of Norwegian shipping, oil, and marine engineering companies is considering the possibility of recovering nodules within the Exclusive Economic Zone (EEZ) of the Cook Islands. These nodules are in somewhat shallower water than most (~5000 m) and are said by the Cook Island government, which is actively seeking a miner, to be richer than other nodule fields (Pryor, 1995; Kingan, 1997).

The mining of manganese crusts will be even more challenging than for manganese nodules. Although the crusts are in shallower water, which makes some operations at least conceptually easier, the nature of the crusts requires them to be removed from their rock substrate by scraping or cutting. Only the thickest crusts are likely to be recoverable and their commercial exploitation will not likely take place until some time after nodule operations have been established.

Of the three types of metal deposits discussed above, only polymetallic sulphides are known to occur within

Figure 3 Manganese crust coating the flank of a guyot south of Hawaii. Field of view is approximately 5 m. Photograph courtesy of the United States Geological Survey.

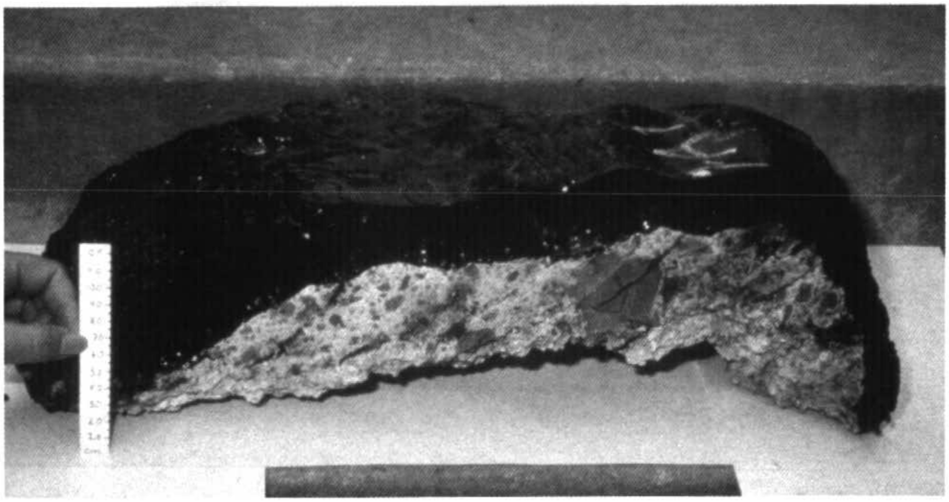

Figure 4 Piece of manganese crust (black layer) on a substrate is phosphatized basalt breccia. Photograph courtesy of the United States Geological Survey.

the Canadian EEZ. These are the subject of the remainder of this paper.

POLYMETALLIC SULPHIDES

Actively forming concentrations of iron sulphides and oxides containing significant base and precious metals were first discovered on the sea floor in the Atlantis II Deep of the Red Sea in the mid-1960s (Degens and Ross, 1969). These deposits are essentially metalliferous mud formed from hot, dense brines. In late 1978, submersible dives at 21°N latitude on the East Pacific Rise encountered high-temperature (to 350°C) geysers depositing sinter-like mounds and chimneys of metal sulphides, oxides, silica, and sulphates (Rise Project Group, 1980; Hekinian *et al.,* 1980). Deposits such as these (Figs. 5, 6) have similarities to so-called volcanogenic massive sulphide (VMS) ores being mined on land in Canada and elsewhere, and which formed in ancient oceans as much as 2700 m.y. ago. Elements of potential commercial interest in both the modern and ancient deposits are copper, zinc, lead, silver, gold, and barium. Veins, disseminations, and stockworks of relatively low metal grade impregnate the underlying rocks. Many more deposits of this type have now been discovered in a variety of geological settings in both volcanic rocks and sediments. About 150 active and fossil seafloor sites are known in all of the world's oceans and several seas (Fig. 1). The deposits mostly lie in depths of between 1500 m and 3500 m, although a few are in much shallower water. Some have geological and mineralogical similarities with ancient ores mined on land (Table 1). Actively forming sulphide chimneys are known even in Lake Tanganyika (Tiercelin *et al.,* 1993) and some other lakes in volcanic terrains.

Size and Grade Considerations

Many of the early discoveries of seafloor polymetallic sulphides were at mid-ocean spreading ridges and on seamounts. Recent investigations have centred on island arcs which, together with rifted continental margins, are preferred settings of ancient analogous VMS ores, some of which reach gigantic proportions of >100 million metric tons (mmt). Examples include the Ordovician-age 134 mmt Brunswick #12 deposit at Bathurst, New Brunswick, and several Carboniferous-age deposits of the Iberian Pyrite Belt in Spain and Portugal. The tectonic setting of giant Precambrian deposits, such as the 161-mmt Kidd Creek mine in Ontario, is uncertain but such deposits have attributes in their associated volcanic rocks resembling those of island arcs. Some

Figure 5 Black smoker complex at 13°N East Pacific Rise. The "smoke" is metal-laden hydrothermal fluid emanating from a chimney at about 350°C that has mixed with 2°C ambient seawater causing precipitation of fine sulphides. Surrounding this smoker are other active and inactive edifices of sulphides (Fe, Cu, Zn, trace Ag, and Au), sulphates and silica. Field of view about 5 m. Photograph courtesy of R. Hekinian, IFREMER, France.

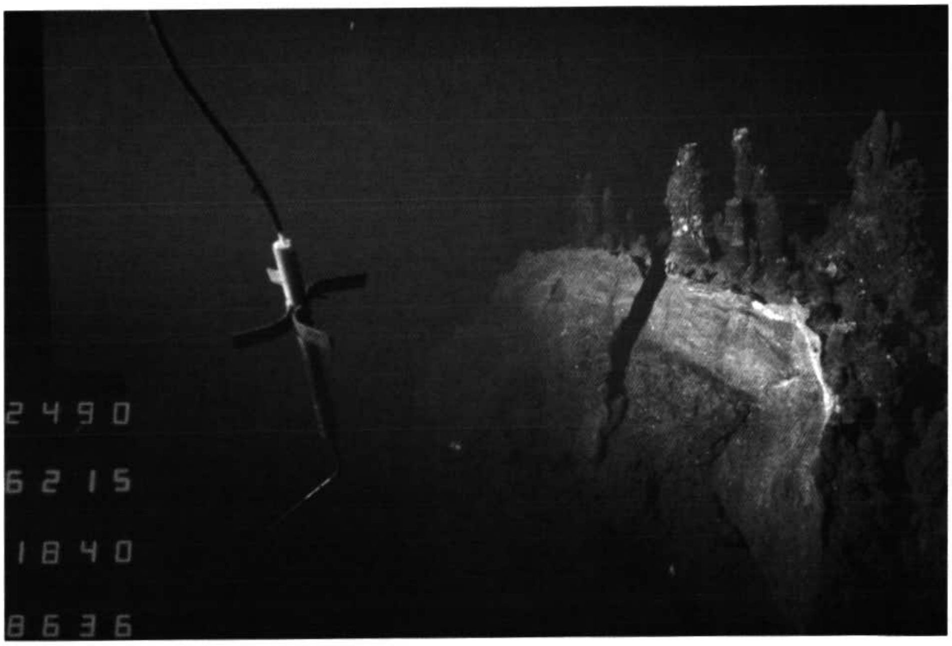

Figure 6 Sulphide mound at 13°N East Pacific Rise split by a fault and topped by inactive chimneys. The exposed interior of the mound is about 3 m across. Photograph courtesy of R. Hekinian, IFREMER, France.

features in these ancient ores can be identified in modern seafloor deposits, although none of comparable size has yet been found in a modern island arc.

The size and, particularly, the grade of the seafloor polymetallic sulphide deposits are largely unknown. Most of the discoveries so far are small, perhaps averaging only a few thousand tons, but there are some that appear to be of a similar size — a few mmt — to mineable VMS land deposits (Scott, 1992). Others are likely to be found as seafloor exploration continues, especially in such tectonic settings as island arcs and continental margins, where large deposits are known from the ancient geological record. The approximate sizes of some of the larger seafloor deposits are given in Table 2. To put these sizes in perspective, the two largest VMS deposits mined in Cyprus, which formed in a basalt-hosted back arc, were Mavrovouni at 15 mmt and Skouriotissa at 6 mmt (Bear, 1963). Production plus reserves of 12 VMS mines in the back-arc felsic volcanic rocks of the Hokuroku district of Japan totalled 140 mmt but consisted of 39 individual ore lenses ranging from 0.034 mmt to 30 mmt (Tanimura *et al.*, 1983). Sixty-three VMS deposits in Quebec, most of which are Archean age, range in size from 771 tonnes to 54 mmt, average 4.8 mmt, and have a median value of 1.49 mmt (Franklin, 1995). The median size of more than 800 VMS deposits worldwide is 1.25 mmt (G. Riverin, Inmet Mining Corporation, personal communication, 2001).

Only the Atlantis II Deep in the Red Sea has been investigated sufficiently in three dimensions to know its true size and grade, and it is likely that only the highest-grade portions of its 94 mmt would ever be recovered. Except for the Atlantis II Deep, the true grade (average metal content) of the seafloor deposits is unknown. The only information available is analyses of samples, such as that shown in Figure 7, taken from different parts of deposits by dredging, submersible operations, and a few drill holes by the Ocean Drilling Program. Table 3 gives representative examples from back arcs in both basalt and felsic volcanic settings, compared with actual grades from representative VMS land deposits. Although some of these average analyses are spectacular, especially for precious metals, it is not likely that these are representative of the entire deposit.

In addition to these massive sulphide ores, there are numerous occurrences of lower-temperature ("epithermal") gold and silver deposits on the sea floor. The best studied of these is the Conical Seamount site, only a few kilometres from the giant Ladolam gold deposit on Lihir Island, Papua New Guinea, which it resembles geologically (Herzig, 1999). None of these precious metal epithermal deposits, including Conical Seamount, have been sufficiently well surveyed to know if they may be economically viable, but surficial indications look promising.

PROSPECTS FOR MINING POLYMETALLIC SULPHIDES

Early activities in ocean mining of polymetallic sulphides were government sponsored. A German company, Preussag, explored for seafloor sulphides until 1990, supported by large government subsidies. The company, on behalf of the Red Sea Commission, systematically evaluated the Atlantis II Deep, and conducted trial mining of the metalliferous mud using a modified drill ship. Full mining was deemed to be uneconomic. The Metal Mining Agency of Japan and associates carried out extensive seafloor surveys in the EEZs of some Pacific island nations and elsewhere during the 1990s but did not pursue mining.

The past 4 years have seen a dramatic increase in activity to develop seafloor polymetallic deposits as a viable resource, this time by the private sector. The Nautilus Minerals Corporation based in Sydney, Australia was first off the mark when it obtained an exploration license from the government of Papua New Guinea covering polymetallic sulphide discoveries made by research scientists in the Bismarck Sea of Manus back-arc basin

Table 1 Phanerozoic massive sulphide ores and their modern analogues.

Ore Type	Metals	Host Rocks	Setting	Ancient Example	Modern Analogues
KUROKO	Zn, Pb, Cu, Ag, Au	· Felsic volcanics and benthic (>2000 m) sediments	· Back arc on continental crust	· Hokuroku, Japan · Iberian Pyrite Belt · Bathurst, Canada	· Izena, Okinawa Trough · E. Manus Basin · Sunrise, Izu-Bonin
CYPRUS	Cu, Zn	· Basalt	· Back arc oceanic crust (ophiolite)	· Cyprus · Oman · Iran	· Central Manus Basin · North Fiji Basin
BESSHI	Cu, Co	· Basalt and benthic sediments	· Sedimented back arc oceanic crust or rifted arc	· Besshi and Hitachi, Japan · Windy Craggy, Canada	· None known (Guaymas and Middle Valley have some similarity)
SEDEX	Pb, Zn, Ag	· Fine-grained terrigenous clastic sediments	· Rifted continental margin	· Meggen and Rammelsberg, Germany · Selwyn Basin, Canada	· None known (Atlantis II Deep, Red Sea has some similarity)
	Cu (Mt. Isa)			· Mt. Isa, Australia	

Table 2 Size of some large seafloor sulphide deposits.

Site	Host Rocks	Estimated Million MetricTons	How Estimated	Reference
Atlantis II Deep, Red Sea	· Sediment	· 94 (actual reserves)	· Close-spaced coring	· Mustafa *et al.,* 1984
Middle Valley, Juan de Fuca Ridge	· Sediment	· 28	· 34 ODP cored holes and surface exposure	· Davis *et al.,* 1992 · Fouquet *et al.,* 1998
TAG, Mid-Atlantic Ridge	· Basalt	· 10 (main, Mir and Alvin mounds)	· 13 ODP cored holes in main mound and surface exposure	· Rona *et al.,* 1986, 1993 · Humphris *et al.,* 1995
Sunrise Izu-Bonin Arc	· Rhyolite	· 9	· Surface exposure with fault scarps	· Iizasa *et al.,* 1999
Izena Cauldron, Okinawa Trough	· Andesite and sediment	· 5? (includes recently discovered deposit at bottom of depression)	· Surface exposure and comparison with dimensions of Fukazawa Kuroko deposit	· Maeda *et al.,* 1997 · Halbach *et al.,* 1989, 1993
Southern Explorer Ridge	· Basalt	· 3-5 (Magic Mountain and 6 other largest of the 60 known deposits)	· Surface exposure. · Magic Mountain is 250 m in diameter and 18 m thick on one side	· Scott *et al.,* 1990
Seamount, 13°N East Pacific Rise	· Basalt	· 2-4 (additional recently discovered sulphides not included)	· Surface exposure and geophysical (resistivity) data	· Hekinian and Fouquet, 1985 · Francis, 1985

(Both *et al.,* 1986; Binns and Scott 1993; Binns and Dekker, 1998). A front-page article by William Broad in the 21 December 1997 issue of the *New York Times* reported this first-ever granting of an offshore license for polymetallic sulphides, and set off a flurry of activity elsewhere. Soon thereafter, an American company, Deep Sea Minerals, with a major American mining company as a partner, began to establish itself with worldwide activities. Another Australian company, Neptune Resources, with an application pending for an exploration license covering parts of the Havre Trough region north of North Island, New Zealand, has merged recently with Deep Sea Minerals. There are at least three other "entities" investigating investment and mining opportunities in the deep ocean. All are facing formidable challenges raising high-risk venture capital despite the decade-long buoyancy of the American financial markets. The Bre-X gold scandal of the 1990s is still scaring off investors from even traditional junior mining companies.

Much of this new marine activity is being driven by environmental and land-claim problems being encountered increasingly on land, as well as the recognition by at least one large mining company with worldwide operations that a secure supply of smelter feed is diminishing in the long term. The success by environmentalists in stopping the 300+ mmt Windy Craggy copper project in the Yukon, and ongoing jurisdictional problems at Inco's Voiseys Bay property are but two Canadian examples. As discussed below, environmental degradation may actually be less of a problem with mines in the ocean than on land.

Ocean mining for polymetallic sulphides will have high start-up costs, perhaps as much as $US300 million ($C450 million), but this must be seen in the light of discovery and development costs for new land mines that are typically of the same order of magnitude. For example, approximately $C400 million is required to find and develop a VMS deposit in the Abitibi region of western central Quebec (G. Riverin, Inmet Mining Corporation, personal communication, 2001), and Noranda will spend about $US198 million ($C300 million) to develop 30 mmt of ore between 2000 m and 3000 m depths in its Kidd Creek mine. The anticipated start-up cost for ocean mining of polymetallic sulphides is favourable relative to the $US650 million spent on the failed attempt to mine manganese nodules. Ocean mining may even have some economic advantages over

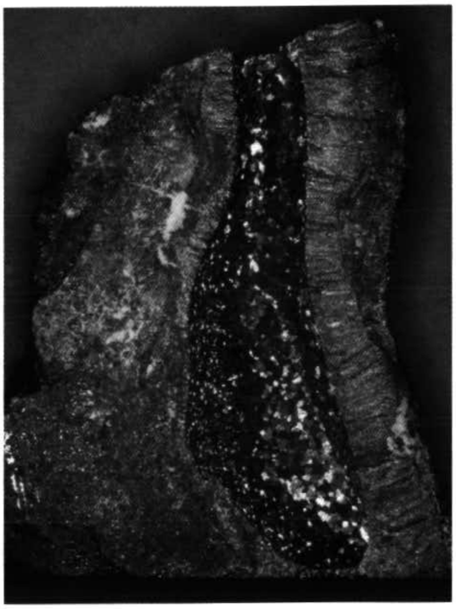

Figure 7 Interior of an 11-cm high chimney from 13°N East Pacific Rise. The exterior is primarily fine-grained anhydrite, silica, and zinc sulphide. The interior fluid conduit is coarse-grained Cu-Fe sulphide (chalcopyrite or isocubanite). Photograph courtesy of Y. Fouquet, IFREMER, France.

conventional land mining. Unlike ocean mines, land mines require expensive permanent installations such as shafts ($C4500-9700 per metre) and tunnels ($C1500-3000 per metre) if an underground mine, extensive excavations if an open pit mine, power lines, roads and, in some cases even a town site, all of which are left behind when an ore body on land is exhausted. Recent costs for developing a mine site from a green field condition have ranged from $US130 million ($C195 million) for a modest-sized gold mine with a ramp in Nevada, to $C315 million for a large base metal mine with a 900-m deep shaft in the Abitibi region (W. Shaever, Dynatec Corporation, personal communication, 2001). Because these costs have to be amortized over the life of a mine, small deposits have to be located near existing infrastructure to be economic. A deposit that is remote from areas of existing infrastructure has to be very large and/or very rich to be mined. An ocean mining platform, on the other hand, can be moved easily from site to site so that much smaller deposits can be recovered than is possible on land. Shipping of ore or concentrates to smelters would be largely or entirely by sea and therefore at relatively low cost.

Although the technology does not exist for recovering seafloor polymetallic sulphides, some schemes that were developed by the Lockheed Corporation for recovering manganese nodules, such as robotic bottom mining vehicles and lift systems (Welling, 1981), probably can be adapted to sulphide mining. The sulphides are at shallower water depth than nodules and are relatively soft so should be easy to break up. The subsurface stockworks typically have a lower metal content than the massive sulphides, are harder and would require excavation, so they probably would not be recovered unless by solution mining or bio-leaching. For the softer surface deposits, Scott (1992) envisaged a robotic continuous miner (Fig. 8) with a cutting blade, much as is used in coal and potash mines, that would extract, grind and preconcentrate the desired minerals, lift these to surface in a slurry (air lift or pump) and leave the waste minerals on the sea floor. Leaving the rejects on the sea floor instead of lifting them to surface and concentrating them there would reduce recovery costs substantially and also has attractive environmental advantages. Alton *et al.* (1989) demonstrated in bench tests that a strong magnet is as effective as conventional froth flotation in separating sulphides from their gangue. Scaling up to a mining operation would require a superconducting magnet operating at seafloor temperatures of 2-4°C. Such a magnet does not yet exist, but operating temperatures for superconductors are rising with continuing research in this field.

Simply piping the 350°C metalliferous solutions from the hydrothermal vents to surface and precipitating the metals is not realistic. The solutions are very corrosive, rich in hydrogen sulphide, and contain only a few ppm of the desired metals. Furthermore, the hot fluids would boil vigorously as the confining pressure is released on the ascent to surface, causing minerals to precipitate, most of which, such as anhydrite, pyrite or pyrrhotite and silica, are undesirable and would clog the pipe in similar manner to the build-up of scale in geothermal fields.

ENVIRONMENTAL CONSIDERATIONS

Small scale mining tests of manganese nodules, also applicable to sulphide mining in sedimented areas, suggest that the resuspension of the fine sediment may do ecological damage well outside of the mining area as the sediment plume is carried across the sea floor by currents and settles out on the gills of filter feeding animals (Thiel *et al.*, 1991). It is expected, however, that the affected areas would be repopulated eventually as the species concerned are widespread. Most of the known sulphide deposits occur in volcanic areas that are relatively free of sediment other than that produced by the disaggregation of the sulphides during mining and recovery. However, this local suspension of particles in the water column probably has no lasting effect on

Table 3 Grades of ancient (Cyprus, Kuroko) massive sulphide deposits in island arc settings and averaged analyses of samples from modern seafloor analogues.

	BASALT-HOSTED			FELSIC VOLCANIC-HOSTED				
	Cyprus	N. Fiji	Central Manus	Kuroko	Eastern Manus	Lau	Izena (Jade)	Sunrise
No. analyses		24	25		26	47	17	37
Wt%								
Cu	~4	7.5	2.2	1.6	10.9	4.6	3.1	5.5
Zn	0.5	6.6	29.7	3.0	26.9	16.1	24.5	21.9
Pb	~0	0.06	0.6	0.8	1.7	0.3	12.1	2.27
ppm								
Ag	39	151	—	93	230	256	1160	1213
Au	0.3	1.0	—	0.6	15	1.4	3.3	20

Cyprus: Mavrovouni (Bear, 1963)
N. Fiji Basin (Bendel *et al.*, 1993)
Central Manus Basin (Tufar, 1989)
Kuroko: entire district of 12 mines (Tanimura *et al.*, 1983)

Eastern Manus Basin, PACMANUS site (Scott and Binns, 1995)
Lau Basin, Valu Fa Ridge (Fouquet *et al.*, 1993)
Jade deposit, Izena Cauldron, Okinawa Trough (Scott, 1997)
Sunrise, Izu-Bonin arc (Iizasa *et al.*, 1999)

the biota. For example, as pointed out by Binns and Dekker (1998), the Manus site occurs in an area of very strong and frequent earthquakes that must stir up the bottom, and there are dense clouds of mineral precipitates in the water column resulting from the hydrothermal venting. Neither of these has affected the masses of healthy organisms. By preconcentrating the metals on the sea floor rather than at surface, not only would operating costs be reduced but also there would be no pollution of the water column caused by dumping the waste back to the sea floor. Organisms densely populate areas of active hydrothermal venting but such areas would be avoided during mining in any case, because of the deleterious effects of the hot corrosive vent fluid on the mining equipment.

There may actually be some environmental advantages of marine mining over land mining for polymetallic sulphides. Three of the greatest adverse environmental consequences of land mining are acid mine waters produced by exposing iron sulphide to the atmosphere, large surface excavations of open pit mines, and unsightly piles of waste rock from surface or underground excavations. Acids produced by submarine weathering are quickly neutralized by the alkaline seawater. The surficial sulphide deposits are mounds sitting on the sea floor so there would be no excavations and no waste-rock piles. The separation process would produce waste, amounting to some 80% of the mined material, but this could be done on the sea floor and the residue simply reoccupy the space from which it was originally extracted.

Mining may release into the water column toxic elements such as mercury, arsenic, antimony and selenium that occur in very low concentrations in the sulphides. The hydrothermal venting process is releasing these continuously and the amount added by mining is expected to be relatively minimal. Besides, as pointed out by Binns and Dekker (1998), the resident animals not only survive but they actually thrive in this naturally occurring toxic environment. Undoubtedly, there would be some loss of habitat of some marine organisms, at least temporarily, and biologists would be called upon to determine if mining would result in the permanent loss of some species (*e.g.,* environmental impact assessments and monitoring). All of these anticipated consequences of ocean mining could be tested by well-designed experiments (Exon *et al.,* 1992; Scott, 1992), such as that illustrated in Figure 9, which would monitor the dispersal of particulates as simulated mining is carried out. In the experiment, the vicinity of an isolated, hydrothermally inactive, small sulphide mound would be instrumented with moorings to monitor the fluxes and dispersal patterns of particulates before, during, and after the disaggregation of the mound by a television-guided grab. The concentration of particulates would be measured with optical transmissometers and some of the particles would be recovered in traps to give further information on their concentrations, composition, and size. Dispersal patterns outside of the instrumented area could then be predicted from the measured size and density of the trapped particles and knowledge of the bottom currents.

CANADIAN SITUATION

Large polymetallic sulphide deposits occur within Canada's western Exclusive Economic Zone in Middle Valley (Davis *et al.,* 1992; Fouquet *et al.,* 1998) and southern Explorer Ridge (Scott *et al.,* 1990). Despite these having been known since the mid-1980s and the existence of a government agency within Natural Resources Canada to deal with offshore resources, Canada still does not have a mechanism for establishing marine mining claims. Attempts by two major Canadian mining companies to obtain exploration licenses in the late 1980s were thwarted by this lack of regulations, as was a more recent attempt by a junior company. Canada, a developed country with a large minerals industry, is lagging behind some European countries, New Zealand and even developing island nations in the western Pacific such as Papua New Guinea and the Kingdom of Tonga. These countries are already issuing or are preparing to issue marine exploration and mining licenses, and are developing protocols for administering exploration and marine scientific research in their territorial waters. In Canada, a new round of provincial-federal negotiations, instigated by the provincial mines ministers, has been underway for more than 2 years and new legislation is expected following open public discussion of the issues.

Canada is in the forefront of designating marine protected areas in the deep ocean such as the Endeavour hydrothermal vent field at a depth of 2250 m on the Juan de Fuca Ridge (Juniper, 1999). With its skilled marine industries and research community in universities and government, Canada has an opportunity to be a leader in establishing operational and environmental guidelines for the fledgling marine mining industry.

The oil industry made its major move to the offshore 40 years ago despite there being lots of oil remaining on land

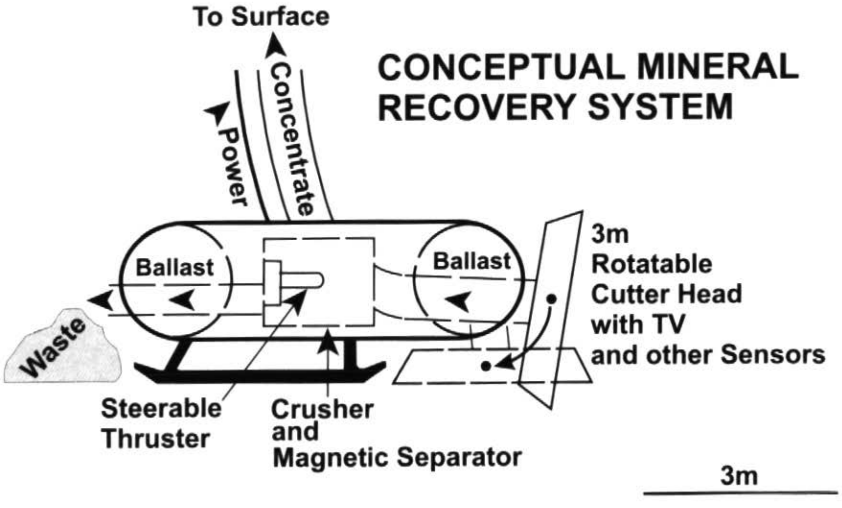

Figure 8 Schematic of a robotic mining machine for the recovery of seafloor polymetallic sulphides.

and not having yet developed the technology. Today, this is a major economically viable activity. Can marine mining be far behind?

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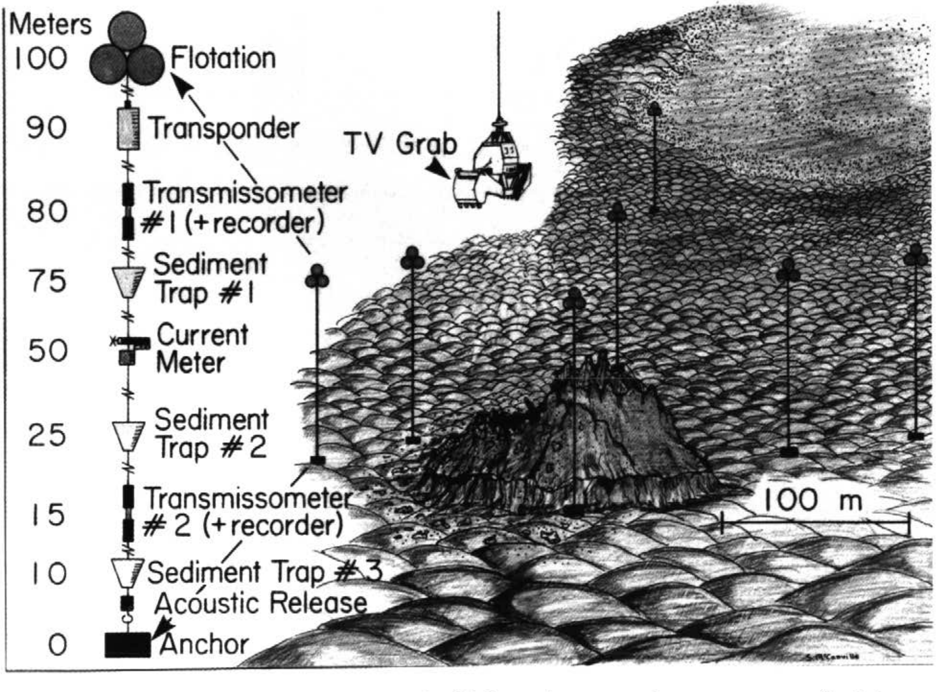

Figure 9 Simulation experiment to test the likely environmental consequences of mining seafloor polymetallic sulphides.

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