

## Earth resources\*

(minerals/metals/ores/geochemistry/mining)

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Communicated by Preston Cloud, June 14, 1979

**ABSTRACT** Reliable supplies of metals have historically been the keys to industrial and technological development. But many metals are subject to the possible exhaustion of traditional kinds of deposits. A continued supply of such metals, which include tin, tungsten, silver, lead, zinc, and many others, will require their recovery from common rocks, in which they are found in solid solution in common silicate minerals. Recovery from unconventional sources will be so energy intensive that we may eventually have to stop mining such metals. The greatest challenge facing the U.S. Geological Survey in its second century will be the problem of resource limitations.

Clarence King, first Director of the U.S. Geological Survey in 1879, reasoned that industrial development requires reliable supplies of basic mineral resources. His reasoning led him to conclude that the USGS was an investment for the future of the country and should help resource development by emphasizing those areas of geology that most directly aided the finding of mineral wealth. Later Directors encouraged other interests to flourish, but the discovery, assessment, and exploitation of the country's resources continues to be one of the USGS's central interests and one of the keys to its remarkable success. Its century-long studies of the country's mineral wealth have been spectacular. No other group of scientists has so influenced our knowledge and ideas about how, why, and where mineral deposits form. Few countries have enjoyed such excellent geological maps to aid prospecting and the development of mineral wealth.

One of King's first activities was the collection of mineral production data for the entire country. His efforts led, eventually, to annual reportings of mineral statistics by the U.S. Bureau of Mines, and in those reports the growth, development, and changing fortunes of the country's mineral resources can be read. The story has been a spectacular one, and our material well-being is proof of the bounty won from the ground. But the record tells us too that production of some metals is now declining and production of others grows less rapidly than our needs. As a result, we are becoming more and more an importing country, less and less a producer and exporter of minerals. The pattern is familiar because it is one seen in the history of essentially all industrial countries—as their mining districts become depleted, foreign sources have to fill their needs (Figs. 1 and 2). Remarking on the pattern, Lovering (3), a later-day member of the USGS, observed that "Rich mineral deposits are a nation's most valuable but ephemeral material possession—its quick assets."

If industrial development means depletion of resources and eventual dependence on others, what happens when every country has cashed its quick assets? Equal volumes of Earth's crust, when assessed in continent-sized units, contain approximately equal amounts of mineral wealth. The notion that some

continents start out resource-rich and others resource-poor proves false on close examination. Richness and poorness are a matter of history. The resource-poor of today were the resource-rich of yesterday (Fig. 3). As populations increase and living standards rise, the worldwide demand for mineral products grows ever larger. To support the growth rate we cash our quick assets at ever faster rates. Not surprisingly, the ranks of resource-poor countries grow larger while the ranks of the resource-rich become smaller and smaller.

The world is finite in size, so the worldwide pattern must also come to an end. Although we may debate when the end will be reached, it is already apparent that, for many resources, an end to rich, quick assets will arrive during the century ahead—not only for the United States but for the world as a whole. The resource challenge beyond that point remains to be explored. It is unfamiliar territory, but it will, I believe, present the USGS with its greatest challenge of the 21st century.

### Nature of the challenge ahead

People tend to approach questions of Earth's resources in two ways. Aware that material consumption has grown exponentially since the Industrial Revolution, many seek answers in the history of technology and of economics over the past 2 centuries. Those centuries have been times of technological triumph, so the answers tend to be optimistic and the conclusion that mineral resources are so many and so varied that a flexible economy and a responsive technology can offset any material limitation. But technology has never had to face a real, global shortage of any material. For this reason, most geologists believe that the history of technology offers few guides, so they use a different line of reasoning and seek answers in the way materials occur on earth. Mineralogical and geochemical studies lead them to draw the less optimistic conclusion that resource challenges will be so abrupt and might be so costly that technology may not be able to evolve smoothly and produce antidotes for the shortages that will arise. Nature, not man, will dictate our use of resources.

The future will eventually reconcile the opposing viewpoints and that is the challenge ahead, but in the meantime the debate is thrusting all geologists, not only those of the USGS, into unfamiliar areas of societal involvement. Geology has traditionally been a less predictive science than most, but that tradition is passing. We are being asked, and will continue to be asked, to predict the magnitude of resources still to be found, to identify new and unfamiliar kinds of materials that might be exploited, how we might find and use new materials, how exploitation will influence the environment, and, most importantly, to provide our answers in language that is intelligible to all.

### Uses of mineral resources

The sum of materials won from the Earth numbers in the hundreds, but we can group resources into five broad use groups: (i) food and clothing derived from plants; (ii) stone, cement, abrasives, and similar materials with special physical

\* Presented at the symposium "Earth Science and Earth Resources—A Centenary Salute to the U.S. Geological Survey," 23 April 1979, at the Annual Meeting of the National Academy of Sciences of the United States of America.

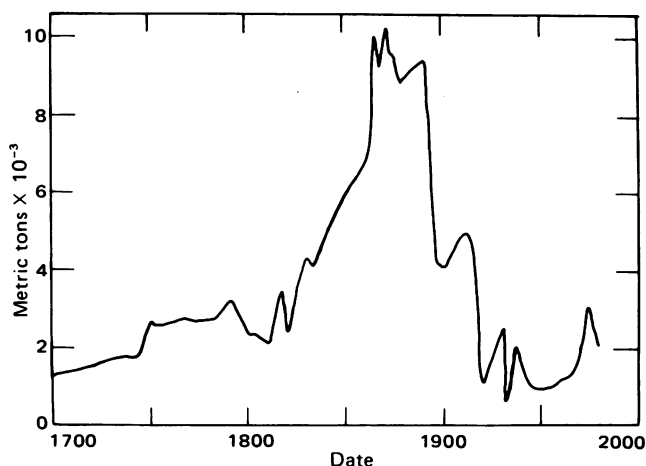


FIG. 1. Production of tin from Cornwall demonstrates the life cycle of a mineral district. The rise and fall of production can be seen in the history of every mine, mining district, and country. (Data from ref. 1 and the annual *Minerals Yearbook of the U. S. Bureau of Mines*.)

properties suitable for activities such as building, grinding, and polishing; (iii) materials useful for their chemical properties, especially fertilizers to increase plant yields; (iv) metals and special minerals for machines; and (v) energy to run the machines.

Use rates of the five groups are related. Food production, for example, is proportional not only to fertilizer applied but also to the amount of machinery and energy used for intensive cultivation (5). If we can pinpoint the weakest link in the resource chain, we have taken a first step toward assessing the challenges ahead. Food production is presumably limited by the growing space available. Fertilizers are, of course, limited in magnitude and availability but, fortunately, supplies of potash, phosphate, nitrogen, and sulfur are very large so they do not loom as a near-term threat. A great deal of interchange is possible among stone, sand, gravel, cement, plaster, abrasives, and other materials used for their special physical properties, and, in any case, supplies are truly enormous. Oil and gas are clearly limited in abundance, but of energy itself—from the Sun, from coal, from oil-shales, from nuclear fission, and possibly from nuclear fusion—there is no real shortage, provided

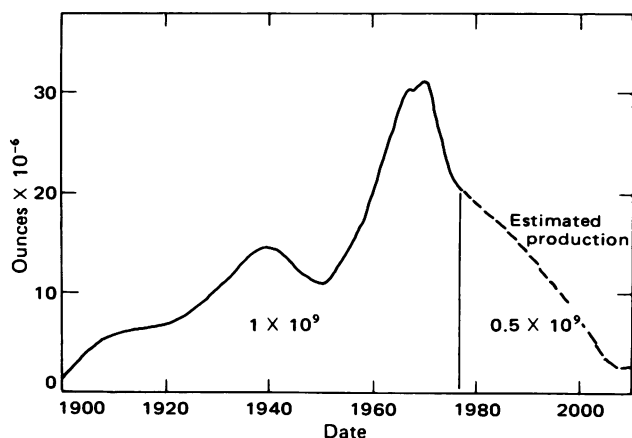


FIG. 2. Past and estimated future production of gold from one of the world's largest and richest mineral districts, the Witwatersrand Basin, Republic of South Africa. Beyond the year 2010, a small production may continue, maintained by continually rising prices, but the major production phase will be over by 2000 (2).

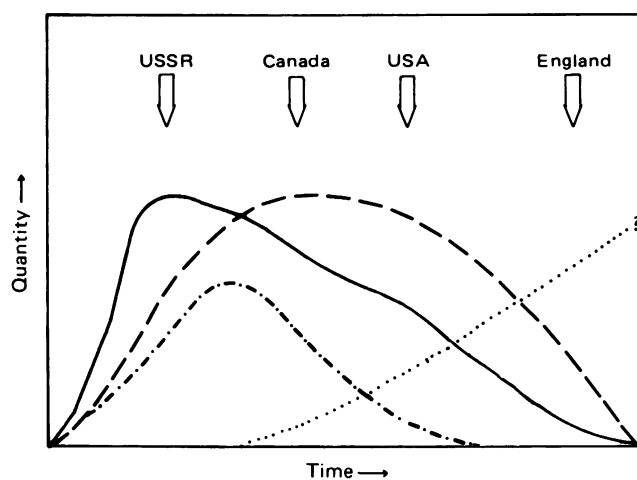


FIG. 3. The stages in mining (—), new metal production (---), metal exports (-·-·-), and metal imports (····) in an industrial country as deduced by Hewett (1) and discussed by Lovering (4). The estimated positions of the four countries is the author's opinion and is based on their nonferrous metal productions. As time passes, a country moves from left to right.

we are smart enough to learn how to use it. However we do learn to use the energy, we will need machines; many are sure to be very complex and specialized. And machines are made from metals. The more complex the machines, the greater the variety of metals needed to make them work efficiently. If we are to be faced with limitations in supplies of metals, then, our usage of all resources will be influenced because metals are the enzymes of industry. Global limitations have not yet occurred, but I suggest that during the next century they will.

**The way metals are distributed in the Earth**

The average content of any chemical element in Earth's crust, expressed as percentage by weight, is called the "crustal abundance" of that element. Geologists draw a distinction between the crust beneath the ocean and that beneath the continent, because small differences are present in their bulk compositions. For reasons I will present later, I will concentrate this discussion on the continental crust.

The chemical elements found on Earth, of which there are 88, combine to form *minerals*, which are solid, crystalline chemical elements or chemical compounds formed by the inorganic processes of nature; each mineral has a characteristic crystal structure and a specific chemical composition. Examples are quartz, diamond, and mica. *Rocks* are natural aggregations of one or more minerals; granite, limestone, and rock salt are examples.

Although 88 chemical elements could, in theory, combine to produce an astronomically large number of stable compounds, the total number of minerals identified to date is only 2400. The reason for the seeming disparity lies in the crustal abundances of elements, nine of which (Table 1) make up 99.0% by weight of the entire crust, both continental and oceanic. The remaining 79 elements total only 1.0% of the crust and are therefore present in essentially trace amounts.

The most abundant element is oxygen which readily serves as an anion and forms complex anions with silicon. Earth's crust is, therefore, 99% by weight a mass of oxide and silicate minerals in which aluminum, iron, calcium, magnesium, sodium, and potassium are the cations combined with oxygen and silicon. There are, to be sure, other kinds of minerals, but quantitatively they are minor constituents of the crust. The most important of the minor mineral families, based on the next two most abundant anions, carbon (0.02%) and sulfur (0.03%), are the

Table 1. The most abundant elements in the continental crust

Element	% (wt/wt)
Oxygen	45.2
Silicon	27.2
Aluminum	8.0
Iron	5.8
Calcium	5.1
Magnesium	2.8
Sodium	2.3
Potassium	1.7
Titanium	0.9
Total	99.0

carbonates, sulfides, and sulfates. The most common carbonate, sulfide, and sulfate minerals, however, are all formed by combinations with the six most common cations. The general chemistry of the crust is therefore largely the chemistry of silicate minerals with a leavening of a few oxide minerals plus the carbonates of calcium, magnesium, and iron, the sulfides of iron, and the sulfates of calcium. When the chemistry of other minerals is considered, as it must be when mineral resources are discussed, we are considering the chemistry of quantitatively minor and necessarily limited materials.

The late V. M. Goldschmidt, who is sometimes called the father of geochemistry, elucidated a number of rules governing mineral compositions. One of the rules provides an explanation for the restricted number of minerals. When two cations have similar charges, one can substitute for the other in a mineral without producing a change in the geometry of the crystal structure and therefore without producing a new mineral. The extent of substitution is partly a function of temperature and pressure but is also a function of the closeness in size of the substituting cations. If the radii of the cations differ by less than about 15%, complete substitution is usually possible. Thus,  $\text{Fe}^{+2}$  with a radius of 0.76 Å and  $\text{Mg}^{+2}$  with a radius of 0.65 Å can substitute freely for each other in many different minerals. Examples are olivine  $[(\text{Mg},\text{Fe})_2\text{SiO}_4]$  and pyroxene  $[(\text{Mg},\text{Fe})\text{SiO}_3]$ . When the differences in ionic radii are greater than 15%, some substitution is still possible, but there are definite limits beyond which the addition of much larger or much smaller cations will cause mineral structures to change to accommodate the new cations or, more commonly, to form a separate mineral in which the substituting element becomes the major charge-balancing cation.

Because most chemical elements occur in such tiny amounts in the crust they can readily be accommodated by substitutions in common oxide and silicate minerals without the saturation point being reached and therefore without separate minerals being formed. The only way minerals of the scarce elements can form is for some geological process to cause a local enrichment of one of the scarce elements so that substitution limits are exceeded.

The major rock-forming processes—which are (i) weathering and sedimentation to form sedimentary rocks, (ii) melting and fractional crystallization to form igneous rocks, and (iii) new mineral growth by heat and pressure to form metamorphic rocks—rarely cause sufficiently great enrichments of the scarce elements, so separate minerals of scarce elements rarely (and for most elements never) form in common rocks. Consider lead, for example. The crustal abundance is 0.0010%. Rock-forming processes produce enrichments in the lead contents of some rocks to as much as 0.02%, or 20 times the crustal abundance, but the minerals present are still not saturated in lead, so no lead mineral forms. Instead, the lead (radius, 1.20 Å) substitutes for potassium (radius, 1.33 Å) in common minerals such as mica and feldspar.

No hard or definite rules can be drawn as to the concentration that any given element must reach before a separate mineral can form. Obviously, the level depends in part on the presence or absence of compatible ions for which substitution is possible, in part on the minerals present, and in part on the temperature, pressure, and chemical state of the local environment. A rough rule of thumb is that most elements will start to form separate minerals when a concentration of about 0.1% is reached. There are many exceptions, however. Gold, uranium, and molybdenum are three elements that have ionic radii or ionic charges such that possible substitutions are limited, so they often form minerals at concentrations much lower than 0.1%. Gallium, however, is twice as abundant in the crust as lead, but it is so close in size to aluminum ( $\text{Ga}^{+3} = 0.62$  Å;  $\text{Al}^{+3} = 0.57$  Å) that the substitution limit is much greater than 0.1% and is practically never exceeded; gallium minerals are therefore among the rarest of all minerals.

Metals can be roughly divided into three groups on the basis of the way they are found in minerals.

**Group 1.** This consists of five metals—silicon, iron, aluminum, titanium, and magnesium—that have crustal abundances in excess of 0.1% and that form common minerals in a great many kinds of rocks.

**Group 2.** These elements have crustal abundances between 0.01 and 0.1%. They lie in an abundance range such that many rock-forming processes produce the concentration necessary for separate minerals to form, and this group is therefore also present as minerals (although usually accessory minerals) in many common rocks. The group includes barium, manganese, phosphorus, vanadium, and zirconium, but only two, manganese and vanadium, are metals of sufficiently great industrial importance to warrant attention.

**Group 3.** This group contains all of those metals with crustal abundance  $<0.01\%$ . They rarely form separate minerals and, when formed, those minerals are not found in any of the common rocks. They are found, instead, in mineral deposits formed by special and unusual chemical circumstances. The mass of mineral deposits is minute compared to the mass of common rocks, so it is in this last group of metals, which I refer to as being geochemically scarce, that both absolute and local shortages must first appear.

### Influence of geochemistry on mining and metallurgy

Production of geochemically scarce metals involves two distinct and separate operations: the first is the mining and separation of the desired ore mineral into a pure concentrate; the second is a chemical processing (usually called smelting) of the concentrate to free and purify the metal. We can measure the two operations in terms of the energy involved. As an example, consider the mining of an average copper ore as presented by Kellogg (6).

A typical copper ore mined from an open pit consists of a mass of valueless silicate minerals mixed with a small quantity of a copper sulfide mineral. In order to mine the ore, approximately 2.5 tons of waste rock must be removed for every ton of ore recovered. The energy used in mining (including the energy equivalent of materials used in the process) is 40,000 BTU/ton, with a conversion factor of 10,500 BTU/kWh used for those parts of the process using electricity. For a typical ore deposit containing 0.7% Cu, this amounts to 10,000 BTU/lb of copper ( $22 \times 10^6$  J/kg) in the mined ore. The mined ore must then be crushed and the copper sulfide mineral separated from the valueless silicate minerals by some process based on a difference in physical properties such as flotation or density. Typically, a concentrate of chalcopyrite ( $\text{CuFeS}_2$ ) will contain as much as 30% Cu and the concentration process will recover

Table 2. Energy used to mine and process a copper ore in which copper is present as the mineral chalcopyrite ( $\text{CuFeS}_2$ )\*

Grade, % Cu	Energy used, BTU/lb of copper		
	0.7	0.1	0.01
Mining plus concentration	33,040	231,280	2,312,800
Smelting and refining	20,000	20,000	20,000
Total	53,040	251,280	2,332,800
Equivalent thermal energy in bituminous coal (lb of coal)	4.1	19.3	180

\* An overburden stripping of 2.5 tons of waste rock/ton of ore is assumed and concentration is 80% efficient.

80–90% of the copper in the ore. Assuming an 80% recovery, Kellogg calculated the energy needed for mining plus concentration to be 33,040 BTU/lb of copper ( $76.4 \times 10^6$  J/kg). Smelting and refining of a chalcopyrite concentrate consume an additional 20,000 BTU/lb of copper, giving a total energy consumption of 53,040 BTU/lb of pure copper. If ores with lower copper contents are used, use of energy for mining and concentration increases in proportion to the decreasing content of copper in the ore, but the energy needed for smelting the concentrate remains the same. Table 2 presents the energy consumption for sulfide ores of three different grades, and Fig. 4 presents the same information graphically.

Consider now the circumstance when metals are to be freed from entrapment in silicate minerals. The one case in which this already has been done, for aluminum, can be used as a guide. Aluminum is traditionally prepared by mining and concentrating bauxite (an impure aluminum hydroxide), processing the bauxite chemically to produce pure  $\text{Al}_2\text{O}_3$ , and electrolyzing a solution of  $\text{Al}_2\text{O}_3$  in a suitable flux. Because bauxites are limited in extent, considerable research effort has been devoted to the preparation of an  $\text{Al}_2\text{O}_3$  concentrate from silicate minerals in common rocks, minerals such as clays [ideally,  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ] and anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ). Data by which we can compare the two kinds of ore are presented by Bravard *et al.* (7). They calculated the case for a clay-ore containing 15.9%

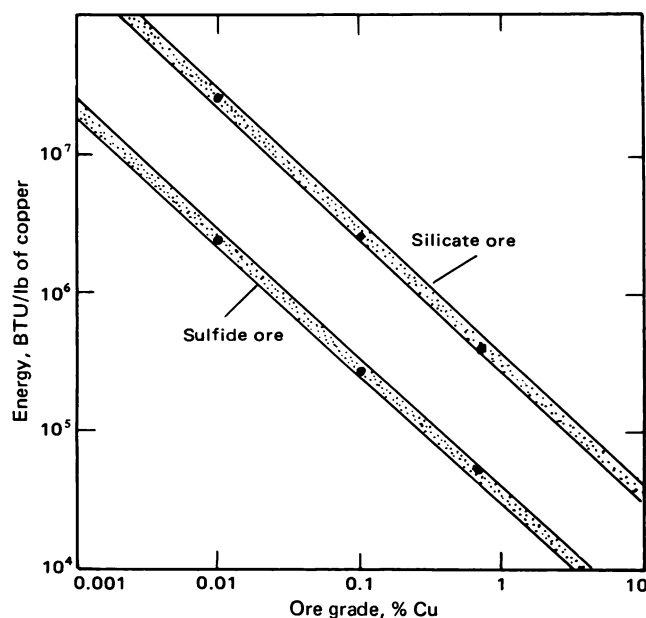


FIG. 4. Energy needed for mining, concentrating, and producing copper from sulfide and silicate ores. ●, Data on which the diagram is based (see Tables 2 and 3).

Al. The important part of their calculations for our purposes is that 43,170 BTU/lb of Al are required to produce the  $\text{Al}_2\text{O}_3$  from the clay.

The data for Al recovered from a clay can be used to build a hypothetical case for recovering copper from a common silicate mineral. Much of the copper in common rocks is present in a mica called biotite. If we assume that the biotite makes up one-third of the rock by weight, a rock containing 0.1% Cu will yield a biotite concentrate containing 0.3% Cu. Biotite and clay are similar mineralogically, so to a close approximation we can model the production of a copper salt from biotite on the production of  $\text{Al}_2\text{O}_3$  from clay.

We make the optimistic assumptions that no overburden need be stripped away and concentration of biotite from the rock is 100% efficient. Energy demands of mining and concentration are approximately the same for a silicate ore as they are for a sulfide ore—that is, 40,000 BTU/ton of rock for mining and 230,000 BTU/ton of rock for concentration or a combined 135,000 BTU/lb of Cu for a 0.1% ore. Assuming it takes no more energy to produce a copper salt from biotite than it does to produce an aluminum salt from clay, a biotite containing 15.9% Cu would require 43,170 BTU/lb of Cu. By projection, a biotite containing 0.3% Cu requires 2,288,010 BTU/lb. The copper salt produced can then be reduced to metallic copper for an additional 20,000 BTU/lb, for a total of 2,433,010 BTU/lb of copper—approximately 10 times as much energy as a sulfide ore at the same grade (Table 3).

The curves for copper produced from sulfide and from silicate ores of different grades are compared in Fig. 4. The silicate curve is, if anything, an optimistic one because it is based on a long extrapolation and an assumption that everything works as efficiently as possible. Switching from sulfide to silicate ores at some future date does not seem to be difficult at first glance. The magnitude of the problem only becomes apparent when another geochemical fact is added. The approximate lower limit of copper in sulfide ores is about 0.1% (8). The upper limit for copper in large bodies of common rock is still unknown, but it is certainly below 0.1%. Thus, transfer from a sulfide curve to a silicate curve will probably be somewhat like the situation shown in Fig. 5.

It is quite clear from our present knowledge of geochemistry that every metal with a crustal abundance below 0.01% will reach the same kind of mineralogical barrier as that shown for copper in Fig. 5. It is possible that the size of the mineralogical barrier may even be a function of the crustal abundance of an element—being larger for the scarcest element. Despite such uncertainties it is clear that a new era of extractive metallurgy and energy use lies ahead, and hand-in-hand with the new metallurgy will come a new era of resource geology.

Are there any stepping stones to ease the passage between the two curves in Fig. 5? Geologists cannot trace an exact path

Table 3. Energy used to mine and process a copper ore in which all copper is present in biotite\*

Grade, % Cu	Energy used, BTU/lb of copper		
	0.7	0.1	0.01
Mining plus concentration	19,300	135,000	1,350,000
Preparation of Cu salt	326,858	2,288,010	22,880,100
Smelting	20,000	20,000	20,000
Total	366,158	2,443,010	24,250,100
Equivalent thermal energy in bituminous coal (lb of coal)	28	188	1866

\* No overburden need be stripped, and concentration and smelting are assumed to have 100% recovery.

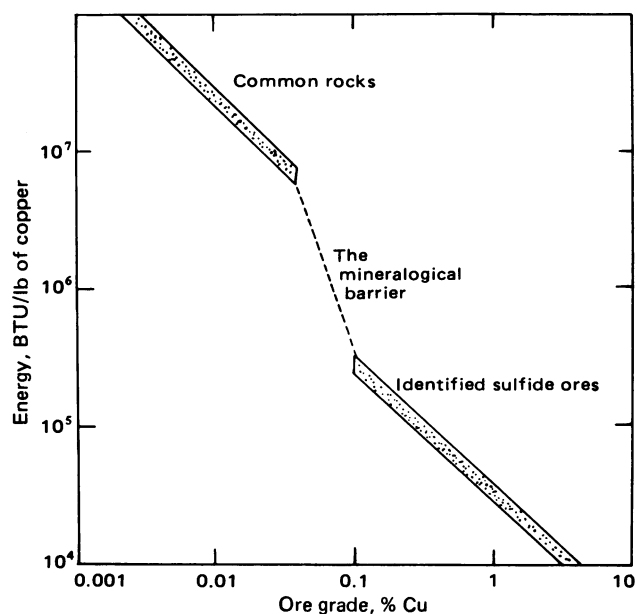


FIG. 5. The mineralogical barrier that must be jumped if we are to produce copper from ordinary rocks after all sulfide ores are used up. All geochemically scarce metals will present us with the same challenge (9).

for the future, but there are indications that suggest that, for a few metals, Fig. 5 represents a limiting condition. Consider the case of copper again. Some of the ferromanganese nodules on the deep-sea floor have copper contents as high as 1.5%, and this copper is trapped in solid solution in the manganese oxides. Assuming that recovering nodules from the deep-sea floor is no more energy intensive than is mining on land, the total energy requirements for processing manganese nodules will plot approximately on the silicate band in Fig. 4. Where copper is concerned, therefore, the future may possibly be as shown in Fig. 6. Unfortunately there is little in our present knowledge

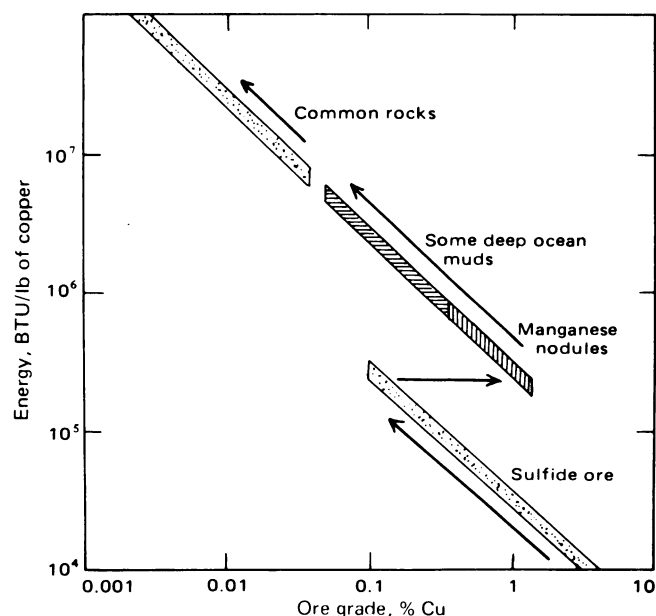


FIG. 6. Possible intermediate steps between sulfide ores and common rocks in the future production of copper. The amount of metal that can be produced from the intermediate steps is limited, just as sulfide ores are limited. Most geochemically scarce elements do not have identified intermediate steps.

of the chemistry of scarce elements to suggest that Fig. 6 is the pattern for most. Rather, the pattern of Fig. 5 is the one that we will have to cope with.

Two of the many questions that immediately follow from this line of reasoning are: (i) Are there possible unfamiliar or unknown kinds of mineral deposits that might drastically change the picture? and (ii) How much and how easily found is the material in mining deposits we know how to process?

### Unconventional and presently unrecognized sources of metals

There is a long history of successful discoveries of new and previously unexpected kinds of mineral deposits. Beryllium, for example, has traditionally been recovered from the mineral beryl, but in recent years unexpectedly large deposits of another beryllium mineral, bertrandite, have also been discovered. Niobium and tantalum offer another example: traditionally recovered from small amounts of their oxide minerals found in a type of rock called pegmatite, they are now recovered in much larger amounts from another rock, carbonatite, which was not even recognized as a distinct rock by most geologists until after World War II.

Despite such successes—and they are only two among a larger group—it is not realistic to expect that all or even many metals have new and unexpected kinds of mineral deposits waiting to be found. I suggest this is so because the large-scale geochemical sampling and geophysical programs now used as prospecting methods have not demonstrated the existence of many unsuspected kinds of deposits. Where mineral deposits have been found by such methods, they have usually been the kinds of deposits with which we are already familiar. One could argue that we only prospect those areas likely to contain conventional deposits, but the argument becomes continually less compelling as larger and larger areas are subjected to sampling. We can also argue that testing is highly selective and tends to be concentrated on a few elements such as copper, lead, zinc, and uranium and that some metals, whose chemistry in the crust is less well understood, have not been tested at all. This is a valid assertion and it points to a neglected area for research. Our knowledge of the geochemistry of many metals (for example, tungsten, tin, and tantalum) is so limited that we still cannot make an accurate assessment of the way the metals are distributed in the crust and cannot, therefore, design systematic prospecting programs. Deposits still tend to be found by accident.

There is an important conclusion to be drawn concerning the question of unsuspected kinds of deposits. Metals with chemistries that limit the possibilities for atomic substitution are more likely to be concentrated in unsuspected hiding places than are elements with less distinctive chemistries. As examples of elements with distinctive chemistries likely to form unsuspected deposits I suggest tin, tungsten, niobium, tantalum, beryllium, uranium, gold, and antimony. Examples of some elements less likely to form unsuspected kinds of deposits are copper, lead, zinc, nickel, and chromium. I am led to conclude from this line of argument that most of the mineral deposits still to be found will be similar to deposits that have already been discovered and will prove to have been formed by similar deposit-forming processes. Or, to use Lovering's terminology, we are unlikely to be surprised by the discovery of new and unexpected rich assets.

### How many conventional deposits?

It is not at all difficult to calculate the mass of any geochemically scarce element in the crust, but it is quite difficult to estimate the fraction of a metal trapped by atomic substitution

and the fraction present in separate ore minerals. The question can be approached through empirical geochemical methods. The first person to show how it might be done is a former Director of the USGS, Vincent McKelvey, who in 1960 suggested that the mass of any metal concentrated into ore deposits seemed to be roughly proportional to the crustal abundance of the element (10). Further refinements and extensions of McKelvey's data have confirmed his suggestions. Determine the amount for one metal, therefore, and the rest follows from their crustal abundances. Attempts to estimate the factor of proportionality are rather crude and depend on data from the most intensively mined and prospected areas, but they suggest that the amount of a scarce metal present in ore minerals falls somewhere in the range 0.01–0.001% of the mass of that metal in the crust.

Knowing how much of a given scarce metal occurs in sulfide or oxide ore minerals is only part of the problem, however. The remainder of the problem concerns the way the mineral grains are distributed in the crust—that is, the grade and size distribution of the ores. A partial answer to this question can be supplied from the records of past and present mining activities. Historic data are, of course, strongly biased toward high-grade ore deposits, but it is already apparent that specific types of deposits are characterized by distinct size and grade ranges (11). As we might expect, USGS geologists are in the forefront of this important work.

We are still a long way from providing an exact and reliable estimate of the amount of material yet to be found in conventional deposits. Attempts to do so for copper (8) suggest, however, that within the well-prospected United States we have already found a large fraction of what there is to be found. The historic pattern shown in Fig. 3 is apparently still operating.

Three interesting questions are often raised about the probable future discovery of mineral deposits. Each deserves attention. The first concerns the possibility that equal numbers of mineral deposits occur in any given depth range in the crust. Unfortunately, this widespread and long-held belief is probably not correct. A great many mineral deposits are formed through the agency of circulating aqueous solutions and these solutions are most prevalent in the top 2–5 km of the crust. Thus, we must anticipate that the frequency of deposits will decrease with depth. The second concerns the search for undiscovered ore bodies—Where does one look in the United States? The easiest places to search are those where rocks outcrop and deposits can be seen. The most difficult areas are those covered by deep piles of sediment or barren sedimentary rock. Approximately 40% of the country is in the latter class and is essentially inaccessible to present-day prospecting. Although we cannot sense or see through more than a few hundred feet of overlying cover, it is

not impossible that we will find ways to do so in the future. But it will be very expensive and will require a coordinated and far-sighted effort by the USGS to provide a framework of geophysical measurements and drill-hole sampling within which detailed and localized prospecting for completely buried deposits can eventually be carried out.

The third question concerns the deep-sea floor. Does it contain a treasure trove of metallic mineral deposits waiting to be mined? I believe that this is unlikely. Formation of most metallic mineral deposits requires a localized energy source to drive the circulation systems that deposit the ore minerals. The oceanic crust certainly encounters such a heat source at the spreading edge of a plate, but thereafter the oceanic crust seems to remain quiet and unaffected by mineralizing processes until it reaches a subduction zone. There are only two chances for most of the oceanic crust to become mineralized. By contrast, much of the continental crust has been subjected to many periods of mechanical and thermal activity and has therefore had many chances for ore deposits to form. The oceanic crust is, I believe, too young and too little changed compared to continental crust and thus will have fewer mineral deposits per unit volume.

I conclude that the U.S. Geological Survey will face larger and even more exciting problems during the next century than it did in the past. I am confident it will rise to the occasion and continue to be the leader we have all come to recognize and respect.

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