BY JAMES R. HEIN, TRACEY A. CONRAD, AND HUBERT STAUDIGEL

Seamount Mineral Deposits

A Source of Rare Metals for High-Technology Industries

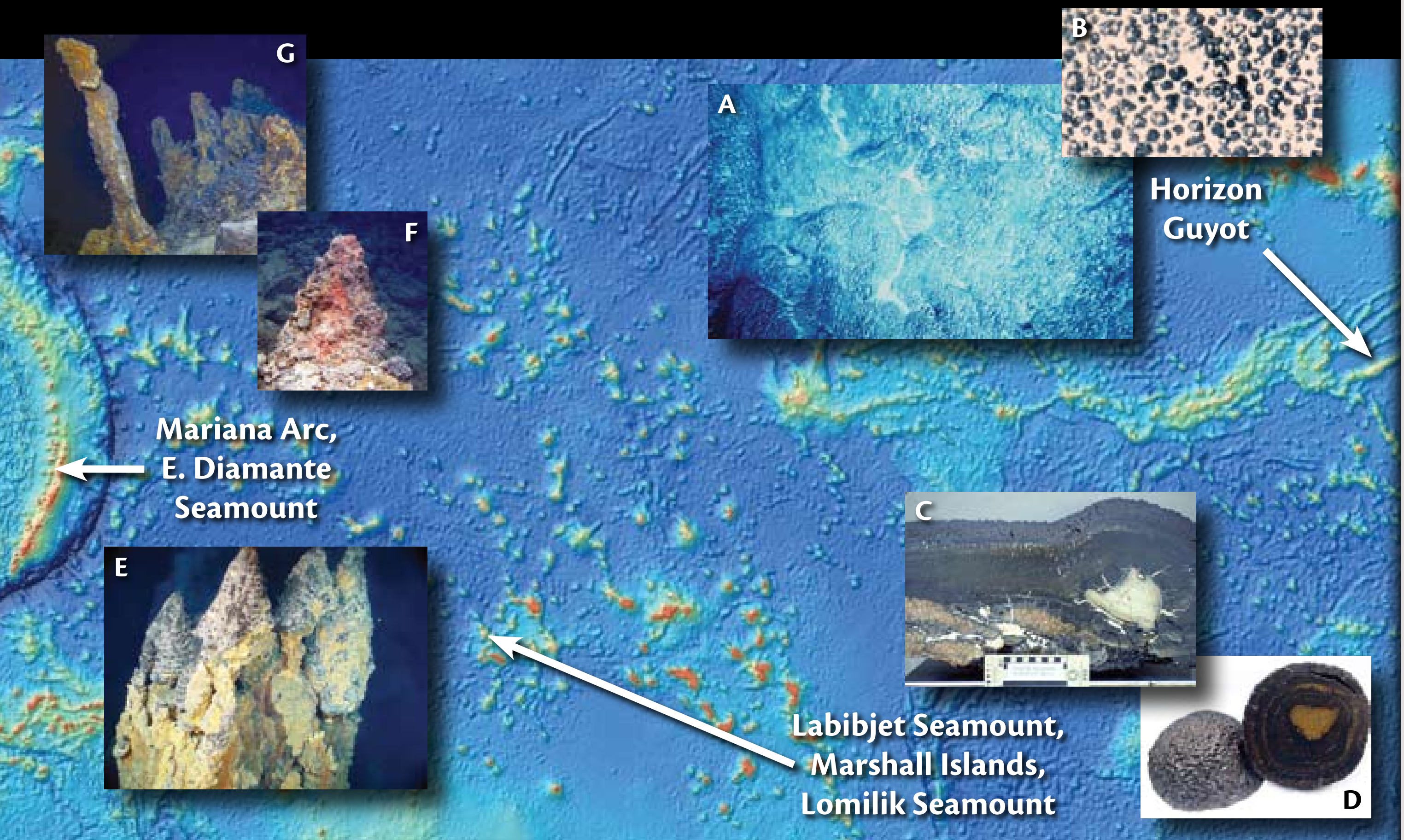

Figure 1. (A,B) Two seabed photos showing Fe-Mn nodules and Fe-Mn crust from Horizon Guyot. Seamount nodules typically have a larger nucleus than abyssal nodules and are really encrusted pebbles and cobbles. (C,D) Slabbed samples from the Marshall Islands. (C) Thick Fe-Mn crust from Labibjet Seamount. (D) Fe-Mn nodule from Lomilik Seamount. E–G are from East Diamante caldera, Mariana Islands. (E) Active gray-smoker zinc-sulfide chimneys from 345-m water depth (Hein et al., 2005). (F) Inactive, oxidized hydrothermal sulfide spire from 375 m (JAMSTEC, 2009 Natsushima cruise NT0908). (G) Group of inactive zinc-sulfide chimneys from 348 m (JAMSTEC, 2009, Natsushima cruise NT0908). Bathymetry from Smith and Sandwell (JAMSTEC, 1997), with Mariana Islands at the western margin and Hawai`i just off the eastern margin; this region is the most prospective for Fe-Mn crusts (Hein et al., 2009).

ABSTRACT. The near exponential growth in Earth's population and the global economy puts increasing constraints on our planet's finite supply of natural metal resources, and, consequently, there is an increasing need for new sources to supply high-tech industries. To date, effectively all of our raw-metal resources are produced at land-based sites. Except for nearshore placer deposits, the marine environment has been largely excluded from metal mining due to technological difficulties, even though it covers more than 70% of the planet. The case can be made that deep-water seabed mining is inevitable in the future, owing to the critical and strategic metal needs for human society. In this paper, we evaluate the case that seamounts offer significant potential for mining.

INTRODUCTION TO METAL-RICH DEPOSITS ON SEAMOUNTS

Seamounts are abundant (Wessel et al., 2010) and have metal resource potential because of enrichment processes that may occur at any stage in their geological history (see Staudigel and Clague, 2010). These processes can be related to their volcanic and hydrothermal activity or their prolonged history of exposure to seawater that allows them the build up metals that occur in trace amounts in seawater. Six types of metal-rich deposits on seamounts have been identified:

1. Hydrogenous ferromanganese crusts (Fe-Mn crusts) form pavements on hard-rock surfaces swept clean of sediment. Such crusts are found on seamounts, ridges, and plateaus throughout the global ocean (e.g., Hein, 2008).
2. Hydrothermal iron oxides have been found precipitated at and near the seabed in areas of diffuse flow and as fallout down-current from hydrothermal plumes. They are commonly found on active hotspot volcanoes (e.g., Puteanus et al., 1991) as well as in Cretaceous seamounts in the Pacific (Hein et al., 1994).
3. Hydrothermal manganese oxides can be found on active hotspot volcanoes and on volcanic-arc seamounts (e.g., Hein et al., 1996, 2008).
4. Hydrothermal sulfide, sulfate, and sulfur deposits have been found on land in dissected seamount sections in geological exposures (Sawkins, 1990), and they also have been found to form on seamounts along most active volcanic arcs (e.g., de Ronde et al., 2005; Embley et al., 2007).
5. Phosphorite deposits form by diagenetic processes on most central Pacific Cretaceous seamounts (e.g., Benninger and Hein, 2000).
6. Hydrogenetic Fe-Mn nodules precipitate on sediment-covered seamount surfaces (Bu et al., 2003).

Of these six types, only Fe-Mn crusts on Pacific Cretaceous guyots and hydrothermal sulfides and sulfates on volcanic-arc seamounts are likely to be mined in the next decades. Although it is well understood that massive sulfide deposits can be formed in volcanic arc seamounts, no commercially viable deposits have yet been identified in the submarine environment. However, a substantial body of research suggests that hydrogenous Fe-Mn crusts may provide significant resources, especially for "high-tech metals" that are increasingly used in solar cells, computer chips, and hydrogen fuel cells.

THE IMPORTANCE OF HIGH-TECH METALS IN HYDROGENOUS Fe-Mn CRUSTS

Hydrogenous Fe-Mn crusts form during the dormant and extinct phases of seamounts when they reside on the seafloor for up to 140 million years until they are subducted (see Staudigel and Clague, 2010, for details). During these volcanically quiescent periods, seamount surfaces come in contact with enormous quantities of ocean water that flows past (e.g., Hein, 2008) and forms Fe-Mn crusts (Figure 1). These so-called hydrogenous Fe-Mn crusts precipitate layer by layer from cold bottom water at the incredibly slow rates of one to seven millimeters per million years (Hein et al., 2000). Their slow growth rates coupled with the extraordinarily high surface area in these Fe-Mn crusts (mean 325 m^2 per gram of crust) and high porosity (mean 60%) promote the adsorption of many rare metals that are not found in such high concentrations in any other geological-oceanographic setting. Examples of high-tech metals highly concentrated in these crusts

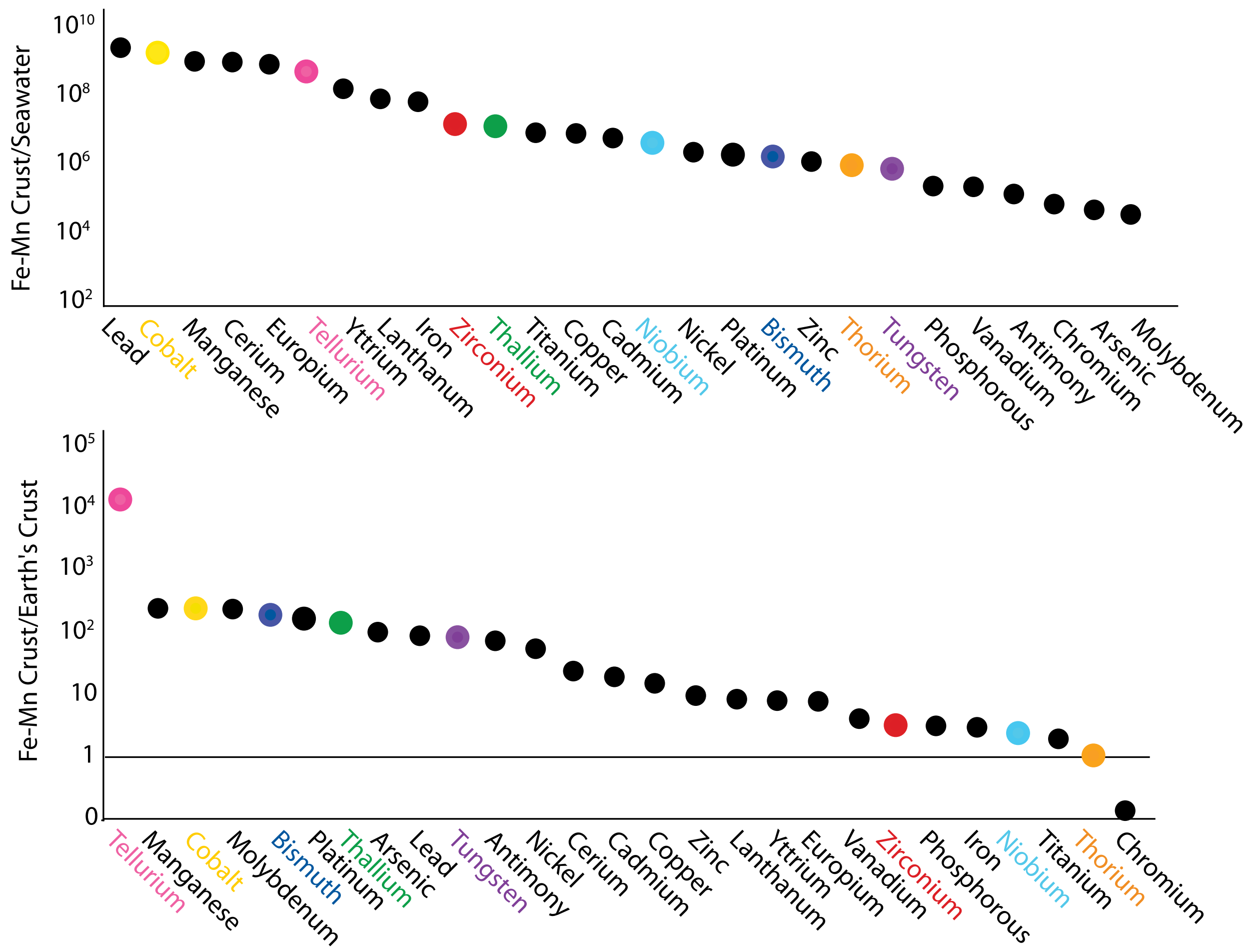

Figure 2. Mean concentrations of selected elements in Fe-Mn crusts from the central Pacific compared with their concentrations in seawater and continental crust. A metal may have higher mean concentration over smaller geographic areas; for example, thorium (Th) is at its Earth's crustal abundance in this data set, but in local areas in other parts of the global ocean, it can be strongly enriched (see Figure 3). Colors keyed to Figure 3.

include tellurium, cobalt, bismuth, zirconium, niobium, tungsten, molybdenum, platinum, titanium, and thorium.

Figures 2 and 3 show metal enrichments in Fe-Mn crusts relative to their average abundance in seawater (Bruland, 1983) and in Earth's continental crust (Govett, 1983). A large number of elements in Fe-Mn crusts are highly enriched relative to seawater (Figure 2a), in particular, lead, cobalt, manganese, tellurium, and several rare earth elements (Ce, Eu, La) and yttrium. In Figure 2, high-tech metals are color coded, showing that among them, Co is enriched most, by a factor of 10^9, and tungsten least, by a factor of 10^6, both witness to the extremely efficient processes of metal sequestration. However, when comparing the resource potential of seabed metal deposits to terrestrial deposits, it is more important to explore their enrichment factors relative to Earth's crust (Figure 2b). It is striking that tellurium is enriched by a factor of 10^4 but that cobalt, bismuth, platinum, thallium, and tungsten are enriched only by factors of about 100. To put this into perspective, mean cobalt concentrations in Fe-Mn crusts, for example, are three- to tenfold higher than those in mined land-based deposits.

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Tellurium has remarkable enrichments compared to both seawater and Earth's crust, and it has a mean global concentration of about 50 ppm in Fe-Mn crusts and a maximum value of 206 ppm (Hein et al., 2003). Figure 3 shows the central Pacific mean values and global maximum values for the high-tech metals. The central Pacific is a large geographic region that shows the greatest enrichment of high-tech metals (Hein et al., 2009), with the notable exception of thorium (see white horizontal lines in the vertical bars).

TELLURIUM DEEP-SEA MINING

The metal enrichments in Fe-Mn crusts discussed above all point to tellurium as the likely main candidate of the high-tech metals that might lead to seabed mining of Mn deposits. Cobalt, predominantly used for high-strength steel (Table 1), is already being considered, and it would certainly be a key economic factor in the evaluation of the feasibility of tellurium extraction from the seabed. Tellurium is currently used primarily in steel, copper, and lead alloys (Table 1), and is produced mainly as a byproduct of copper production; there is no primary source for tellurium in any land-based mines. The US government withholds US tellurium production and consumption numbers to avoid disclosing company proprietary data. However, 90 metric tons were imported and 50 tons exported in 2008. A rough estimate of global production for 2005 is 430–480 tons (Fthenakis, 2009).

This production rate can probably be doubled, but even that increase will not be able to meet the demands of emerging high-tech industries in the near future. Key new demands for tellurium will come from photovoltaics and possibly from computer chip manufacturing. For example, a cadmium-tellurium alloy is considered the best material for production of multiterawatt solar-cell electricity using thin-film photovoltaic technology (e.g., Fthenakis, 2009), and a bismuth-tellurium alloy is being tested as a next-generation computer chip that is more efficient and immensely faster than existing chips (Chen et al., 2009). Finding enough tellurium is the biggest barrier in these developments, and Fe-Mn crusts may offer a solution. The solar-cell industry has expressed interest in mining Fe-Mn crusts, but thus far no companies have applied for leases.

ENGINEERING AND DEVELOPMENT ISSUES

As mining expands into the marine environment, substantial engineering and development issues have to be considered. Such technologies are well underway for the mining of deep-sea sulfide deposits, but the mining of Fe-Mn crusts has to overcome key exploration and extraction problems. The first-order problem relates to reliable resource assessments that effectively determine the tonnage of potential ore per unit of seabed surface area. For this determination, a remotely operated instrument is needed that measures Fe-Mn crusts over a wide area in real time. Gamma radiation-based instrumentation is most promising because gamma radiation shows the greatest contrast between Fe-Mn crusts and substrate rocks even though signal attenuation by seawater remains to be addressed (Hein et al., 2000). A key extraction challenge is to properly separate Fe-Mn crusts from substrate rock on a rough seabed. This obstacle requires a mining vehicle and cutter-head tool that will negotiate rough topography and collect most of the crust without recovering substrate rock.

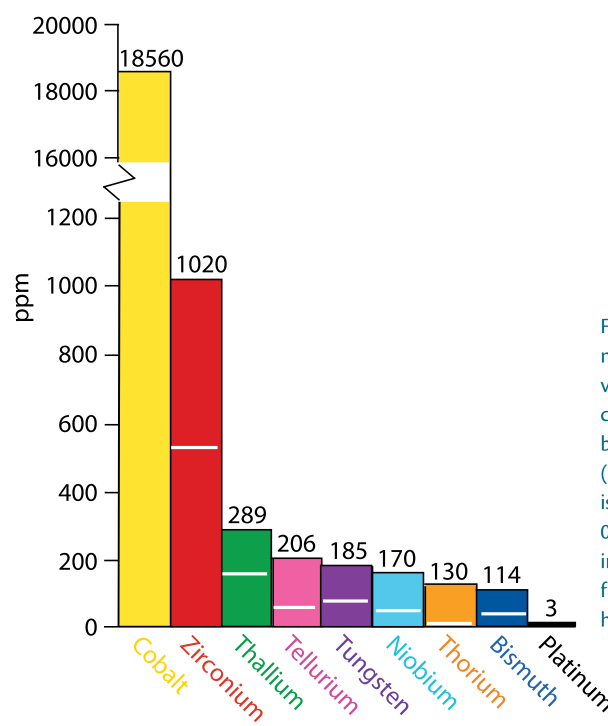

Figure 3. Global trace-metal maxima and central Pacific mean values (white lines) in Fe-Mn crusts based on data presented by Hein et al. (2000) and Hein (2008). The mean value for cobalt is 6500 ppm, and platinum is 0.5 ppm. Metal maxima have increased over time as more data from broader geographic areas have been collected.

Table 1. United States 2008 imports, exports, and uses for selected high-tech metals

	Imported (Tons)	Exported (Tons)	Main Uses	Emerging and Next-Generation Technologies
Tellurium	90[1]	50[1]	Steel, Cu, and Pb alloys, pigment	Photovoltaic solar cells, computer chips, thermal cooling devices
Cobalt	11,000	2,900	Steel superalloys (e.g., jet engines), batteries, chemical applications	Hybrid and electric car batteries, storage of solar energy, magnetic recording media, high-T superalloys, supermagnets, cell phones
Bismuth	3,480	566	Metallurgical additives, fusible alloys, pharmaceuticals, chemicals	Liquid Pb-Bi coolant for nuclear reactors, Bi-metal polymer bullets, high-T superconductors, computer chips
Tungsten	12,700	5,675	Wear-resistant materials, superalloys, electrical products, chemicals	Negative thermal expansion devices, high-temperature superalloys, X-ray photo imaging
Niobium	10,500	600	Steel and superalloys	High-temperature superalloys, new-generation capacitors, superconducting resonators
Platinum	195	27	Catalytic converters, liquid-crystal and flat-panel displays, jewelry, petroleum refining, electronics	Hydrogen fuel cells, chemical sensors, cancer drugs, electronics

Data in metric tons from USGS Minerals Information Team (http://minerals.usgs.gov/minerals/pubs/commodity)
[1]Estimate

Solutions to these problems will require creative engineering.

A mine-site model was developed for Fe-Mn crust mining on seamounts, in particular for cobalt, which is an attractive mining target and for which we know the global supply and demand relatively well (Hein et al., 2009). Such models can be used to estimate the sizes of viable exploration and mine-site areas and are actively being considered by the International Seabed Authority for developing regulations for mining the deep-water seabed in areas beyond national jurisdictions. The Hein et al. (2009) model shows that only 3.7% of the seamount surface above 2500-m water depth in the Pacific Ocean would be sufficient to sustain a 20-year mine site if cobalt were the primary metal of interest. The global market for cobalt would not support more than one or perhaps two such mines at one time. Fe-Mn crusts have traditionally been considered a potential ore for cobalt (and also a source of nickel), yet demand for the more rare metals may drive development of Fe-Mn crust mines in the future. If rare metals become the primary target rather than a byproduct of cobalt mining, then larger mine sites might be supported.

ENVIRONMENTAL IMPACTS

As we predict that seabed mining development at seamounts will happen under any circumstances for economic reasons, it is important to explore the environmental impacts of such activities. Although there will undoubtedly be a negative local impact on benthic communities, potentially a severe effect if not addressed properly, seabed mining impacts will be substantially less than those of deep-sea trawling (see Pitcher et al., 2010) because of the limited area that will be affected. The economics of seabed mining is such that only a very small size area will be mined, and it will be relatively easy and commercially viable to leave biological corridors and refuges to enhance recolonization of newly exposed rock surfaces (see Hein et al., 2009, for a discussion of these issues). In addition, overburden rock does not need to be removed, as is common for land-based mines. Large marine areas within the US Exclusive Economic Zone in the Pacific, which include seamounts, have recently (January 2009) been set aside as Marine National Monuments, where mining will be prohibited. However, the bulk of the seamounts in the Pacific are not protected by such declarations, and they are not subject to nationally regulated mining. Strong international regulations must be carefully considered to guarantee fair use and minimal environmental impact.

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