Introduction

The authors of this paper are members of the Engineering Committee on Ocean Resources (ECOR) specialist panel on marine mining (S.D. Scott, Chair). They each represent different aspects of mineral resources in the oceans. The first report of the panel published in 2006 covered phosphorites, manganese nodules, ferromanganese crusts and seafloor massive sulfides. The report is available at http://oceanicresources-ecor.amc.edu.au/a06marineminingpanelreport.pdf. In this second report, the commodities in the first report have been updated and to them have been added tin and other heavy minerals, sand, diamonds, lime, solutes and precious metals, the latter as a separate report.

Table 1 lists the various marine minerals that are or could be recovered from the sea. Detailed compilations may be found in Rona (2008), Lenoble et al. (1995), Cruickshank (1998), Antrim (2005) and Hein et al. (2005). A map locating the seafloor resources is in Figure 1.

Table 1. Commodities in the marine environment.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Setting</th>
<th>Status</th>
<th>Growth Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregates (sand and gravel)</td>
<td>Beach and shallow marine</td>
<td>Operational</td>
<td>High</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Deep sea nodules</td>
<td>Nonoperational</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Crusts on seamounts</td>
<td>Nonoperational</td>
<td>Low</td>
</tr>
<tr>
<td>Copper</td>
<td>Deep sea nodules</td>
<td>Nonoperational</td>
<td>Moderate</td>
</tr>
<tr>
<td>Copper</td>
<td>Deep sea sulfides</td>
<td>Nonoperational</td>
<td>High (2010)</td>
</tr>
<tr>
<td>Diamonds</td>
<td>Shallow marine</td>
<td>Operational</td>
<td>High</td>
</tr>
<tr>
<td>Gold</td>
<td>Shallow marine placer</td>
<td>Nonoperational (Some artisanal)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Gold</td>
<td>Deep sea sulfides</td>
<td>Nonoperational</td>
<td>High (2010)</td>
</tr>
<tr>
<td>Heavy minerals (chromium, rare earths, thorium, titanium, zirconium)</td>
<td>Beach and shallow marine placer</td>
<td>Operational (minor)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Lead</td>
<td>Deep sea sulfides</td>
<td>Nonoperational</td>
<td>High</td>
</tr>
<tr>
<td>Lime (coral, shells)</td>
<td>Beach</td>
<td>Operational (minor)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Methane (gas hydrate)</td>
<td>Shallow/intermediate marine</td>
<td>Nonoperational (test well on land)</td>
<td>Moderate but technological challenges</td>
</tr>
<tr>
<td>Nickel</td>
<td>Deep sea nodules</td>
<td>Nonoperational</td>
<td>Moderate</td>
</tr>
<tr>
<td>Nickel</td>
<td>Crusts on seamounts</td>
<td>Nonoperational</td>
<td>Low</td>
</tr>
<tr>
<td>Phosphate</td>
<td>Shallow marine and seamounts</td>
<td>Nonoperational</td>
<td>Moderate / Low</td>
</tr>
<tr>
<td>Platinum Group Metals</td>
<td>Crusts on seamounts</td>
<td>Nonoperational</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 1 continued ……. 
Mineral Deposits in the Sea

<table>
<thead>
<tr>
<th>Rare Earth Elements</th>
<th>Crusts on seamounts</th>
<th>Nonoperational</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt</td>
<td>Very shallow marine (evaporation)</td>
<td>Operational</td>
<td>Moderate</td>
</tr>
<tr>
<td>Silver</td>
<td>Deep sea sulfides</td>
<td>Nonoperational</td>
<td>High (2010)</td>
</tr>
<tr>
<td>Tin</td>
<td>Shallow marine placer</td>
<td>Operational to 50m water depth</td>
<td>High to depth &gt;80 m water depth</td>
</tr>
<tr>
<td>Zinc</td>
<td>Deep sea sulfides</td>
<td>Nonoperational</td>
<td>High (2010)</td>
</tr>
</tbody>
</table>

The name of the panel (“marine mining”) is a misnomer because the majority of the commodities in Table 1 and those discussed in more detail here are not actually being produced from the seabed today but there is the potential to do so.

Oceans and seas cover 71% of Earth’s surface, an area almost equal in size to that of the surfaces of two Moons plus two Mars. About 60% of Earth’s surface is deep ocean basins beyond the continental slope at water depths typically in excess of 2000 metres. The surface area of the Pacific Ocean alone is twice that of all the continents. Both the shallow continental margins and the ocean basins harbour mineral resources, many of whose economic potential and especially those in the deep basins, we are only beginning to appreciate.

![Figure 1. Distribution of known marine mineral resources (Rona 2008). Reprinted from Ore Geology Reviews 33 (2008) 616-666, published by Elsevier B. V., with permission.](image-url)
Marine 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), 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 to water depths of about 150 m, and exploration extending to 250 m, represents a multi-billion dollar industry utilizing 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. Today, about one third of world petroleum production comes from this source and is growing as technology allows for increasingly deeper installations. Wells are producing from 1500 m water depth offshore Brazil. In the Perdidi Fold Belt in the Gulf of Mexico, exploration is taking place at 2700 m depth (World Oil, November, 2005, p. 75-82) and a lease at 3379 m water depth was issued in 2000 (U.S. Mineral Management Service; www.mms.gov). Off Canada’s east coast, where exploration leases extend to 4000 m (B. Taylor, Jacques Witford Environmental, personal communication, 2000), an exploration well was recently completed in 2400 m of water 325 km offshore Newfoundland (www.chevron.ca/operations/exploration/atlantic.asp). The technological challenges of working in deep water are being overcome by the oil industry. The mining industry can capitalize on oil’s experience in developing its marine mineral resources.

For this paper, the panel evaluated where the industry stands now for each of the commodities under consideration, the most pressing issues, where the industry needs to be in the near future, and how it can get there.

Phosphorite (Hein, Rona)

Phosphorites (calcium phosphate) are distinguished from other sedimentary rocks by their high phosphorous pentoxide (P$_2$O$_5$) contents and consist of varieties of the mineral apatite (5 to 40%; Riggs, 1979; Bentor, 1980; Kudrass, 2000). Phosphorite deposits are part of a biogeochemical cycle that involves aqueous dissolution of phosphorous from terrestrial rocks and transport by rivers into the ocean, uptake by marine plankton, transfer into deep water masses by sinking and dissolution of the plankton tests, return to surface water by upwelling, and deposition as authigenic precipitates by the diagenetic replacement of carbonates and precipitation from pore fluids (Burnett, 1990). Phosphorite is used as a fertilizer in agriculture and in the food industry as phosphoric acid, found in nearly all soft drinks. It also has many industrial uses.

Where the industry stands now
Phosphorites occur in four geographic-tectonic settings in the modern ocean basin (Hein et al., 2005): (1) The best studied phosphorite occurs on continental shelves and slopes, primarily off the west coast of continents where easterly trade winds blow offshore
thereby inducing upwelling. These deposits formed beneath zones of coastal upwelling from early diagenetic processes very near the seawater-sediment interface in an organic matter-rich environment. Examples are phosphorite deposits of Quaternary age at four localities: offshore Peru and Chile (Veeh et al., 1973; Burnett, 1977, 1990); offshore Namibia (Baturin et al., 1972; Baturin, 1982; Veeh et al., 1974; Thomson et al., 1984) and South Africa south of the trade wind belt (Birch, 1980; McArthur et al., 1988); offshore Baja California in Mexico (Jahnke et al., 1983); and offshore the Atlantic margin of Morocco (Summerhayes and McArthur, 1990); (2) Phosphorite occurs extensively on some submarine plateaus, ridges, and banks, the best studied being Blake Plateau off the southeastern United States where phosphorites are present to water depths of 1 km (Riggs, 1979; Manheim et al., 1980) and Chatham Rise off New Zealand in water depths of 350 m to 450 m, with an average $P_2O_5$ content of 22 percent (Cullen, 1986; Kudrass, 1984; Exon et al., 1992). Plateau phosphorites formed from cementation and replacement of carbonates in an organic matter-rich environment; (3) Phosphorite forms on islands, atolls, and within atoll lagoons. These insular deposits replace and cement reef carbonates within the freshwater lens, or within the seawater-freshwater mixing zone, and may mark periods of sea-level change. The source of phosphorus is primarily guano; (4) Phosphorite forms on mid-plate seamounts and may be the most widely distributed but least studied of the marine phosphorites. These deposits result from the replacement of carbonates by carbonate fluorapatite (CFA). Of these four types of phosphorites, the subaerial insular type has been mined at many places, mostly during WW II, but also up to today, such as on Nauru Island, which at one time had the highest per capita income in the world as the result of the phosphate industry.

**Pressing issues**

The Nauru deposit and many of the large phosphorite deposits on land have nearly been depleted and finding additional large deposits on the continents is unlikely. The last large deposit to be found is in northern Saudi Arabia and mining will soon begin there. Offshore deposits that have been considered as likely sources of phosphate are located off Florida and Georgia in the southeastern U.S. and on Chatham Rise in the New Zealand EEZ. Phosphorite off the southeastern U.S. has been drilled and is fairly well characterized and the New Zealand deposit has been well studied from surface samples. The main issue with mining these deposits is that the on-land supplies are still good enough for on-land mines to fulfill demand. However, the global market prices have nearly tripled in the past year, which should make offshore mining more attractive and promote the realistic determination of costs of offshore phosphate mining. Off-the-shelf technology could be used for ore recovery and processing plants are available at numerous near-coastal locations, such as Florida. Environmental research related to mining these deposits is very limited, which would be a significant concern within the U.S. and New Zealand EEZs. Regulatory issues for offshore mining remain unresolved, but are essential to ensuring the kind of investments from companies that will undertake the risk.

**Where do we need to be in the near future?**

Global markets are at a level that should promote a serious look at offshore deposits and phosphate supplies need to start considering this option. Better deposit characterization
and environmental studies would be prudent next steps. However, little if any research is taking place on marine phosphorites, except for the continental-margin type deposits because of scientific interest.

**How do we get there?**
Foster governmental and industry interest in the offshore deposits as a real alternative to the mining of lower-grade and smaller on-land deposits in the future.

**Manganese Nodules** (Atmanand, Heydon, Morgan)

Manganese nodules are cm- to dm-size potato-shaped lumps of manganese and iron oxides that litter much of the ocean’s sediment-covered abyssal plains at about 4500 – 5500 m water depths (Figures 2 and 3).

![Map showing manganese nodule fields and some seafloor massive sulfides](from Scott, 2001). See also Figure 1.

The manganese nodule deposits in the Clarion-Clipperton Zone (CCZ) of the northeastern tropical Pacific (5° - 20° N; 110° - 160° W; Figure 2) have been extensively explored by commercial and research interests and are estimated to contain large quantities of manganese (>7.5 x 10⁹ metric tons), nickel (>3.4 x 10⁸ mt), copper (>2.7 x 10⁸ mt) and cobalt (>7.8 x 10⁷ mt) (Morgan 1999). Smaller but still significant deposits occur in the Indian Ocean.
Exclusive exploration rights to portions of these deposits have been granted by the International Seabed Authority (ISA) under the authority of the United Nations Convention on the Law of the Sea to Contractors from Japan, Korea, China, India, France, Russia, Germany and a consortium of Eastern European countries together with Cuba. Nodule deposits are also known to occur in the Exclusive Economic Zones of some island nations such as Cook Islands and Kiribati.

The abundance and grade of the nodules tend to be highest well away from land, where dilution from sediment settling in the water column is lowest, and where biological productivity is moderately high. The metals in the South Pacific deposits, and probably the CCZ deposits as well, are believed to be derived primarily from sedimentation of fine-grained inorganic materials that are incorporated into planktonic fecal matter, subsequently reduced through consumption by benthic biota, and then ultimately adsorbed onto the manganese oxide surfaces of the nodules (Verlaan et al., 2004).

A proprietary economic assessment from the 1990’s (C.G. Welling, personal communication to Morgan, 1995) concluded that the key constituent of these deposits for commercial extraction is nickel, which occurs in concentrations between 1.2% and 1.45% in the CCZ deposits. However, the changing economic situation with improvements in extractive technology and rising metal prices means that copper would also be a critical product of nodule mining. Offshore nodule mining will compete with on-land mining of nickel laterite. Offshore mining may be more complex and capital intensive than nickel laterite mining but the nodules contain an order of magnitude greater manganese and around 1.3% copper. The added value of the copper in nodules could more than account
for any cost differences between nodule and laterite mining. Manganese, an essential element in steel making that is also finding other industrial uses, constitutes 25-30% of the higher grade nodules and may someday itself become economic to recover as a by-product of nodule mining as land mines wane.

Where the industry stands now
The commercial viability of mining these deposits has yet to be demonstrated but, in the late 1970’s, one consortium successfully operated a remote miner under a trial mine scenario of mining and pumping, recovering approximately 800 tons to the surface. Another consortium conducted a bulk sampling operation towing a collector and successfully pumped approximately 1,000 tons of nodules from 5,000mbsl to the surface. The sheer size of the resource continues to motivate these Contractors to retain their exclusive rights (Kudrass et al. 2006). In addition, a recent workshop sponsored by the International Seabed Authority (ISA, February 2008) concluded that, based on the most recent economic models available, mining of these deposits could generate an internal rate of return of between 15% and 38%. With magmatic copper-nickel sulfide mining waning, the on-land competitor for nodules is large tonnage nickel ± cobalt laterite ores produced by tropical weathering of ultramafic rocks (serpentinite). These deposits contain on the order of 1% nickel, similar to nodules, but do not contain copper as nodules do.

Currently, there are eight groups with contracts with the ISA for seabed exploration in international waters and two groups who have submitted applications. These are:

- Government of India: The National Institute for Ocean Technology (NIOT) of India, the technical arm of Ministry of Earth Sciences, has the mandate to develop the technology for mining manganese nodules. India is working on a crawler based mining system with a flexible riser. The mining system tests were carried out at a 410 meter depth using a crawler and Ocean Research Vessel (ORV) Sagar Kanya. An in-situ soil testing system has been developed and tested by India, and several facilities such as a hyperbaric test facility (to test sub-systems up to 900 bars pressure) and a state of the art research vessel Sagar Nidhi have been established. India has developed the processing technology for nodules through three routes: hydrometallurgy based on ammonia leaching; pyrometallurgical pretreatment followed by leaching; and reductive acid leaching.

- Institut français de recherche pour l’exploitation de la mer / Association française pour l’étude et la recherche des nodules (IFREMER/AFERNOD) of France: This group has completed its exploration activities within its Contract area, but continues to support environmental research. In the summer of 2004, it conducted deep-submersible (Nautil) surveys within its area that were designed to characterize the benthic habitats within the CCZ.

- Deep Ocean Resources Development Company (DORD) of Japan: DORD is not currently sponsoring active exploration in its CCZ Contract area, but maintains its exploration Contract with the ISA.
• State Enterprise Yuzmorgeologiya of the Russian Federation: They have studied the size and operational parameters of a mining vessel as well as the technical requirements for their proposed collector and other mining subsystems. They have reported recovery of molybdenum from nodules in addition to nickel, copper, cobalt and manganese.

• China Ocean Mineral Resources Research and Development Association (COMRA) of the People’s Republic of China: COMRA is responsible for the development of polymetallic nodule mining technology in China. They have worked on both a tracked miner and an Archimedes screw miner; hydraulic and mechanical collectors; and air and hydraulic lifting systems. They are developing a rigid riser system with a self propelled miner. COMRA’s studies have indicated that deep seabed polymetallic nodule mining is feasible from the viewpoint of technology. This was especially true if polymetallic nodule mining was compared to cobalt-rich ferromanganese crusts and polymetallic sulfides mining.

• Interoceanmetal Joint Organization (IOM): IOM is a consortium formed by Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia. Its technology development strategy is to address the recovery and processing of polymetallic nodules; model the production of three metals (copper, nickel and cobalt); utilize a ship based slurry lift system; and assess the economics of their mining operation in terms of its internal rate of return; and establish the phases of pre-investment, construction, and operation. IOM’s conceptual design includes: a mining vessel or floating platform; a seabed nodule collecting miner; a buffer or platform for temporary storage of nodules placed in front of the vertical transport system; a control and management system; and an energy subsystem.

• Government of the Republic of Korea’s Korea Ocean Research and Development Institute (KORDI) / Korea Institute of Geosciences and Mineral Resources (KIGAM): Phase I of the Government of the Republic of Korea’s work was limited to feasibility studies and some fundamental research. In phase II, technology development and at-sea tests will be undertaken. Korea is also pursuing a flexible riser system like India’s. Korea has developed an ROV, an underwater launcher, and a support vessel. For technology development, they are utilizing model and simulation techniques. Design methods have been established through systematic fundamental research such as a dynamic simulation method for analysis of the mechanical feasibility of the total system; experiments on collecting operations devices such as pick-up, seafloor driving and slurry transport; Multidisciplinary Design Optimization (MDO) for developing a self-propelled miner; and 2- and 3-phase slurry pipe flow analyses. The Korean government has large scale test facilities namely its Deep-Sea Mining Laboratory and Lifting Test Laboratory.

• The Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany: Germany only recently obtained its exploration license. It is preparing an inventory of the benthic community in its contract area, has proposed
an exploration cruise during the latter part of 2008, and has started to analyze trace metals in nodules from its exploration area.

- **Nauru Ocean Resources Inc.:** Sponsored by the Government of Nauru and currently a subsidiary of Nautilus Minerals Inc. (51% ownership), this is the first private company to make application to the International Seabed Authority for a Contract to Explore for Polymetallic Nodules in the Reserved Area. The 75,000 sq km application was considered by Legal and Technical Commission at the May 2008 session and will be further considered at the 2009 session. Importantly, this marks both the first application by a commercial enterprise and industry participant since the ISA was formed in 1994 and the first application sponsored by a Developing State. The Regulations in the United Nations Convention of the Law of the Sea embody a parallel system that recognizes that Developing States do not have the same technical and financial capacity of Developed States and provide a regime under which they can participate in the potential exploitation of these resources.

- **Tonga Offshore Mining Limited:** Sponsored by the Kingdom of Tonga and currently a subsidiary of Nautilus Minerals Inc. (51% ownership), this private company is one of the first non-Government funded enterprises to make application to the International Seabed Authority for a Contract to Explore for Polymetallic Nodules with a 75,000 sq km application in the Reserved Area. The application was considered by the Legal and Technical Commission at the May 2008 session and will be further considered at the 2009 session.

In addition to the exploration work being conducted under the jurisdiction of the ISA, a consortium of Norwegian shipping, oil and marine engineering companies has considered the possibility of recovering cobalt-rich manganese nodules within the Exclusive Economic Zone of the Cook Islands. More recently, a Canadian mining merchant banking company, Endeavour Mining Capital Corp. (now Endeavour Financial Corp.), has sought exclusive mining rights covering an area of 1 million km$^2$ (Cook Island Herald Online edition, www.ciherald.co.ck/articles/h382a.htm, November 24, 2007). These nodules are in somewhat shallower water than most (~ 5000m) and are said by the Cook Island government, who is actively seeking a miner, to be richer in cobalt than in other nodule fields. A preliminary resource assessment, based on exploration data collected during three research cruises by the Japanese vessel R/V Hakurei-Maru-2, suggests that the total quantities of metals contained in these deposits include 33 million metric tons of cobalt, 24 million metric tons of nickel and 14 million metric tons of copper (Clark et al., 1995).

**Pressing issues**
Public perception of marine mining, particularly in the developed countries, is generally negative. Any development has to face steep uphill battles to win the environmental and regulatory hurdles that are in place.
Where do we need to be in the near future?
The public and political visibility of marine minerals in general must be raised to the level where new developments don't have to re-invent regulatory regimes and can compete on a level playing field with land-based development efforts.

We should be mining nodules but, in consort with this, protecting the environment should be the major concern. Countries like India and China with rapidly expanding economies are bearing the brunt of resource developments resulting in pollution of land, air and water. Marine mining of nodules will happen sooner or later and it is in the interest of future generations that this mining be conducted in an environmentally responsible manner. Nodule mining would provide an alternative source of nickel and may offer a reprieve for the land environment and replace the development of some laterite nickel mines, some of which require clearing of large areas of rainforest.

How do we get there?
Get the players in the field to support non-governmental efforts in public education and development of regulatory standards. The economic feasibility of commercial extraction needs to be established.

Ferromanganese Crusts (Hein)

Ferromanganese crusts (Figures 4 and 5) are ubiquitous on hard-rock substrates throughout the ocean basins. They form at the seafloor on the flanks and summits of seamounts, ridges, plateaus and abyssal hills where the rocks have been swept clean of sediments at least intermittently for millions of years. Crusts form pavements up to 250 mm thick on rock outcrops, or coat talus debris. Some are underlain by phosphorite. Ferromanganese crusts form by precipitation from cold ambient bottom waters. They contain sub-equal amounts of Fe and Mn but it is their minor metal content that makes them attractive for potential future mining, especially the high contents of cobalt (on the order of 1%). They also contain minor amounts of titanium (to 2.1%), cerium (to 1.1%) and other rare-earth elements, nickel (to 0.81%), copper (to 0.32%), molybdenum (to 0.25%), zirconium (to 0.12%), tellurium (to 205 ppm), and platinum (to 2 ppm) that could be recovered as by-products. These high values are about twice the mean values, except for tellurium and platinum, which are about four times the mean values for crusts.

Where the industry stands now
Ferromanganese crusts have not been mined but much scientific work has been done on locating the highest grade and highest tonnage (crust thickness) deposits, which it has been found occur in the central equatorial Pacific. Preliminary environmental studies and engineering concepts of mining equipment and processing have been undertaken. Proposed mining techniques include water jets, sonic dislodgement of the crusts, in situ leaching, line-bucket dredging, and rip-up crawler and roller crushing machines.
Figure 4. Manganese crust coating the flank of a guyot south of Hawaii. Field of view is approximately 5 m. Photograph courtesy of United States Geological Survey.

Figure 5. Piece of manganese crust (black layer) on a substrate is phosphatized basalt breccia. Photograph courtesy of United States Geological Survey.

Pressing issues
Ferromanganese crusts are thin, attached to the substrate rock, and therefore difficult to mine without collecting substrate at the same time, thereby diluting the ore. The extractive metallurgy for this oxide matrix has been adopted from manganese nodules and is not a sufficient technology for economic mining. However, techniques newly developed for extraction of nickel from laterites also work well for the main metals (Co, Ni, Cu) of interest in crusts and tests are being preformed to determine the efficacy of these techniques for other metals of interest to high technology industries. The present
world market for cobalt is only 60,000 tons per year, which is partly controlled by cobalt
being the byproduct of mining of other metals, principally copper. If ferromanganese
nodule mining were to start, then the question becomes whether mining of cobalt crusts
could operate alongside nodules without flooding the world market and driving down
prices. It has been suggested that offshore production of cobalt could supply about 20%
of the world market without affecting prices and that the market for cobalt is likely to
increase significantly if a primary source of the metal becomes available. Competing
operations would have to work within those limitations.

From the engineering side, development of mining equipment and extractive metallurgy
are key issues, but some basic data need to be collected before a mining method can be
chosen. Most important are knowing the small-scale topography of seamounts and the
variability in the thickness of crusts over short distances. This information is critical
before viable technological equipment can be designed.

Where do we need to be in the near future?
The global markets for the metals found in ferromanganese crusts are making them more
and more attractive as potential mining targets. However, technology needs to be put in
place that can determine the small-scale topography and the variability in thicknesses so
that engineers can better design appropriate mining equipment. These are not
technologically trivial matters and will require dedicated efforts. Japan, China, and Korea
are putting the most effort into resolving these issues, but commonly keep such
information proprietary. There needs to be a much larger effort going into technology
development by other groups. Environmental studies of crust mining are only in their
infancy; however, several large international programs are underway to address the
biological diversity and community structure on seamounts (e.g., Census of Marine Life;
Seamounts-online).

How do we get there?
There needs to be national commitments to acquiring the scientific information needed
and developing the technology required to recover this type of mineral deposit. That
national commitment is not presently seen outside Japan, Korea, China and Russia, but
perhaps changes in global markets and supplies of some of the critical metals will change
that lack of commitment by many industrialized nations. This is already being seen by the
increased demand for copper and nickel in Asia that is rapidly increasing prices.
Regulatory issues for offshore mining remain unresolved, but are essential to ensuring the
kind of investments from companies that will undertake the risk.

Seafloor Massive Sulfides (Heydon, Scott)

Actively forming concentrations of iron sulfides 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. 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 sulfides, oxides, silica and sulfates. Deposits such as these (Figures 6 and 7) have geological and mineralogical similarities to so-called volcanogenic massive sulfide (VMS) ores being mined on land and which formed in ancient oceans as much as 2700 million years 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 content impregnate the underlying rocks but, unlike for similar deposits on land, are not likely to be recovered. 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 (Figure 1). The deposits mostly lie between 1500 and 3500 meters depth although a few are in much shallower water and at least one is at a water depth of 4050 meters.

Figure 6. Black smoker complex at 13ºN 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 sulfides. Surrounding this smoker are other active and inactive edifices of sulfides (Fe, Cu, Zn, trace Ag and Au), sulfates and silica. Field of view about 5 m. Photograph courtesy of R. Hekinian, IFREMER, France.

Where the industry stands now
The seafloor massive sulfide industry is at a very early stage of mine development but its activities are ahead of those of phosphorite, crusts and perhaps nodules. There are only two serious commercial players in this field. Nautilus Minerals Inc. (listed on the Toronto Stock Exchange and on the London Stock Exchange – Alternative Investment Market) has extensive exploration leases in the Manus and Woodlark Basins territorial waters of eastern Papua New Guinea, in the EEZ of Solomon Islands and Tonga, and applications in New Zealand and Fiji. Neptune Minerals (listed on the London Stock Exchange –
Figure 7. Small sulfide mound at 13ºN 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.

Alternative Investment Market) has exploration leases in the territorial waters of Papua New Guinea, and the EEZ of New Zealand, the Federated States of Micronesia and Vanuatu, and applications in New Zealand, Japan, Commonwealth of Northern Mariana Islands, Palau and Italy. Nautilus as of March, 2008 held US$310 million in cash to develop the first mining operation. Neptune has limited capital. Bluewater Metals, an unlisted private company based in Australia, has exploration licenses and applications in the SW Pacific region to explore for seafloor massive sulfides. The partnership of Korea Ocean Research and Development Institute (KORDI) and Korea Institute of Geosciences and Mineral Resources (KIGAM), both government agencies, has exploration licenses from Tonga (Chosun Ilbo, April 3, 2008). Deep Ocean Resources Development Company (DORD), a Japanese private-government consortium under government control, has applied for concessions in the Japanese EEZ.

Nautilus has defined a resource to rigorous NI43-101 specifications at its flagship Solwara 1 project in the Manus Basin of Papua New Guinea. The inferred + indicated ore based on 153 drill holes to a maximum depth of 19 meters, 38% of which terminated in sulfides, is 2.17 million tonnes averaging (at 4% copper cut-off grade) 7.2% copper, 0.6% zinc, 31 g/t silver and 6.2 g/t gold. Drilling of one of Neptune’s exploration targets in the crater of Brother’s Seamount in the Kermadec region offshore North Island, New Zealand encountered sulfides but showed no accumulation at or near the surface of commercial quantities of mineralization. The focus of scientists to date has been the hydrothermally active (“black smoker”) vent fields that produce a ready signature which can be located up to 10 km away. Previously there has been very limited consideration of
Nautilus plans, subject to timely permitting, to be in production by the end of 2010 at its Solwara 1 copper – gold project in 1,600 meters of water. The mining system is shown in Figure 8. Nautilus has let a GB £33 million contract for two deep sea mining machines and a US $114 million engineering procurement, construction management contract for the riser pipes and pumps to lift the ore to the surface. A 160 meter mining vessel is under construction in Turkey and Spain by a third party for delivery in 2010. Neptune has applied to the New Zealand government for a permit to conduct trial mining. It also anticipates commencing mining operations in 2010 although it has yet to define a resource.

Pressing issues
The key issue is the absence of legislation and regulation in many maritime states that would allow commercial exploration in their EEZ. Under UNCLOS, marine scientific researchers have the right, subject to the granting of clearance from the maritime state, to ‘explore’ but commercial enterprises are unable to explore in many countries because the legislation and regulation to allow commercial exploration in the EEZ of these countries does not yet exist. This is not a level playing field for exploration and can create conflict if the maritime state believes that marine scientific researchers are fronts for companies. Without a wider range of tenements, it will be more difficult for industry to advance. Exploring several tenements in different geological provinces increases the chances of success, especially given the offshore attribute of aggregate deposits by moving the floating infrastructure. Exploration is the only way to gain knowledge. Exploration does not imply mining will be allowed; it is simply needed to gather information that may have a wide variety of applications.

Another issue is the development of appropriate ISA regulations for exploiting ‘polymetallic sulfides’ in international waters. Many Pacific island nations will likely adopt these regulations or parts thereof, and are waiting to see them. Thus the impact of the proposed ISA regulations for ‘polymetallic sulfides’ will be far greater than for waters beyond national jurisdictions. Consequently, the ISA must have input from stakeholders, especially from commercial enterprises such as mining companies, marine contractors and environmental contractors who would likely carry out the work of preparing an Environmental Impact Assessment. Earlier ISA draft regulations for ‘polymetallic sulfides’ appeared to be largely based on inputs from scientific stakeholders who have a poor understanding of business fiscal reality. The ISA has now solicited input from industry and has incorporated a number of its suggestions.
Figure 8. Seafloor mining system being built for Nautilus Minerals (courtesy of Nautilus Minerals Inc.).

Where do we need to be in the near future?
More maritime nations need to establish legislation and regulations whereby commercial enterprises can have access to areas to explore in the same manner that scientific researchers have access. Note we are talking exploration here and not mining. Mining only comes after exploration and discovery along with related environmental studies so a case for mining with sufficient supporting data can be presented to the host nation.
How do we get there?
The most effective approach may be a coordinated effort by a range of institutes and related bodies who have an interest in marine mining (exploration) of seafloor massive sulfides. These organizations could take the lead through a series of workshops to define a consensus of regulations like many ‘self regulated’ industries who define their regulations. It is not suggested that marine exploration and mining be ‘self regulated’ but at least a consensus of regulations could be offered to the ISA and island nations for their consideration. The International Marine Minerals Society <immsoc.org> produced in 2001 a “Code for Environmental Management of Marine Mining” that is currently undergoing review.

Heavy Mineral Placers (Rona)

Marine metallic heavy minerals are derived by mechanical erosion of terrestrial rocks and transported, sorted, and concentrated by flowing water as placer deposits in beach and offshore sediments of continental margins as a consequence of their higher density (>3.2 g cm$^{-3}$) relative to the bulk of detrital minerals consisting mostly of quartz and feldspar (2.5-2.7 g cm$^{-3}$). The resistance of a mineral (hardness, cleavage, density, solubility) to mechanical action during transport determines the distance it can be transported from its source without material change of state (Kudrass, 2000; Yim, 2000). The median distance of transport from a bedrock source to an offshore placer deposit is 8 km (Emery and Noakes, 1968). As noted, an outstanding feature of the distribution of placer deposits is the multitude of coastal sites known and the few of these sites of past or present mining (Table 2).

Three generic types of placer deposits are recognized (Kudrass, 2000; Rona, 2008): (i) disseminated beach placers usually containing light heavy minerals (density <6 g cm$^{-3}$; e.g., rutile for Ti; ilmenite for Ti; magnetite for Fe and REE; monazite for Ce, La, Y, Th; zircon for Zr; sillimanite and garnet), which are concentrated by waves and longshore currents; (ii) drowned fluviatile placers comprising coarse sand and gravel overlying the bottom of river channels containing heavy metals (e.g., cassiterite for Sn, gold); and (iii) eluvial or lag deposits also containing heavy metals. Placer deposits may lie above, at, and below present sea level related to the history of regional and eustatic sea level change. In the geologic record, fluviatile placers are the presently most important from an economic point of view (Minter and Craw, 1999). Gold, tin and diamond placer deposits are treated separately by other authors.

The known distribution of marine metallic placer deposits is considered by region (Lenoble et al., 1995; Rona and Lenoble, 2004; Rona, 2008). The realm of placer deposits can extend to continental slopes, rises, and abyssal plains where they are presently inaccessible to exploration and exploitation.

North America and Central America: Placer deposits other than gold that occur offshore North America are largely undeveloped. Consolidated layers containing barium have been mined on Castle Island off Alaska. An underground coal mine extends offshore of
Table 2. Operational marine metallic heavy mineral deposits (modified from Lenoble et al., 1995; Rona, 2008).

<table>
<thead>
<tr>
<th>Name</th>
<th>Commodity</th>
<th>Type of Deposit</th>
<th>Water Depth, m</th>
<th>Location Latitude, Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heinze Basin</td>
<td>Tin, Tungsten</td>
<td>Placer</td>
<td>16-30</td>
<td>Myanmar, 14.7° N, 97.8° E</td>
</tr>
<tr>
<td>Richard's Bay</td>
<td>Titanium, Zirconium</td>
<td>Placer</td>
<td>0-30</td>
<td>South Africa, 28.8° S, 32.0° E</td>
</tr>
<tr>
<td>Fort Dauphin</td>
<td>Titanium, Thorium, Rare Earths, Zirconium</td>
<td>Placer</td>
<td>0</td>
<td>Madagascar, 25.0°S, 47.0° E</td>
</tr>
<tr>
<td>Kanniyaknmari Manavalakurichi</td>
<td>Titanium, Zirconium, Thorium</td>
<td>Placer</td>
<td>0</td>
<td>India, 8.2° N, 78.5° E</td>
</tr>
<tr>
<td>Chatrapur</td>
<td>Titanium, Zirconium, Thorium</td>
<td>Placer</td>
<td>0</td>
<td>India, 19.4° N, 85.0° E</td>
</tr>
<tr>
<td>Castle Island</td>
<td>Barium</td>
<td>Consolidated Layered Material</td>
<td>0-5</td>
<td>Alaska, USA, 56.8° N, 133.0 W</td>
</tr>
<tr>
<td>Sulawesi</td>
<td>Chromite</td>
<td>Placer</td>
<td>0</td>
<td>Indonesia, 2.0° S, 121.5° E</td>
</tr>
</tbody>
</table>

Cape Breton Island of Canada. Sand and gravel are recovered at many sites in the coastal zone of Canada and the United States primarily for beach restoration and shore protection. Beds of Jurassic (Tithonian) salt up to kilometers in thickness underlie sediments of the continental margin off eastern North America and the Gulf of Mexico.

The continental margins of Central America are practically unexplored for placer deposits with few exceptions. Porphyry mineralization at sites in volcanic belts along the west coast of Central America generated by subduction of the Cocos plate (Sawkins, 1990) suggests potential for metallic mineral placers (Fig. 2).

**South America:** The continent of South America is noted for Andean Cu-Mo-Au porphyry and massive sulfide deposits related to volcanism generated by eastward subduction of the Nazca plate (e.g., Camus and Dilles, 2002). The middle Eocene to early Oligocene belt of the central Andes contains the largest concentration of Cu resources known in the world (Sillitoe and Perrello, 2005). The apparent absence of metallic placer deposits along the western continental margin seaward of the mineralized zones, except for a few placer gold occurrences offshore Ecuador, Chile, and Tierra del Fuego (R.H.T. Garnett, personal communication), is an artifact of the early stage of exploration. Although desert conditions presently prevail along a large section of western South America, rivers may have transported metallic minerals from the Andean deposits to the
coast under former pluvial climates. Accordingly, the narrow western margin of South America may have significant potential for metallic placer deposits.

**Africa:** Placer deposits offshore the African continent are sparsely developed other than a large placer diamond province encompasses beaches and the adjacent continental shelf from 100 m above to at least 200 m below sea level and extends between 450 km south and 300 km north of the present Orange River that bounds Namibia and South Africa (Garnett, 2000b; 2001). Placer deposits containing titanium, thorium, rare earth elements and zirconium have been mined at a location on the southeast coast of Madagascar (Fig. 1; Table 2). The Corridor Sands (1,765 million tonnes containing 73 million tonnes of ilmenite at an estimated average ilmenite grade of 4.14%; Mining Review Africa, 2003) and the Moma disseminated beach deposits (estimated 60 million tonnes of ilmenite; Planet Ark, 2003) onshore near the coast of Mozambique are both under development and are considered, respectively, the world’s largest and second largest undeveloped resources of titanium dioxide (TiO$_2$).

**Europe:** Numerous marine metallic mineral placer deposits are identified, but none have been developed.

**Asia:** A diverse suite of marine metallic placer deposits exists on the continental margins of Asia. Of these various deposits, placers of the tin mineral cassiterite offshore Southeast Asia are the principal deposits that have undergone sustained mining. The Numerous undeveloped placer deposits of light heavy minerals (ilmenite, rutile, magnetite, zircon, garnet, and monazite) are present on beaches and offshore the Indian subcontinent (Roonwal, 1986; Rajamanickam, 2000) and P. R. China (Institute of Marine Geology, 1988; Tan et al., 1996).

**Oceania:** The titanium minerals rutile and ilmenite have been mined from beach sand of southeast and southwest Australia (Roy, 1999). The other Australian coasts are relatively unexplored for such deposits (CSIRO, 2006). Iron-titanium-rich placer magnetite has been mined from the northwestern coast of New Zealand (North Island) and Indonesia (Java; Kudrass, 2000). Placer chromite has been produced from a site on the east coast of the Indonesian island of Sulawesi.

**Where the industry stands now**

The marine metallic mineral placer deposit industry ranges from continental margins of whole continents like South America that are largely unexplored, to margins of other continents that have been initially explored but remain largely undeveloped. Although numerous sites of placer mineral deposits are known on continental shelves worldwide, current activity pertains primarily to diamond mining off southwestern Africa, tin mining off southeastern Asia, and intermittent gold mining off northwestern North America, which are all surpassed economically by worldwide recovery of marine sand and gravel, in turn dwarfed by offshore oil and gas.
Pressing issues
Grade and tonnage of marine metallic mineral deposits and the environmental impact of their recovery need to be determined so they can be evaluated in context of other sources of metals.

Where do we need to be in the near future?
We need to continue to investigate and develop an information base on marine metallic mineral deposits both as potential resources for the future and for the scientific record that they hold of the regional geologic evolution of continents.

How do we get there?
Stimulate academic interest in the potential of these deposits to yield insights to Earth processes and industrial interest in the economic potential of these deposits. Academia is in a better position to carry out the initial exploration that opens the opportunity for industry, as demonstrated in the case of deep-sea sulfides.

Tin Placers (Batchelor, Surawardi)

Where the industry stands now
Tin placer dredging has represented for many years the largest scale marine metal mining operations in the world. The major offshore tin mining activity remains in Indonesia and is dominated by the majority government-owned, PT Tambang Timah (TIMAH), who is mining submerged and buried fluvial and alluvial fan deposits from around Bangka Island, the east coast of Belitung Island, and off Karimun and Kundur Islands near Singapore. TIMAH has fourteen bucket ladder dredges ranging in bucket capacity from 7 to 30 cubic feet. The maximum dredging depth of TIMAH’s fleet is currently 50 metres below sea level (BSL) using the largest dredges, Kundur I (Figure 9) and Singkep I. The largest dredges can move 3 million cubic meters per annum and currently work zones with ore grades as little as 0.05% Sn (i.e. 1.0 kg Sn/m$^3$) and stripping ratios around 3:1. In 2007, marine dredging contributed 21% of TIMAH’s total production of 58,100 tonnes of tin metal. The market value of TIMAH’s offshore tin production in 2007 was approximately US $160 million.

The tin industry has been boosted by a rapid rise in tin price from a low in 2002 of around US $4,000/tonne to the current US $23,275/tonne (07/07/08, LME), which brings the price in real terms nearer to the high level it was just prior to the major price collapse in the early 1980s.

Offshore alluvial tin resources are also reported in submerged fluvial palaeochannels in Ringarooma Bay in northeast Tasmania (200 million cubic meters), and off King Island and Cape Barren Island in Tasmania, Australia. Deposits are known offshore Perak state and Malacca state in Malaysia but have not been worked due to governmental concerns that dredging may cause unacceptable environmental impacts to nearby beaches of importance to tourism. Rona (2008) reported tin deposits lying offshore Myanmar in the
Heinze Basin, as well as the well-known worked deposits of Thai Muang, Tongkah Harbour and Takua Pa in southern Thailand.

In Indonesia, offshore discoveries of fluviatile tin placers continue to be made, particularly off the west coasts of Bangka and Kundur Islands and the east coast of Belitung Island. Some of these have offshore primary mineralization sources associated with submerged granites.

Pressing issues

*Limited dredging depth below sea level (BSL).* TIMAH is currently considering construction of a state-of-the-art bucket-wheel dredge that is capable of dredging to 70 m BSL. A feasibility study is underway based on the extensive TIMAH placer resources lying between 50m and 70m depth BSL. A study conducted by MTI Holland as to the technology required for dredging at such depths, concluded that the most appropriate would be an integrated dredge system performing both overburden stripping and tin-bearing wash excavation with onboard processing using space-saving IHC circular jigs – currently the practice used by the larger TIMAH marine dredgers. The most appropriate digging technology, which is technically feasible beyond 50 m depth, uses a reinforced articulated ladder, attached midway on the dredge pontoon, comprising two hinged sections, with a bucket wheel cutter suction excavator operating at the cutting face. Computer modeling showed that it is best to use hydraulic transport for lifting the tin ore from the sea floor to the surface and to use barges to transport the tin ore to land-based processing plants. This scenario involves modifications to the design of the existing TIMAH dredge KK Kundur I. Double suction grab dredges and trailing suction hopper dredges had also been considered but were rejected as being less suitable.

![Figure 9. PTTT dredge KK Kundur I, off Kundur Island, Indonesia (Source: D. Batchelor, 17/04/08)](image)

*Illegal mining.* A few hundred small illegal offshore dredges using suction pumps and primitive onboard sluice boxes are currently operating in the waters around Bangka Island (Figure 10). They encroach on Timah’s dredge operations, often operating on fresh tailings being discharged. They represent a growing threat to the security of TIMAH’s...
tailings resources. TIMAH is planning itself to have suction dredges working its own fresh tailings and intends to register contractors to operate 14 suction dredges in tandem behind its own bucket ladder dredges. Traditionally, alluvial tin mine tailings in Malaysia and Indonesia have been reworked numerous times, and the likelihood of profitable return from the TIMAH tailings venture appears good.

**Figure 10. Illegal small dredge boats using suction pumps and onboard sluice boxes, Northwest Bangka Island, Indonesia (Source: D. Batchelor, 01/04/08).**

Where do we need to be in the near future?

*Maximum dredging depth to 90 m BSL.* Alluvial tin resources are known to exist below 80 m depth BSL. Even if TIMAH’s new deep dredge is commissioned, it will only be able to dredge to 70 m depth. Consideration needs to be given in developing conceptual designs for commercial dredgers at even greater depths.

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**No illegal mining.** The potential consequence of large numbers of illegal miners should be considered closely. For example, illegal miners operating in the southern Thai offshore tin concession areas in the late 1970s impacted severely on the legal concessionaires, caused considerable social unrest, and they “picked the eyes” of the higher grade portions of the offshore tin resources. This haphazard and inefficient exploitation resulted in their rapid depletion. By the early 1980s, the overall magnitude of illegal operations was beyond the ability of the local Thai authorities to control. In Indonesia today, local and provincial Indonesian governmental support is essential to ensure TIMAH’s security of tenure over its marine concession areas is improved.

**Environmentally Compliant.** Studies incorporating hydrological modeling of tailings discharges in relation to sensitive zones such as reefs, beaches and mangrove ecosystems,
should be conducted in Malaysia to assess whether the known offshore tin deposits off the Peninsular west coast could be dredged without significant environmental impacts.

How do we get there?
Investment is required to develop technologies to mine the deeper deposits. It will be necessary to know whether these are deep “sea bottom” deposits amenable to working with suction dredges, or more likely, deposits overlain by relatively thick overburdens, which require continued development and application of more robust bucket dredges.

TIMAH plans to commission a new drilling vessel capable of drilling alluvial deposits to 100m depth BSL. It believes, given that eustatic sea levels were deeper than 100 m BSL during much of Late Cenozoic time, that alluvial tin deposits could form at such locations in the former, currently submerged, Sundaland Continent, which comprises the sea areas of modern Malaysia and western Indonesia.

Enforcement of existing laws requires political will and appreciation by the citizens of the benefits of “law and order”. This situation has been successfully demonstrated in the Riau Islands in Indonesia where no illegal marine mining problem exists. In the right direction, the Indonesian Parliament is also considering the passage of new legislation that will provide greater opportunities for small scale miners to participate in mining on their own permit areas.

Developing an appreciation by all participants in the industry in complying with environmental laws is essential. Marine tin dredging companies could consider acquiring a capability for modeling current flow and tailings disposal and take measures to ensure that muddy plumes resulting from dredge tailings disposal will not impact on environmentally sensitive ecosystems.

Marine Diamonds (Goodden)

 Shortly after intrusion of kimberlites into the host rocks of the Karoo in South Africa in the Cretaceous period, massive erosion occurred when torrential rivers carried diamonds from their kimberlitic source rocks down the rivers and into the sea. In the sea they have been subject to a transporting and concentrating dynamic, which has deposited them in trap sites along the West Coast of Africa for hundreds of kilometers.

In the last 60 million years, the sea level along the West Coast has varied in steps from the current sea level to -300m. With time, at each beach level, the sea has re-concentrated the diamonds previously carried down. These old beach levels exist at roughly 10 meter intervals. Each previous sea level now provides a target for marine miners.

As well as the African West Coast, there are other potential coastal areas around the world wherever alluvial systems have the opportunity to transport diamonds from
kimberlite sources to the sea. Known opportunities exist in West Africa, East Africa, Australia, Thailand and Indonesia. There are also prospective areas in Canada and Russia.

Where the industry stands now
Marine diamond mining was started 46 years ago along the coast of Namibia and South Africa by the first pioneer, a Texan, Sammy Collins. Collins brought the potential of marine diamonds to the attention of major mining companies. The known potential resource is huge stretching up to 30 kilometers offshore along the West Coast of Africa from South Africa to Angola.

Four established companies are now producing diamonds on a planned and sustainable basis and another three are currently prospecting. This work provides quality employment for local people offering jobs offshore, onshore, in the shipyards and mills. Revenues from diamonds are helping to sustain the economies and governments of South Africa and Namibia.

Currently, mining is carried out in all water depths up to 150m. To date mining methods rely on dredging techniques using pumps and airlifts from floating vessels. In some cases remote sub sea crawler vehicles track along the seabed carrying suction nozzles and pumps to transfer diamond bearing gravels to the vessels above. Diamonds are recovered before the gravel and sand are returned to the seabed. Vessels range from small dory-type diver support vessels about 10 meters long to large offshore vessels over 150m long.

From a production standpoint, the main player is De Beers Marine Namibia owned by De Beers (70%) and Namdeb (30%) working for Namdeb Offshore. Current annual production from De Beers Marine Namibia vessels offshore Namibia is over a million carats and, in South Africa, De Beers Marine with a new vessel the “Peace in Africa” is producing a further 240,000 carats a year. DeBeers Marine operates four vertical airlift vessels and two seabed crawler vessels for production mining with a further vertical airlift vessel, an AUV support vessel, and sampling vessel for exploration.

Other companies mining diamonds offshore are Samicor, Diamondfields, Trans Hex and AfriCan. Two other companies, Boneparte and Woduna Mining, are working as partners with the others.

As well as offshore, there are diamonds in shallow water which have to date been exploited by divers working from small vessels. Divers excavate manually and transport diamond bearing gravels to small screening plants on their vessels by pumping. The last few years has seen a drop off in diver activity. This may be due to worsening sea states that are being recorded. Alexkor in South Africa have recorded reductions in workable sea states by as much as 75%. Despite this, Namdeb have just announced an investment of N $750 million (ca. US $100 million) for exploration in shallow water and are showing determination to extend their land mining operations into the sea out to a depth of 80 meters. For the first time, Namdeb are commissioning work in the ultra shallow water areas where the surf is breaking continuously. To work in this hostile environment, a new technology based on walking platforms is currently being developed.
Overall marine mining for diamonds is a growing industry and has the benefit of following the offshore oil and gas industry, which has advanced the technology of working in the sea. With sensible management, it is poised to provide the world with a better source of gem diamonds.

Sand Mining on the Continental Shelf of the Atlantic and Gulf Coasts of the USA (Hobbs, Finkl)

Essentially all marine mining along the East and Gulf coasts of the USA is for sand to be used in beach nourishment projects. The present minimal commercial production of sand and aggregate may increase as on-shore sources become exhausted or are lost to competing land use. Studies published in the late 1990s document a history of nearly 900 individual episodes of beach nourishment with a total cost in excess of US $2 billion with several hundred million cubic meters of sand placed along over 645 km (400 mi) of shoreline.

Because mining marine sands disturbs the sea floor, there are environmental concerns. It generally is assumed that dredged areas will be left barren but are likely to be (re)inhabited. The disruption of bottom habitat also affects feeding and spawning areas for fishes and other organisms. Alteration in local currents and wave transformation processes need to be modeled and their consequences assessed.

Where the industry stands now
Aggregate, sand in particular, is the hallmark of nonmetallic mineral mining on the continental shelf. Sand mining is used to sustain developed coasts where beach nourishment is increasingly viewed as a cost-effective and environmentally sound method of mitigating coastal erosion, reducing storm and flooding risk, restoring degraded coastal ecosystems, and enhancing recreation. For beach nourishment to be viable, however, large volumes of high quality sand located relatively close to the intended project beaches are necessary. Marine sand bodies in ~10 m to 40 m water depths are attractive potential sources of sand for beach nourishment.

Beach nourishment has become the shore protection measure of choice (Finkl and Walker, 2002, 2005). Of the $1 \times 10^9$ m$^3$ ($1.3 \times 10^9$ yd$^3$) of sediments removed from America's beaches by engineering works and anthropogenic activity in the past century (Douglas et al., 2003), about $650 \times 10^6$ m$^3$ ($850 \times 10^6$ yd$^3$) have been returned to the beaches by dredging sand from the continental shelf, harbors, and ebb-tidal deltas.

Many beach protection and restoration projects utilize sand mined from areas managed by the Minerals Management Service (MMS), a bureau of the U.S. Department of the Interior (e.g. Finkl et al., 1997). Apart from projects that use sand from upland sources, the remainder of the sand mining for beach nourishment occurs in waters regulated by the individual states. Other federal agencies have interests and official roles in the process. Some material is acquired from dredging of navigation channels, but this probably should not be considered mining as the sand or aggregate is a byproduct, the dredge spoil.
According to Leonard et al. (1990), as of 1988 approximately 90 Atlantic coast beaches and 35 Gulf coast beaches had been replenished. Beach nourishment in the United States has resulted in more than $300 \times 10^6 \text{ m}^3$ ($392 \times 10^6 \text{ yd}^3$) of sand being placed along more than 645 km (400 mi) of shoreline. The Atlantic coast has the greatest length of replenished shoreline (> 435 km (270 mi)), followed by the Gulf coast (> 160 km (100 mi)), and the Pacific coast (> 48 km (30 mi)).

Although the end uses of the mined sand are few, the extent of the effort is not. Trembanis et al. (1998) cite 889 individual episodes of beach nourishment along the Atlantic and Gulf Coasts at a “total adjusted cost” of $2,045,530,000 in 1996 dollars. Valverde et al. (1999) tabulated data on 573 episodes of nourishment between 1923 and 1996 at 154 locations. Hedrick (2000) provided information of the various state programs relating to beach nourishment.

ICES (2007) reported that $1.22 \times 10^6 \text{ m}^3$ ($1.56 \times 10^6 \text{ yd}^3$) of construction aggregate was extracted from the New York Harbor area in 2006. According to Bokuniewicz (1988) more than $32 \times 10^6 \text{ m}^3$ ($42 \times 10^6 \text{ yd}^3$) of sand and gravel were mined from the mid-1960s to the mid 1980s from marine sites in the vicinity of New York. However, in the period following 1978, the majority of the material was obtained from projects to maintain navigation channels.

Although there have been indications of potential deposits of economic heavy minerals within the sediments of the continental shelf (e.g. Grosz and Eskowitz, 1983; Berquist, 1990), there has been little commercial interest. The minerals with apparent potential are zircon, monazite, and the titanium minerals rutile, ilmenite, and leucoxene. See the section by Rona on Heavy Mineral Placers.

Sand is not uniformly distributed across the continental shelf. It occurs in deposits that Hobbs (1997, 2007) has characterized as shoal, filled channel, and stratigraphic facies of gradational deposition. Finkl et al. (2007) and Finkl and Andrews (2007a,b; 2008) presented an expanded classification of shelf sand deposits: 1) deltas, both riverine and tidal, including abandoned deltas, 2) bar systems, 3) paleo-shorelines and barrier islands, 4) ridges, hills, and waves, 5) sheets and veneers, 6) incised paleochannel fills of various types (with and without overburden), 7) inter-reef sand flats, 8) reef gaps, and 9) storm deposits.

As exemplified by studies in Florida, prospecting for offshore deposits of sand usually follows elucidation of a need, although some studies have been proactive. Finkl et al. (2003), among others, described an organizational system for use in prospecting for sand. Prospecting begins with a review of the literature in light of local knowledge and experience. For those lacking local experience, a review of the pertinent nautical charts might suggest geomorphology that would be deserving of further study. High-resolution seismic profiling follows to outline the three dimensional extent of the sand bodies. Finally, vibratory cores are collected to verify the interpretation of the seismic data and to provide samples for geotechnical, especially granulometric, analyses. The actual method
of production often is determined by the availability of different dredge types. The logistics of dredging (e.g., the distance to the site needing the commodity, the water depth over the potential deposits) contribute to the preliminary selection or exclusion of areas to be considered for possible mining.

There are valid concerns about potential environmental consequences of mining sand from the sea floor. Even when the view is limited to the mining site alone, discounting environmental changes accompanying beach nourishment, physical oceanography, geology, habitat characteristics, indwelling and epibenthic fauna, and transitory species of fishes, turtles, and marine mammals, among other topics, must be considered.

The biological aspects of the environmental concerns usually generate the bulk of the effort. The biological arena is much larger and less easy to define than the physical and geological arenas. In addition to the fauna and flora that live on and beneath the sea floor, there are potential impacts on the animals that feed on those organisms or simply transit the area.

In 1996 Sustainable Fisheries Act (Public Law 104-297, 104th Congress), which defines Essential Fish Habitat (EFH) as “those waters necessary to fish for spawning, breeding, feeding, or growth to maturity”, was passed and signed into law. Since then, much of the continental shelf has been classified as EFH. Thus it generally is necessary that entities proposing to modify the sea floor on the shelf demonstrate that the actions would not adversely affect fish populations.

There is a general assumption that all of the fauna dwelling in sediments that are dredged will die (Hobbs, 2002). In order to estimate the potential impacts of sand-mining, it is necessary to determine the types and quantities of organisms that would be lost. As the species, the number of individuals and the biomass vary throughout the year, especially in temperate regions, the assessment cannot be accomplished with a one-time snapshot.

An important aspect of the assumption that the dredged area will be left barren of indwelling organisms and epiflora and epifauna is the pace at which the area will be (re)colonized and the similarity of the new population to the old. Organisms that inhabit the medium and coarse sands that are preferred for beach nourishment generally are relatively mobile and robust so the potential for colonization with like organisms is good, assuming that the geotechnical characteristics of the new substrate are similar to that of the original. In areas where the mining operation strips a relatively thin layer of sand from a large area, the rapidity with which organisms will move into the mined area can be enhanced by leaving “refuge patches” within the disturbed area as proximal sources for organisms that would move to the uninhabited spaces.

Another potential environmental problem is the turbidity and siltation directly associated with the dredging operation. Newell et al. (1999) determined from a study in Great Britain that the deposition of fine grained material is confined to a relatively small area and that “far field” affects, particularly organic enrichment, “may account for the enhanced species diversity and population density of benthic invertebrates” outside the
dredged areas. Hitchcock et al. (2002), also working in the Great Britain, determined that the impact of dredging “is limited to a zone within approximately 300 m down tide of the dredge area” and that there was “no visible evidence of suspended sediments falling to the seabed beyond this zone.” They also concluded that the type of dredging, from an anchored site versus using a mobile trailing suction dredge, might play a role in the impact on the sea floor although the differences might have been due to differences in the intensity of operations as opposed to the type of equipment. Clearly the nature of the plume of suspended sediment associated with active dredging is related to grain size of the material being disturbed. In dredging for beach nourishment where medium and coarse sands with a minimum of fines are the target material, material should settle quickly.

As beach nourishment is a continuing process, not a one-time activity, the same sites are likely to be visited again and again as long as suitable material remains available. This suggests that, with some planning and interagency coordination, the often required post-dredging environmental surveys can serve as the pre-dredging surveys for the next iteration of exploitation. In addition to documenting the “recovery” of a mined site, the post-/intra-dredging surveys can provide information that, if coherently collected and made available, will enable future workers to make better estimations of potential changes to the bottom and of the rates at which the environment adjusts to the alterations.

Summary
Obtaining sand for beach nourishment accounts for a substantial majority of the marine sand and aggregate mining along the East and Gulf Coasts of the United States. Although not a panacea, beach nourishment has continued to gain popularity as a method of protecting the shore and enhancing recreational beaches. It is likely that demand for utilization of marine sources for construction aggregate and fill will increase as easily or economically accessible land-based sources will be exhausted or lost to competing land uses. Once a need for sand in a specific locale has been defined, a logical process of literature review, geophysical surveys, and coring will determine the presence, if any, of reserves.

In most instances, before the deposit can be used, the potential consequences of mining on the physical and biological environment must be evaluated. These assessments include modeling probable changes in wave transformation, ambient currents, and storm surge likely to result from altering the bottom topography. Both primary and secondary impacts to the biological environment need be considered. Primary impacts are related to the biota removed by the dredging activity and the subsequent rehabilitation of the disturbed areas whereas secondary impacts are those pertaining to the highly mobile organisms, fish, tortoises, and marine mammals that use or simply pass through the area.

The regulatory regime depends upon location and end use. Projects intended for public works, primarily beach nourishment and shore protection, tend to be slightly less encumbered than commercial projects. Generally, if the mine site is 3 n mi (5 km) or more off shore, the U.S. federal government is the permitting authority whereas projects closer to shore also fall under the jurisdiction of the state.
Marine Lime and Solutes (Rona)

Flowing water not only mechanically erodes terrestrial rocks producing placer deposits, but chemically erodes the rocks contributing calcium, phosphorous and other elements to marine precipitates and solutes. The marine precipitates include biogenetic and hydrogenetic (authigenetic) limestone and hydrogenetic deposits of phosphorite (see the report by Hein, above) on continental margins. The solutes comprise salts dissolved in seawater and recovered by desiccation.

Lime

The term “lime” is generally used to refer to limestone (calcium carbonate CaCO$_3$) and its derivatives burnt lime (calcium oxide CaO), and slaked or hydrated lime (calcium hydroxide Ca(OH)$_2$). Limestone is generally formed biogenetically by the accumulation and crystallization shells precipitated by marine organisms and may also be precipitated hydrogenetically (authigenetically) directly from seawater. The rock is formed primarily as the mineral calcite (orthorhombic crystal habit) and secondarily as the mineral aragonite (trigonal) with the same chemical formulas but different crystal structures. Limestone is used as an agricultural fertilizer, in the manufacture of glass and cement, and in particulate form as beach fill and road ballast. Most lime is derived from limestone deposited under former marine conditions and presently on land. A relatively small amount of lime is derived from present marine deposits (Table 3).

Table 3. Operational marine lime deposits (Modified from Lenoble et al., 1995; Rona, 2008).

<table>
<thead>
<tr>
<th>Name</th>
<th>Commodity</th>
<th>Type of Deposit</th>
<th>Water Depth, m</th>
<th>Location Latitude, Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hayward San Leandro</td>
<td>Lime (shell fragments)</td>
<td>Beach</td>
<td>0</td>
<td>San Francisco Bay, USA, 37.7° N, 122.1° W</td>
</tr>
<tr>
<td>Laucala Bay</td>
<td>Lime (coral sand)</td>
<td>Beach</td>
<td>0</td>
<td>Fiji, 18.2° S, 178.5° E</td>
</tr>
<tr>
<td>Faxa Bay</td>
<td>Lime (shells)</td>
<td>Beach</td>
<td>35</td>
<td>Iceland,  65.5° N, 22.5° W</td>
</tr>
<tr>
<td>Vembanad</td>
<td>Lime (shells)</td>
<td>Beach</td>
<td>0</td>
<td>India, 9.6° N, 76.3° E</td>
</tr>
<tr>
<td>Bahia Coast</td>
<td>Lime (algae and shells)</td>
<td>Beach</td>
<td>0</td>
<td>Brazil, 13.0° S, 38.5° W</td>
</tr>
<tr>
<td>Torre de Geco</td>
<td>Coral</td>
<td>Unconsolidated</td>
<td>5-300</td>
<td>Naples Bay, Italy 40.8° N, 14.5° E</td>
</tr>
</tbody>
</table>

Examples of marine operational marine lime deposits include aragonite sand that occurs in shallow waters off Andros, Bimini, and Eleuthera in the Bahama Islands as oolite shoals on the Bahama Banks, a shallow subsiding submarine carbonate plateau constructed of layers of limestone attaining a thickness of kilometers off southeastern
Florida. Coral recovery is an industry in the Bay of Naples. Seashells are recovered in Iceland to produce cement and agricultural fertilizer. Brazil produces lime from seashells and marine plants. Seashells are or have been dredged from areas of the United States Gulf Coast (Alabama, Florida, Louisiana, Mississippi and Texas), east coast (Maryland and Virginia), and west coast (California), as well as from marine areas of other coastal nations. Burnt and hydrated lime derived from limestone is used in many industries to neutralize acid waste, as causticisers in the pulp and paper industry, and as a flux in the steel industry.

**Solutés - Salt**
Salt layers up to several kilometers thick lie buried beneath western and eastern South and North Atlantic continental margins and intrude overlying sediments as diapirs (Fig. 1). The salt was deposited at early stages of opening of the North Atlantic in the Jurassic period (205 to 142 million years ago) and of the South Atlantic in the Aptian stage (121 to 112 million years ago) of the Cretaceous period. Kilometers-thick layers of Aptian salt are present in basins underlying the Brazilian margin where salt structures are associated with offshore petroleum (Rona, 1982). At these times, the Atlantic was a sea with circulation restricted by the positions of the surrounding continents, causing evaporation to exceed inflow and precipitation of salt and organic matter (Rona, 1969, 1982). The salt is associated with petroleum production and potential at sites on continental margins of West Africa (e.g., Meyers et al., 1996), eastern South America, eastern North America and the Gulf of Mexico. Layers of Miocene salt up to kilometers in thickness are buried beneath sediments under large areas of the Mediterranean Sea, where the salt was deposited under former conditions of restricted ocean circulation (Hsu, 1983). Undeveloped phosphorite deposits lie adjacent to areas of deep ocean upwelling on the Atlantic continental shelf of northern Spain (Lamboy and Lucas, 1979).

**Other Solutés**
A number of materials are extracted from seawater at some 300 coastal operations in 60 countries, including rock salt (sodium chloride), magnesium metal, magnesium compounds, and bromine. Salt recovery from evaporation of seawater is practiced at many places around the Mediterranean and western France. Fresh water extracted from seawater by desalination processes is the most critical mineral, in light of the global need for an adequate and safe supply of water for consumption, agriculture and industry. Desalination by reverse osmosis and other processes is energy intensive. The oceans are the largest reservoir for water on Earth. Production of freshwater from seawater is expected to exceed that from all other marine minerals in importance and value as need continues to grow and alternative energy sources for the desalination process are developed (Revenga et al., 2000; Newton et al. 2006; UNESCO, 2006; UNESCO Water Portal at http://www.unesco.org/water).

**Pressing Issues**
Development of cost-efficient desalination processes to produce fresh water from seawater is presently a more pressing issue than those issues associated with recovery of heavy metallic mineral placers.
Where do we need to be in the near future?
We need to implement viable cost-efficient methods to recover fresh water from sea water in response to growing global needs.

How do we get there?
Develop an environmentally compatible cost-effective energy to apply to energy-intensive processes of desalination.

Conclusions

Marine mining of tin, diamonds and aggregates (sand and gravel) are mature industries. We are witnessing the dawning of an industry for deep-sea mining of base and precious metal sulfides with manganese nodules soon to follow. Obstacles to overcome, besides technical and financial, are national and UN regulations governing marine exploration and mining activities, and the public perception that such activities might be unacceptably harmful to the environment. The way forward is to hold open discussions among all stakeholders including industry.

References


Rona, P.A., 1969, Possible salt domes in the deep Atlantic off northwest Africa: Nature 224 (no. 5215), 141-143.


