Articles

Seabed Materials

JAMES M. BROADUS

A large catalog of materials has been proposed as potential seabed resources, and some seabed materials such as hydrocarbons and tin already contribute to the world's economy. Scientific advances have increased our knowledge of other seabed prospects, but realization of their potential will be determined by their relative economic accessibility compared to rival resources on land. Examination of existing stocks of conventional resources, and of the economic process by which new resources are added, suggests that most potential sources of seabed materials will not be exploited in the near future. Strategic behavior in seabed materials development, however, implies that investment in exploration and R&D could proceed on a larger scale and at a more rapid pace than might be expected solely on the basis of apparent commercial potential.

THE OPTIMISTIC RESPONSE TO RECURRING CONCERNS about economically debilitating secular exhaustion of material supplies emphasizes the ability to substitute among materials and to extend available resources through technological innovation and exploitation of previously uneconomic sources (*1, 2*). Although mining of materials directly from the seabed occurred as early as the 16th century and materials of seabed origin have been exploited for millennia, only in recent decades has the inventory of promising unconventional sources been substantially augmented by seabed materials (*3*). Some of these seabed sources, such as hydrocarbons and tin, are already making large contributions to the world's supply of materials. Others, such as the massive polymetallic sulfides at deep-sea hydrothermal vents, probably will not be exploited for many decades or even centuries.

This article summarizes the current position of seabed materials on their long and uncertain way to market. The perspective adopted here is based on the modern economic interpretation of the social process by which natural resources are identified and called into use (*4*). In this view, naturally occurring materials become resources only when they have been brought within reach of practical exploitation, typically through the costly application of human effort and ingenuity (*5*). Materials are valued for the attributes and services they can provide, and the demand for these factors is derived from the demand for the things they are used to make. The "best" (easiest to find, develop, extract, and use) resources tend to be used first, with the use of lower quality, more costly resources postponed until the better ones have been depleted. Increasing reliance on more costly resources tends to raise the price of the extracted materials, prompting substitution, conservation, recycling, and exploration.

The author, an economist, is director of the Marine Policy Center at the Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

New resources are thus created through a combination of (i) increased attractiveness of previously uneconomic sources, (ii) discoveries of previously unknown sources, and (iii) increased accessibility through technological advances.

Because of the unconventional, difficult, and clearly distinct nature of their physical setting, seabed materials provide an attractive case study of this resource-creation process in action. Questions for the seabed materials case are how abundant are better sources and how rapidly are these better sources being depleted. A related question is how quickly are potential seabed sources closing the quality gap through technological gains (including understanding and know-how) and through identification of other advantages. Consideration of the latter question involves some attention to broader issues of public policy, international organization, and long-term industrial strategy.

Seabed Deposits and Material Commodities

Most material prospects from the seabed are minerals, in the broad sense of that term, although living precious coral is harvested from seabed habitats for its $50-million-per-year market. Of the 65 material resources they examined, Goeller and Zucker listed 15 that can be vastly extended with oceanic supplies, but 11 of these are seawater extracts (*1*). Of seabed materials, only four contained in sea-floor nodules are listed by Goeller and Zucker as extending resources (reducing projected depletion by the year 2100 from 120 to 18% for manganese, 152 to 35% for nickel, 150 to 36% for cobalt, and a moderate reduction in copper depletion) [table 2, in (*1*)]. Seabed deposits eventually may provide additional resources for at least 22 other materials (Table 1), although the magnitude and timing of these additions remain open to question and study.

Offshore oil and gas resources are in a class by themselves among seabed materials, making an important contribution to the world's economy. Even at recently lowered prices (*6*), offshore hydrocarbons generate about $80 billion of annual revenues; this sum is comparable to the total world markets for all the other materials with potential seabed sources combined (about $90 billion). Offshore deposits within continental margins account for nearly a third of the world's estimated oil and gas resources, and evidence suggests that additional resources may someday be found on the deep-ocean floor (*7, 8*).

The world's nonfuel seabed mineral prospects (Fig. 1) can be classified into (i) minerals that may be obtained from deposits in relatively shallow coastal waters (less than 200 m), including aggregates such as sand and gravel, shell, calcium carbonate, phosphorites, placer deposits of heavy minerals or gems, barite, and subseabed sulfur deposits; and (ii) deep-sea deposits including the abyssal (3500 to 5500 m) manganese nodules (*3, 9, 10*), the richest deposits of which have been found in the 13-million-km^2 Clarion-Clipperton zone of the Pacific, cobalt-enriched crusts on the flanks of seamounts (*11*), marine polymetallic sulfides (MPS) precipitated around hydrothermal vents at crustal spreading centers (*12*), and perhaps certain deposits of marine phosphorites (*13*).

None of the deep-sea prospects are anywhere near production, but some minerals have been produced from nearshore deposits for many years and now generate revenues of over $600 million per year. Their contribution to the supply of minerals is small, however, compared with the more conventional onshore sources of the same commodities. Only offshore tin, dredged for nearly a century from shallow waters in the "tin belt" of Southeast Asia, supplies more than 1% of its world market. Offshore deposits now represent about half the tin resources for Indonesia and Thailand (*13*) and a growing proportion for Malaysia. Sand, gravel, and shell, amounting to nearly half the value of the world's offshore nonfuel mineral production, are pumped or dredged for construction uses, primarily in Japan and Western Europe. Practical recovery depths are <50 m, and high transport costs limit these construction materials to distribution in local market areas, with great variety in price among markets geographically. Calcium carbonate, whose artisanal mining from nearshore reefs has led to coastal erosion problems in several developing nations, accounts for almost a fifth of the total value of global offshore production. Offshore sulfur production is now limited to a single operation off the coast of Louisiana in the United States, and recovery of waste sulfur from pollution control equipment may replace this source entirely by the year 2000. Altogether, annual revenues produced offshore from the various nearshore sources of nonfuel minerals are <1% of the annual value of offshore oil and gas production.

In view of their relatively trivial economic contribution, nonfuel seabed minerals have generated a surprising amount of interest and activity. Nonfuel seabed minerals were a major stated cause in the refusals of the United States, Great Britain, and West Germany to sign the Law of the Sea (LOS) Treaty, were the central source of contention throughout those negotiations, and appear to have been a rationale in the United States for the creation of a 200-nautical mile Exclusive Economic Zone (EEZ) in 1983. Most of this interest centered on the potential of deep-sea deposits. No sooner, it seems, are the economic limitations of one seabed mineral prospect recognized than another prospect is brought forth to be touted. Partly through this pattern of shifting attention, much has been learned about seabed resource potential in the past two decades. Several overviews have appeared within the last 5 years (*3, 13–16*); slightly older but still useful sources are also available (*8, 17, 18*).

As population and economic growth lead to greater demand for materials, seabed deposits will tend to move closer to expanded exploitation. Changing patterns of materials consumption, environmental restrictions, or higher value alternative uses for resource-bearing lands could work to similar effect. However, the seabed potential resources will have to push their way past both conventional and more speculative rival sources onshore or wait their turn until those sources have been consumed.

Resource Estimates, Scarcity, and Depletion

The best device with which to identify the position of various seabed materials as emergent resources is a long-run supply function for each material. These functions would describe the amounts that could be obtained economically at different levels of incremental or unit cost, given a consistent set of assumptions about prospective changes in technology and costs over time. Ideally, these supply functions would include a description of an estimated probability distribution for each point on the curve. The relative position of each potential source of a material, both onshore and seabed, could then be compared concisely by reference to its "availability" or expected share of output at each cost level. For most materials one would expect a period of exclusive production from successively costlier onshore deposits until a cost level is reached at which the least-cost seabed deposits, as with oil, gas, and tin, join into total production. Beyond that point, the division of total output between onshore and seabed sources would depend on their respective available quantities for each increment of elevated cost. Reliable estimates of such functions have yet to be developed (*19*). Combined geological, engineering, and economic estimates of potential material flows organized in a way similar to this are beginning to emerge for some materials on the seabed list, but none has yet been attempted for any seabed material as such (*20*).

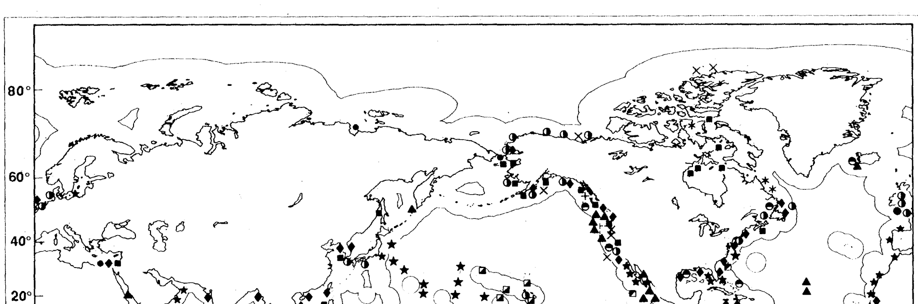

Fig. 1. Approximate locations of major identified nonfuel seabed deposits, showing the extent of existing or potential 200-nautical-mile Exclusive Economic Zones and publicly disclosed license areas for seabed mining activities under domestic laws in the nodule-rich Clarion-Clipperton zone (stippled area).

Table 1. Seabed materials in world perspective. Abbreviation: MT, metric tons.

Seabed deposits	Material commodity	Seabed production (10^3 MT)	World mine production (10^3 MT)	Estimated average price ($ per MT)	Seabed revenues* ($ in millions)	World revenues† ($ in millions)	Seabed share of world revenues‡ (%)	Seabed reported potential resources (10^3 MT)	World onshore resources (10^3 MT)	Seabed comparison to world resources§ (%)	"Resource life" index‖ (years)	Projected onshore depletion by year 2030¶ (%)
Hydrocarbons#	Crude oil	788,834	2,788,913	70	55,218	195,224	28	>61,429,000	181,857,000	34	65	185
	Natural gas	246,670	1,296,405	95	23,434	123,158	19	>60,000,000	228,214,000	26	176	45
Sand and gravel	Sand and gravel	112,300	7,620,480	3	334	22,861	1	665,778,000	Very large	Small	Long	
	Industrial sand		181,440	14		2,540		Large	Very large	Small	Long	
Shell	Calcium carbonate	16,667	1,666,667	6	100	10,000	1	90,000,000	Very large	Small	Long	
Sulfur	Sulfur	381	54,000	105	40	5,670	<1	27,125**	5,000,000	<1	93	120
Barite	Barite		5,652	31		175		2,087**	453,600	<1	80	
Phosphorite	Phosphate rock		159,000	24		3,816		7,939,000	129,500,000	6	814	12
Mineral placers	Tin	28	201	6,614	185	1,329	14	2,500	34,500	7	172	105
	Rutile		356	364		130		13,060	181,440	7	510	
	Ilmenite		4,187	49		205		230,500	907,200	25	217	
	Titanium††		90	12,236		1,101						40
	Zirconium		709	182		129		29,040	54,432	53	77	
	Hafnium		<<1	231,483		17		290	544	53	7,452	
	Yttrium		<1	35,020		14		{3,450**}	172		430	
	Thorium		2	35,850		72			5,168		2,584	
	Chromite		9,616	42		404		30,158**	32,659,200	<1	3,396	1
	Gold		1	10,600,000		10,600		<1**	72	<1	72	443
	Silver		12	206,667		2,480			743		62	295
	Platinum		<<1	9,000,000		1,980		<<1**	99	<<1	446	13
Nodules and crusts	Platinum§§							2–3		2–3		
	Cobalt		32	25,353		811		6,000–24,000	10,886	55–220	340	
	Nickel		745	5,026		3,744		35,000–131,000	129,730	27–101	174	77
	Manganese		23,406	141		3,300		706,000–2,600,000	10,886,400	6–24	465	17
	Copper		7,805	1,475		11,512		29,000–108,000	1,600,000	2–7	205	86
Massive sulfides	Copper‖‖							5,000–216,000		<1–14		
	Zinc		6,560	893		5,858		11,000–518,000	1,800,000	<1–29	274	47
	Lead		3,350	419		1,404			1,400,000		418	46

*Seabed production times estimated average price. †World mine production times estimated average price. ‡Seabed revenues times 100, divided by world revenues. §Seabed reported potential resources times 100, divided by world onshore resources. ‖World onshore resources divided by world mine production. ¶From (*32*), based on low growth case for developing economies. #Hydrocarbons in metric tons of oil equivalent. **Seabed estimate for the United States only; the number in braces (3,450) is for U.S. seabed monazite deposits containing ytrrium and thorium. ††Titanium resources are included in rutile and ilmenite resources. §§See numbers directly above in mineral placers for platinum. ‖‖See numbers directly above in nodules and crusts for copper.

Therefore, we are limited to imperfect stock estimates, which cannot convey the flow of new resources into the line of supply over time. However, it is still useful to compare the reported quantities of seabed materials that have been proposed as potential resources to the stock estimates of existing conventional resources (Table 1). Consistent estimates are available for onshore resources, and "Identified Resources" are reported in nearly every case here (*21*).

In the absence of further exploration and sampling, however, virtually all quantity estimates for the seabed materials must be taken as speculative (*22*). The basis for these estimates differs across commodity and deposit type as well as by investigator and region. A variety of geostatistical approaches to mineral resource estimation have been developed (*23*), and some of the most powerful have been used to estimate remaining resources of oil and gas. Even with a rich body of production experience and extensive offshore search and sampling for these materials, uncertainty about estimates remains high. This was manifest in 1984 when the U.S. Department of the Interior revised downward by nearly 50% a 1981 estimate of undiscovered outer continental shelf oil and gas resources (*24*). This revision was equivalent to a reduction of perhaps hundreds of billions of dollars in the estimated asset value of federal oil and gas holdings (*25*).

Quantity estimates for nonfuel seabed materials are typically based on more limited data and less sophisticated techniques. Geologic information and scientific reasoning are used liberally to condition the estimates because of the typically wide scatter of sample data and the geologic controls on distribution. Resource estimates for sand and gravel tend to be based on a volume obtained by multiplying a defined area by the average thickness of its deposit. In most cases, cutoff depths and distances from shore are not reported. Estimates of manganese nodule resources are based on apparent areal concentration within study areas defined by the average grade of samples (*9*). A large body of global information on nodules is available from years of oceanographic sampling, and more densely spaced data have been obtained by commercial exploration efforts.

"Resource" estimates arrived at in a similar manner have been reported for cobalt crusts in certain areas of the central Pacific (*26*), but these are based largely on limited sampling or hypothetical grade-concentration combinations. For MPS deposits, geological and geochemical inference provide the only basis for estimates of potential quantities in-place because of the limited number of observations (fewer than 50 sites have been sampled to date) and the absence of data on deposit thickness. The Red Sea brines are the most thoroughly investigated, and Mustafa *et al.* (*27*) report resources of 2.4 million metric tons of zinc, 0.6 million metric tons of copper, and 5.2 thousand metric tons each of silver and cobalt. I have reported (*28*) speculative extrapolations of materials in vent deposits on the mid-ocean ridge, on the basis of Mottl's geochemical model of the depositional process of these materials.

With few exceptions the seabed estimates summarized in Table 1 equal surprisingly large proportions of onshore resources. However, the seabed estimates have not been determined on a consistent basis and cannot be read as equivalent to the estimates of identified resources reported for the onshore materials (*29*). All estimates are taken from published reports, are limited to occurrences with concentrations comparable to ores currently worked in onshore deposits, and are presented only as a rough catalog of potential seabed material resources. With further geological exploration (or even broader search of the literature) the reported amounts will expand, although not necessarily their resource potential.

At prevailing rates of consumption, current onshore resources would not be consumed for many years. If we assume broadly that identified onshore resources for each commodity are of higher quality and will be used before any potential seabed sources, this "resource life index" may suggest a waiting time before exploitation of the seabed materials. The life indices for materials in the deep seabed deposits are high, from 174 years for nickel to nearly 500 years for manganese. Barsotti uses mineral availability studies of existing capacity and reserves to reach a similar conclusion that resource limitations alone will not be sufficient to draw nodules into production until many years to come (*30*). Of course, these life indices are naïve in not accounting for increasing materials consumption with population and economic growth (*31*). Neither, however, do they consider the influence of additions to resources over time from previously undiscovered or uneconomic conventional deposits onshore.

Simulation results from Leontief's input-output model of the world economy are shown in Table 1 to help account for projected growth in consumption (*32*). Projected percentage depletion of world resources, based on United Nations low-case assumptions about growth in developing economies, have been reported (*32*). These depletion rates, however, tell little about the rate at which new resources will be added or the cost of doing so. In addition, the input-output technique is not well suited to capture the effects of recycling, conservation, and substitution over time. With the possible exception of phosphates in fertilizer, good economic substitutes exist for all of these materials in most of their uses (*21*), and other substitutes emerge as economic alternatives when a material becomes scarcer and relatively more expensive.

In the absence of a more precise measure of increasing scarcity of natural resources (*19*), the long-term behavior of market price is probably as good a signal as any (*33*). If the relative scarcity of a material is increasing, we would expect its real price to rise. In accordance with Slade (*33*), trends in real price indices for principal seabed deposit types are thus examined here by using both linear and quadratic fits (Fig. 2). From this limited evidence we cannot conclude that price behavior is signaling increased relative scarcity of these materials. In recent years the composite prices of all the deep seabed materials have been well below the fitted trends and have been falling throughout the decade. Further, from the evidence on resource size and projected rates of consumption, depletion effects alone would not prompt a resort to most seabed materials for at least several decades. With sufficient cost advantages, however, and with relative gains in technological progress, more seabed materials might be used before some conventional resources.

Comparative Costs and Pace of Technological Change

In the quiet shallow waters of protected bays or estuaries, dredging costs for sand and gravel, placer minerals, or phosphate may be comparable to those onshore. Indeed, this case is little more than an extension of conventional onshore production. For more exposed, high-energy (weather and waves) offshore environments much greater throughput costs can be expected. Mining costs are controlled by numerous factors and tend to be case-specific, but industry sources suggest as a rule of thumb that seabed dredging for these materials would cost at least three to five times more than inland dredging. When one mining technology is more costly than another for a given level of throughput, it can still be competitive if the ore grade is rich enough to compensate with higher metal yield or if the deposit is large enough to spread fixed costs over greater levels of output. Offshore oil and gas are good examples. Although average drilling and equipping costs tend to be three to four times greater offshore, the large size of the seabed deposits that are in production allows them to compete.

Similarly, other seabed deposits would have to offer compensat-

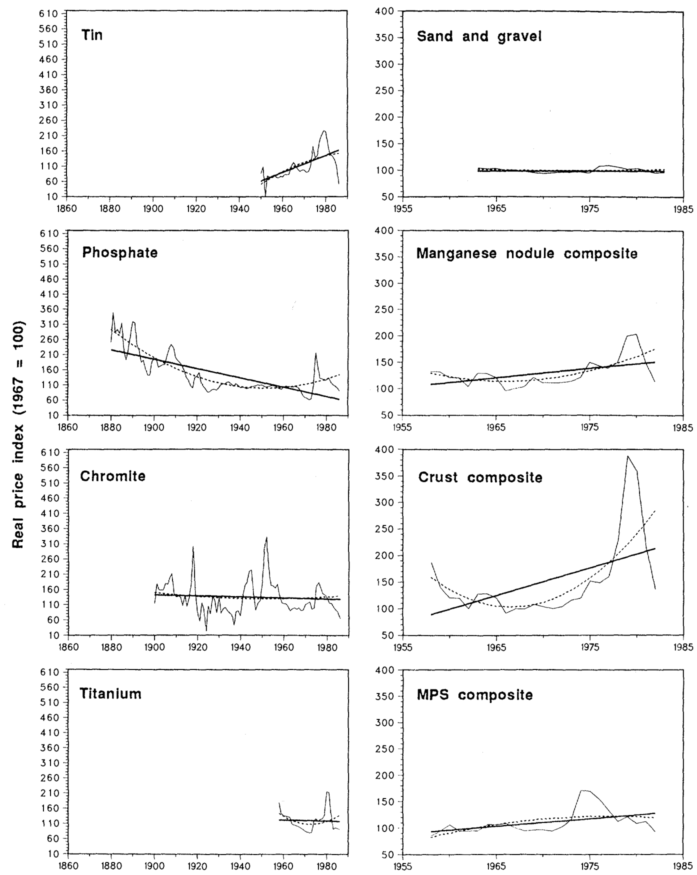

Fig. 2. Behavior of real price indices (1967 = 100) for selected commodities with potential seabed sources, including grade-weighted composite prices of materials contained in typical polymetallic deposits [manganese nodules are 1.28% nickel, 0.24% cobalt, 1.02% copper, and 25.4% manganese, based on (*11*); crust composite is 0.47% nickel, 0.73% cobalt, and 23.06% manganese, from (*11*); MPS is 32.3% zinc and 0.81% copper, based on (*12*)], and showing linear and quadratic fits. Note differences in scale.

ing grade or size premiums to be competitive. Under some local conditions generating locational or deposit-size advantages in delivered cost, offshore sand and gravel overcomes the usual cost differential (*18*). Seabed placer minerals so far reported do not seem to exhibit much larger size or higher grade than their onshore rivals, and Emery and Noakes have shown that strong physical constraints will generally limit the distribution, grade, and accessibility of marine placers relative to those onshore (*34*). McKelvey reported that development of new borehole mining methods may enhance access to subseabed phosphates (*3*), but this technology also favors expansion of deep rival resources onshore.

A number of cost estimates have been attempted for deep seabed nodule mining; these are usually based on detailed engineering scenarios (*35*). The most recent estimates have shown total capital costs that range from \$1.3 billion to \$1.8 billion and annual operating costs from \$224 million to \$440 million. The conclusion of their analysis is that commercial nodule mining is unlikely for "the foreseeable future" (*35*). Several earlier estimates were compared by Dick (*36*) who concluded that seabed nodule mining costs would be roughly comparable to the costs of production from newly developed nickel laterite deposits onshore. Dick did not, however, assign the seabed cost estimates a penalty to account for the uncertainty about operating conditions, engineering problems, and unanticipated costs that might be encountered. Analysis of cost histories in various other pioneer projects reveals that early cost estimates for commercially unproven technologies are not only typically biased low but are often so uncertain that they cannot be relied upon at all (*37*).

Attempts at this stage to characterize potential mining costs for MPS and cobalt crusts might be especially prone to this shortcoming. No technologies are known for breaking, sorting, and lifting these hard-rock deposits at such great depths, and only the most preliminary mining concepts have so far been presented (*38*). No method is known by which the crusts can even be selectively sampled in quantity without obtaining much barren substrate material, and practically nothing is known about the thickness (size) of the MPS deposits. Development of techniques, such as a hard-substrate drill, to overcome these shortcomings is a priority in seabed minerals exploration.

The rate of technical progress in exploration and discovery may be one means by which the seabed deposits are gaining on their conventional onshore rivals. Advances in deep-sea exploration technology, such as multibeam sonar, underwater photographic and electronic imagery transmission, robotics, and deep submergence vehicles, permitted the firsthand verification and continuing refinement of geophysical theories that for several years had predicted the occurrence of the hydrothermal MPS deposits at oceanic crustal spreading centers. Not only were the theoretical results largely exogenous to the search for commercial seabed mineral deposits, but the advances in exploration hardware were too. Technology developed to support offshore oil and gas operations has made a major contribution to the study of seabed nonfuel minerals, and spillover benefits are also provided by investments for military and national security purposes. The work financed by the *Glomar Explorer* submarine recovery effort of the mid-1970s is an obvious example, as more recently is the U.S. Navy sponsorship of the development of the *Argo*/*Jason* system at the Woods Hole Oceanographic Institution.

Marine scientific research will continue to provide an exogenous "input subsidy" for potential seabed material resources. Meanwhile, real discovery costs onshore have been rising, perhaps doubling in the past 30 years (*19*). Reliance on scientific theory to target search for onshore deposits is increasing, and continuing study of marine deposits may also help focus the onshore search. Oceanographic knowledge has already been used successfully in locating onshore occurrences of marine phosphorites, and some scientists expect that observation of deep-sea MPS deposits will eventually help locate commercial analogs on land.

Commercial Activities, Strategic Industrial Behavior, and "Strategic" Materials

Even with substantial exogenous contributions to technological advance, the pace of seabed materials development will be determined mainly by investments directed purposely at seabed materials. The incremental extension of conventional production of sand and gravel, placer minerals, and phosphates to offshore resources can be accomplished in the nearly normal course of business by incumbent producers of those commodities and by dredging contractors. Exploitation of the deep seabed deposits, however, requires the development of entirely new industrial capabilities.

Since the early 1960s, more than \$650 million (constant 1982) has been spent to develop technologies and explore for deep seabed manganese nodules (*39*). The time profile of investments by the international industrial consortia that mounted this effort reveals a sharp decline from the 1978–79 peak spending levels of nearly \$100 million (constant 1982) per year (Fig. 3). These spending estimates

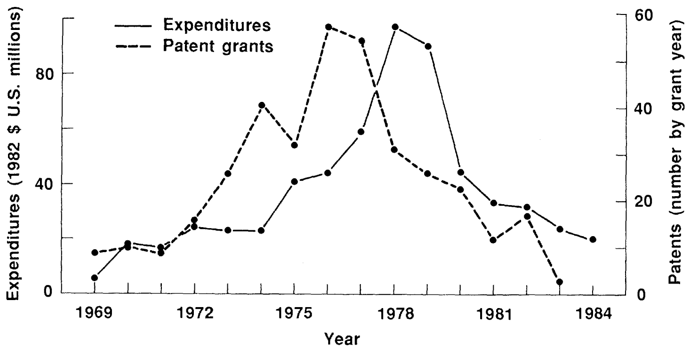

Fig. 3. Estimated seabed mining expenditures and patent activity from 1969 to 1984.

have been reconstructed from a fragmentary published record and spotty clues from industry sources. Nonetheless, they give an accurate general impression of the scale and time profile of industry efforts, as confirmed by reference in the public record to the annual number of patent grants (*40*).

Swayed by growth rates in metals consumption before the embargo of the Organization of Petroleum Exporting Countries and persuaded by the entrepreneurial leadership of seabed mining enthusiasts, parent firms may simply have invested mistakenly in a wasteful, losing venture. Half-billion dollar industrial mistakes are not rare, and a few companies have since withdrawn from their consortia. Certainly, earlier expectations about the scale and pace of development of the nodule resource were greatly overblown. Firms that have already invested in seabed mining R&D may have gained "first-starter" advantages, including learning and skills, patents, and increasingly secure claims to exclusive exploration and mining areas on the seabed (*41*). If the investment in these uncertain assets was a mistake, for most of the firms it was a relatively small one. My estimates of spending behavior indicate that even during the 5-year peak spending period from 1976 through 1980, only one of the 12 companies whose spending was examined devoted more than 7% of its average annual exploration and R&D budget to seabed mining (and most spent less than 5%).

Economists increasingly are interpreting R&D activities, including those aimed at unconventional extractive technologies, as a form of strategic behavior, in the sense that a present course of action is chosen both in anticipation of and to influence the future behavior of rivals for future market rents (*42*). Although their market structure is dynamic, both the history and concentration of the markets for nickel and cobalt suggest that monopoly rents may be earned (*43*). The deep seabed deposits themselves could be extensive enough to provide the basis for a broad-scale, sustained market penetration. A comparable restructuring was witnessed in recent years as large, low-grade nickel laterite deposits were brought into production or, in historical experience, as porphyry ores in the southwestern United States remade the copper industry early in the century (*33*). Potential entrants, or aggressive smaller sellers wishing to expand their market share, might rationally seek to establish a good technical basis for entry by means of seabed mining (*44*). Major incumbent producers may try to preempt such innovative entry by demonstrating with R&D their own commitment to and capabilities in seabed mining. The combined result can be "premature" or excess capacity creation, "sleeping" patents, and idle mine sites. Where the game is played in rounds, a spiral of responses in turn can lead the players to levels of commitment that, but for the observed or expected action of rivals, they would rather avoid.

A high degree of governmental involvement adds further to the strategic dimension of seabed mining investment. Most of the consortia have at least some participation by national governments or state companies, and some are largely or entirely governmental operations. Governments account for more than a third of cumulative investment to date. Their sponsorship appears in most cases to have been motivated more by interest in exploration of alternative long-run sources of materials supply and of advanced technology development than by prospects for commercially generated profits from the production and sale of metals. For the time being at least, while some governmental "catch-up" programs go forward, the commercial consortia, after completing their first-phase planning objectives, have gone largely dormant except for protracted legal maneuvering to secure mine site claims in the Clarion-Clipperton zone.

Although overlaps still exist among the sites sought for exclusive development by various industrial and governmental entities, the international legal situation is becoming increasingly clear. Credible estimates of the number of suitable "first generation" nodule mine sites range from 9 to 40 (*10*). Exploration licenses to define some of these sites further have been issued to four of the international consortia by the United States, West Germany, and the United Kingdom (Fig. 1). Licenses to other sites are being sought under the laws of other governments and through the LOS system. Two international systems have thus emerged to resolve the problem of conflicting claims and to grant security of tenure. One system, of reciprocating arrangements based on the domestic laws of certain seabed mining pioneer states, made a significant advance in 1984 with the signing by the United States, Belgium, France, West Germany, Italy, Japan, the Netherlands, and the United Kingdom of a Provisional Understanding Regarding Deep Seabed Matters (PU). The LOS process embodies another system for resolution of conflicting claims, and strong objections to the PU arrangement have been voiced by the Soviet Union and other LOS participants. Some parties to the PU (Belgium, France, Italy, Japan, and the Netherlands) also are involved in the LOS procedures through which further progress has been made.

In the United States, much of the interest in seabed minerals has shifted from the international area to the EEZ. Reducing dependence on "strategic material" imports is often cited as a rationale for a greater effort to develop seabed materials (*11, 15*). President Reagan referred to "recently discovered deposits" that "could be an important future source of strategic minerals," as he declared the EEZ (*45*). The federal office promoting leasing and development of nonfuel minerals in the EEZ is called the Office of Strategic and International Minerals. Many people disagree about exactly what materials are or are not "strategic" (*46*). A careful attempt to sort out the issue recently narrowed the list to only four "first tier" commodities: chromium, cobalt, manganese, and platinum group metals (*47*). All four are seabed materials, but the Office of Technology Assessment has concluded that a number of options based on substitution, conservation, or production from alternative conventional sources are superior to seabed mining as approaches to reduced dependency on imports.

In recent months major studies of EEZ minerals exploration and policy have been undertaken by the National Academy of Sciences, the Office of Technology Assessment, and the Bureau of Mines. The issue arousing the most attention concerns the best arrangements for governmentally assured access by private parties to explore and develop minerals potential in the EEZ. Questions have been raised about the adequacy of the bonus-bid leasing provisions in the Outer Continental Shelf Lands Act administered by the Department of the Interior. Representatives from some commercial firms, environmental groups, and coastal states have expressed a preference for a licensing system modeled after the provisions of the Deep Seabed Hard Mineral Resources Act, which governs seabed mining activities by U.S. firms beyond the limits of national jurisdiction. Public discussion of this issue will raise questions about the importance of EEZ minerals development, the effects of exclusive licenses or leases on the conduct of scientific research, and fundamental public goals for seabed materials in the EEZ.

Conclusions

An optimistic outlook for long-run materials supply is reinforced by the presence of and increasing knowledge of seabed materials. Knowledge of the resource potential of these materials has grown as a by-product of basic scientific research and with the dedicated efforts of bureaucratic promoters and industrial entrepreneurs. The eventual realization of the resource potential of seabed materials will be determined by their relative economic accessibility compared to rival, onshore resources. For most seabed materials, superior sources are abundant enough to meet projected usage for at least several decades. Furthermore, while increasing consumption of current, conventional resources signals greater promise for seabed materials, it also triggers economic mechanisms that will expand onshore resources (through price effects and discoveries), while moderating consumption (through higher cost, conservation, recycling, and substitution).

More of the nearshore sources of materials will be exploited on an isolated basis in the relatively near future. This exploitation involves scanning and probing for opportunities embodying some combination of deposit grade, size, and locational advantage. Some of this type of exploitation is already taking place, and the important offshore oil and gas resources are being extended to much deeper regions. All the deep-sea marine mineral prospects, including manganese nodules, MPS, and the cobalt crusts, have long-range potential at best. They are attended by great uncertainty and will require considerably more study and investment before they can contribute to materials supplies.

Substantial progress has been made toward bringing metals from deep-sea manganese nodules into the stream of supply, and a higher level of understanding and practical know-how has been achieved for the nodules than for other deep-sea prospects. Strategic behavior in seabed minerals development implies that investment in exploration and R&D could proceed on a larger scale and at a more rapid pace than might be expected solely on the basis of the apparent commercial potential of the deposits. Even so, the commencement of production might not occur as soon as suggested by the pace of preproduction activity, since posturing may be a component of that activity.

The process of improving our understanding of marine minerals can contribute to scientific progress in general, and technological advances achieved in the process can have beneficial applications beyond marine minerals development. Close study of MPS mineralizations, for example, may also foster improved inferences about such basic mysteries as geotectonic processes and the earth's thermal and geochemical dynamics. Further, development of technologies to aid such scientific inquiries will have the spillover effect of generally advancing human capability to function in a hostile environment.

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48. I gratefully acknowledge the assistance with data compilation and interpretation by P. Hoagland and A. R. Solow and helpful comments from K. O. Emery, J. Padan, and R. M. Solow. Prepared with funds from the J. N. Pew, Jr., Charitable Trust and the Department of Commerce, NOAA Office of Sea Grant, grant NA84AA-D-00033. Woods Hole Oceanographic Institution contribution 6352.

Covalent Group IV Atomic Clusters

W. L. Brown, R. R. Freeman, Krishnan Raghavachari, M. Schlüter

Atomic clusters containing from two to several hundred atoms offer the possibility of studying the transition from molecules to crystalline solids. The covalent group IV elements carbon, silicon, and germanium are now being examined with this long-range objective. These elements are particularly interesting because of the very different character of their crystalline solids and because they are intermediate between metals and insulators in the nature of their bonding. Small mass-selected atom cluster ions are formed by pulsed laser techniques and identified by time-of-flight methods. Laser photoexcitation is used to study the relative stability of these clusters and their modes of fragmentation. These modes for C_n^+ clusters, which tend to fragment with a characteristic loss of a neutral C_3, are found to be different from the modes for Si_n^+ and Ge_n^+ clusters, which tend to fragment to "magic" clusters such as Si_4^+, Si_6^+, and Si_{10}^+. These experimental results can be accounted for by recent theoretical calculations of the ground-state structure and stability of small silicon and carbon clusters. Several theoretical approaches give consistent results, showing that small silicon clusters are compact and different from small fragments of the bulk crystal. Calculations show that carbon clusters change from linear structures toward cyclic structures as the cluster size increases, but with significant odd-even differences.

Scientific investigations of the properties of clusters of atoms have expanded rapidly in the last 5 years. The goal in many of these studies is to use clusters with increasing numbers of atoms to understand the transition from molecular behavior to the behavior of bulk condensed matter. The evolution of both the structural arrangement of atoms and the electronic states of the system are of intense interest. In addition, there is a strong technological interest in clusters as unique small systems, for example, as catalysts or for making tailored optical materials.

While there now exists a substantial literature on clusters of rare gas atoms and of metal atoms (*1*), only recently has attention been focused on clusters of the covalent group IV elements: carbon, silicon, and germanium (*2–4*). Clusters of these three elements represent intermediate cases between the alkali metal clusters, whose stability is well described by the free electron model, and the rare gas clusters, whose structure is controlled by simple interatomic pair-potentials. Carbon, silicon, and germanium represent a particularly interesting sequence because of the decreasing importance of π-bonding with increasing atomic number in these covalent systems, while the electronic band structure evolves to a semimetal (graphite) in the case of carbon and to an intrinsic semiconductor for silicon and germanium. Results are also beginning to appear on mixed clusters formed from atoms of group III and V elements (*5*), GaAs and InP, for example, in which cluster properties depend upon both covalent and ionic bonding. However, this article will discuss only

The authors are with AT&T Bell Laboratories, Murray Hill, NJ 07974.