Limits to Exploitation of Nonrenewable Resources

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Nonrenewable resources consist of geochemical concentrations of naturally occurring elements and compounds that can or may be exploited at a profit. The concentrations that are at present exploitable at a profit range from slightly more than twice to several thousand times the average crustal abundance of the desired element (Table 1). Rates of concentration into ore bodies or oil pools appear to be slow compared to the pace of human history. Moreover, the formation of deposits of ores and mineral fuels appears to require unusual to extraordinary geologic conditions; consequently, such deposits are unevenly distributed in space and time, and they commonly occupy very small portions of the lithic prisms in which they are found.

Almost 70 percent of proved crude-oil reserves are in the Middle East, and five countries produce more than 65 percent of the world's copper. These nonuniform distributions are real and do not merely reflect differences in exploration effort. Many of the most common ore deposits appear genetically and spatially related to the boundaries of crustal plates (*1*). Other ore deposits not associated with crustal-plate margins may be localized by uplift of the crust over thermal plumes (*2*). Petroleum as well as metallogenic provinces exist, and the world's coal deposits are strikingly concentrated in the temperate belt of the Northern Hemisphere.

Not only are geologic resources distributed unevenly over the surface of the globe, they are concentrated in the outermost part of the earth's continental crust. Mechanisms that concentrate chemical elements operate most effectively on and near the earth's surface: weathering, erosion, sorting during transport, groundwater leaching, and supergene enrichment are effective only in the upper few hundred meters of the continents. Hot metal-bearing solutions encounter the precipitating effect of colder meteoric waters and find relatively high permeability only in the upper few thousand meters of the crust. Oil and gas formation, migration, and entrapment take place within the thin and discontinuous sedimentary skin of the continents. There is a hoary myth among old prospectors that ore bodies widen and get richer downward. In fact, they generally do just the opposite. The rich gold and silver deposits of the American cordillera are notorious for bottoming at depths of a few tens to a thousand meters. The Comstock Lode and the several ore bodies at Guanajuato (*3*) are excellent examples. The mineral-fuel analog is the transition zone in a reservoir rock between crude oil and water, a zone commonly only a meter or two thick; the world's greatest oil well, Cerro Azul No. 4 in Mexico, after producing more than 50 million barrels of oil, suddenly produced only salt water.

The limited nature of individual deposits, the difficulty of seeing through rock, and the history of many mining districts and oil fields have led to many forecasts of depletion and exhaustion. But, as old deposits have become exhausted and new ones have become harder to find, world mineral and fossil-fuel production paradoxically has continued to increase. There is a wide difference of opinion now on the question of limits to the exploitation of nonrenewable resources.

Three Kinds of Limits

To the mining or petroleum engineer, the profit of exploitation is defined by the difference between the price received for his product and the pecuniary costs of recovering the natural material and turning it into a salable product. To society, however, the profit from mining (including oil and gas extraction) can be defined either as an energy surplus, as from the exploitation of fossil and nuclear fuel deposits, or as a work saving, as in the lessened expenditure of human energy and time when steel is used in place of wood in tools and structures. In this context, the exploitation of earth resources for display, adornment, or monetary backing is a deficit operation, financed by energy profits from other kinds of mining.

The ultimate limit to exploitation of earth resources then is the limit of net energy profit (or work savings). When it takes more energy to find, recover, process, and transport the fossil fuels than can be gotten from them in useful form, there will be no more oil, gas, or coal resources. When it takes so much energy or work to produce a nonenergy material that one must sacrifice other, more needed, items or services to pay for it, there will be no more resources of that material. Short of this energetic limit, one or both of two other limits may intervene. First is the limit of comparable utility. A resource is a resource only while it can be used to perform a function desired by man better or more cheaply than can another substance. If the energy cost of an earth resource such as crude oil rises to a level at which another substance, such as synthetic crude oil from coal, can be substituted in adequate volume at a lower cost for comparable utility, substitution will take place, with the first resource reverting to a mere geochemical anomaly and the source of the replacing substance becoming a resource.

The limit to a resource also may be determined by the unwillingness of society to pay the cost of its exploitation, even though an energy surplus (or saving) might be obtained thereby. According to Sahlins (*4*) many primitive societies preferred to take their energy surplus in leisure rather than in goods (stored energy or work) and deliberately abstained from exploiting available potential resources that could have increased their surplus. Some primitive agricultural societies still do this. Rappaport (*5*) has described a New Guinean society in which agricultural surplus is taken in leisure when the option of taking it in meat or goods is clearly open. A modern decision to forgo the calculable energy benefits of the breeder-reactor power plant would again invoke this limit of living-level degradation, a limit that comes into play when a society is not willing to pay the total costs of production—because so doing would, it is judged, lower the level of living more than would forgoing use of the resource.

Effects of Technology and Cheap Energy

To some, the history of nonrenewable resource exploitation seems to contradict the idea of an energetic limit short of mining common rock and "burning" seawater (*6*). During the past 150 years large increases in the earth-resource base of industrialized society have been attained. By in-

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← *Courtesy Bureau of Mines, U.S. Department of Interior, Washington, D.C.*

creasing the efficiencies of discovery, recovery, processing, and application of such resources, we have been able to find and exploit leaner, deeper, and more remote deposits. By discovering and developing new methods of utilizing previously worthless materials we have created resources where none existed. Important in this rapid technologic advance has been a progressive lowering of the cost of energy per unit of work or useful heat obtained. Cheaper energy, along with technological ingenuity and discovery, has greatly extended the availability of nonenergy resources. In 1900 the lowest grade of copper ore economically minable was about 3 percent; today the economic cutoff has fallen to about 0.35 percent; at that grade each ton of refined copper produced requires the breaking, transport, and milling of almost 300 tons of rock and, in addition, the removal of perhaps an equal amount of waste or barren rock. A great deal of energy—about 26,000 kilowatt-hours (*7*), the equivalent of the energy in about 4 metric tons of Wyoming coal—is required to produce a metric ton of copper today, but the cost of that energy is still low compared to the cost of supporting the equivalent in men and mules.

Many past forecasts of the exhaustion of one or more earth resources have come to appear almost wildly inaccurate in the light of later production. Forty years ago, geologist C. K. Leith, for example, called attention to the coming exhaustion of U.S. mineral resources, claiming (*8*, p. 169) that "despite a magnificent endowment [of metals and fuels], depletion is further advanced than even mining men generally realize." At the time Leith wrote, proved reserves of crude oil, zinc, and lead in the United States were 15 to 20 times larger than annual production rates, the Lake Superior iron ores appeared to have less than 20 years of measured supply remaining, and known copper reserves were about 40 times the 1934 production. Leith went on:

Further discovery and the use of lower grade resources will extend the life of most of these resources, but the range of possibilities is now pretty well understood, and with maximum allowance for such extension, the figures are sufficiently small, when compared with what we hope will be the life of the nation, as to be matters of public concern.... Discovery has not stopped, but the rate has been slowing.... Of 33 metal-mining districts that have yielded the greatest wealth to date only 5 have been discovered since 1900 and none at all since 1907.... The rate of discovery of oil and gas continues high ... but the chances of finding another East Texas or Kettleman Hills are not promising.

Well, what happened? Since 1935, the United States has produced more zinc than it did before that year. In 1974 the U.S. mine production of zinc (Table 2) could

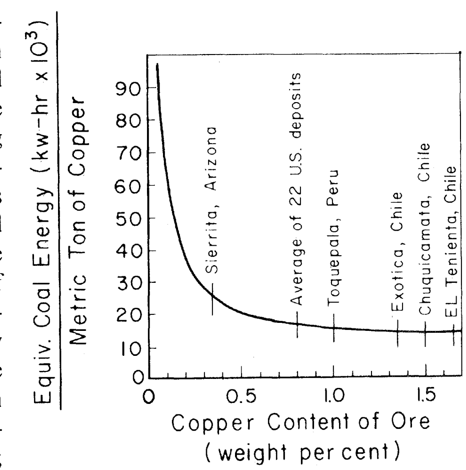

Fig. 1. Equivalent coal energy requirements for different grades of copper sulfide ores. Grades of some copper deposits are shown (*25*, figure 2).

have been maintained for 61 years on the then-known reserves; the ratio of domestic reserves to primary consumption (defined as domestic demand less the recycled or secondary supply) stood at 24, despite the fact that demand had soared.

Although U.S. lead production since 1935 does not equal the pre-1936 total, the ratio of measured reserves to primary consumption in 1974 was 67, and the 1974 mine production could have continued for 87 years without further discovery.

The Lake Superior iron ore of Leith's day has been virtually exhausted, but it has been largely replaced by taconite, a low-grade iron-bearing rock not considered to be ore in 1935. The 1974 ratio of measured reserves to U.S. iron-ore consumption was 14, and at the 1974 rate of U.S. mine production, the reserves would last about 24 years.

Table 1. Ratio of cutoff grade (the lowest concentration economically recoverable in 1975) to crustal abundance for selected elements. Except for carbon, which is from Mason (*27*), crustal abundances are from Lee and Yao (*28*). Values are parts per million (ppm).

Element	Crustal abundance (ppm)	Cutoff grade (ppm)	Ratio
Mercury	0.089	1,000	11,200
Tungsten	1.1	4,500	4,000
Lead	12	40,000	3,300
Chromium	110	230,000	2,100
Tin	1.7	3,500	2,000
Silver	0.075	100	1,330
Gold	0.0035	3.5	1,000
Molybdenum	1.3	1,000	770
Zinc	94	35,000	370
Uranium	1.7	700	350
Carbon	320	100,000	310
Lithium	21	5,000	240
Manganese	1,300	250,000	190
Nickel	89	9,000	100
Cobalt	25	2,000	80
Phosphorus	1,200	88,000	70
Copper	63	3,500	56
Titanium	6,400	100,000	16
Iron	58,000	200,000	3.4
Aluminum	83,000	185,000	2.2

Since 1935, more copper has been mined in the United States than before. Based on 1974 figures, the ratio of reserves to primary consumption was 50, and U.S. mine production could have continued at the 1974 level for 57 years without new discoveries.

More recoverable crude oil (77.3 billion barrels) has been discovered since 1935 than was produced from 1857 through 1934 (62.0 billion barrels). At the end of 1974, however, the ratio of proved reserves to 1974 production was only about 11. Perhaps more significantly, the ratio of proved domestic reserves to 1974 consumption (of both domestic and foreign petroleum) was only 7.7.

In regard to these major earth resources, the United States in 1975 was substantially worse off than it was in 1935 only in crude oil. Despite large increases in consumption rates over the past 40 years, we now have many more "years" of lead reserves than we did 40 years ago, as well as about 25 percent more years of copper and zinc reserves—even if we were abruptly deprived of all imports of these metals. With continued imports, our iron-ore reserve position is much better than it was 40 years ago; without imports, we have lost only 4 years of reserves in 40 years.

In the short term, and except for oil, Leith appears to have been wrong. The continuous-creation school of resource analysts would classify him as a doomsayer of the past whose forecasts went awry for the same reason that those of the present-day Cassandras will miss the mark, a lack of understanding of the impact on reserves of continuously improving technology, which geologist Nolan (*10*) once called "the inexhaustible resource."

The view that advances in technology, stimulated by the market economy, will prolong the availability of a mineral commodity almost indefinitely or will provide adequate substitutes when rising cost begins to slow demand, has much evidence in its favor and many strong adherents (*11*). There is currently an oversupply of both copper and crude oil in the world, and the supply of ores of iron and aluminum, despite enormous increases in the production and consumption of both during the past 50 years, seems almost boundless.

Why, then, do some (*12*) persist in the opposite view, that physical limits will slow or halt the development and utilization of most earth resources long before crustal concentrations can be regarded as reserves? Perhaps it is because they are impressed by the steepness of the geochemical gradients at the margins of most ore and fossil-fuel deposits, by the fact that such deposits do not show a compensating increase in tonnage of reserves (calculated as recoverable metal or fuel) as grade decreases, by the environmental limitations on their origin, and by the fact that the energy or work cost of recovery increases exponentially with decreasing grade of the ore or with increasing cumulative recovery in the case of crude oil.

Table 2. Comparison of the ratio of reserves to production (R/P) in 1934 with the same ratio and the ratio of reserves to primary consumption (R/Cp) in 1974 for five major earth resources. Figures are for the United States. Figures for copper, iron ore, lead, and zinc are in thousands of metric tons; for crude oil, in millions of barrels. The 1974 statistics, except for crude oil, are from the Bureau of Mines (*29*); values have been converted to metric tons. Crude oil production and reserve figures are from (*9*), net imports and primary consumption from (*30*). The 1934 approximate R/P figures are from Leith (*8*).

Resource	1934 R/P approximate	1974 Domestic mine (well) production	1974 Net imports (primary and secondary)	1974 Domestic secondary supply	1974 Domestic reserves (R)	1974 R/P	1974 Domestic primary consumption (Cp)	1974 R/Cp
Copper	40	1,441	391	455	81,800	57	1,640	50
Iron ore	18	83,000	46,000	NA*	2,000,000	24	140,500	14
Lead	15–20	615	82	564	53,600	87	800	67
Zinc	15–20	447	655	77	27,300	61	1,150	24
Crude oil	15–20	3,043	1,268	NA*	34,250	11.2	4,447	7.7

*NA, not applicable.

Examples of Exploitation Limits

The so-called porphyry copper mines, which now produce more than half the world's copper, are worth looking at in the context of exploitation limits. Although differing considerably in detail, they have certain features in common (*13, 14*). They are sharply restricted in age of formation to three periods, or pulses, within the range of 30 million to 200 million years ago. They are associated with small intrusive bodies of stocklike form, averaging 1200 by 2000 meters in outcrop. The ore bodies tend to be pipelike and oval in plan, with dimensions of approximately 1000 by 2000 meters. Mineralization is in concentric zones (*15*), with the copper content in the center of the body reaching ten times that at the outer edge of metallization (*16*). Vertical dimensions can reach 3000 meters, but the pipe narrows downward. If, as Sillitoe (*17*) believes, the porphyry copper deposit spans the boundary between the plutonic and volcanic environments, it occupies a very special geologic position indeed, sharply limited in both time and space.

The Toquepala and Cuajone mines in Peru are typical of the porphyry coppers (*18, 19*). The mass of mineralized rock in these deposits has the shape of an inverted and truncated cone, within which the copper content ranges from 1.32 percent to less than 0.45 percent, the present cutoff grade, below which mining and processing would be unprofitable. Rock containing between 0.20 and 0.45 percent copper is, however, being mined and stockpiled for later leaching by sulfuric acid. Below an average of about 1 percent copper, the copper content of the ore (Table 3) decreases sharply as the grade drops. The deposits, although the ore minerals are irregularly disseminated through them, have rather sharp geochemical boundaries, and the diameter of the mineralized cone decreases downward. The energy cost, per kilogram or ton of refined copper, of mining and milling the ore increases inversely with grade and directly with depth.

At Cuajone, if the ore cutoff grade were to fall from the present 0.45 percent to 0.20 percent (the upper and lower boundaries of the 102 million tons that average 0.32 percent), the total copper recovery would be increased by only 7 percent. At Toquepala, a similar lowering of the cutoff grade would increase recoverable copper by less than 4 percent. Because economies of scale appear to have been exploited fully, and because energy costs are rising, it does not appear likely that the ore reserves in these mines will be extended much either by technological advances or rises in the price of copper.

A tonnage-grade analysis of known North American porphyry copper deposits (*20*) indicates that 70 percent of the copper metal is in deposits above 0.7 percent copper; lower-grade deposits do not represent increasingly larger amounts of copper, but the reverse. Analyses of the known deposits of the two other principal types of copper deposits, strata-bound and massive sulfide, suggest similar tonnage-grade relations (*21; 22*, p. 167). Significant, too, is the fact that the rate of additions to reserves of copper metal appears to have been falling off since 1960, during a period when the price of copper has risen strongly; here it is important to distinguish between tonnage of ore and tonnage of contained metal. Many more deposits will need to be found, at a faster pace than recently, if copper production is to continue at high levels into the coming century. Furthermore, there appears to be a geochemical barrier to copper recovery at about 0.1 percent copper (16 times the geochemical background),

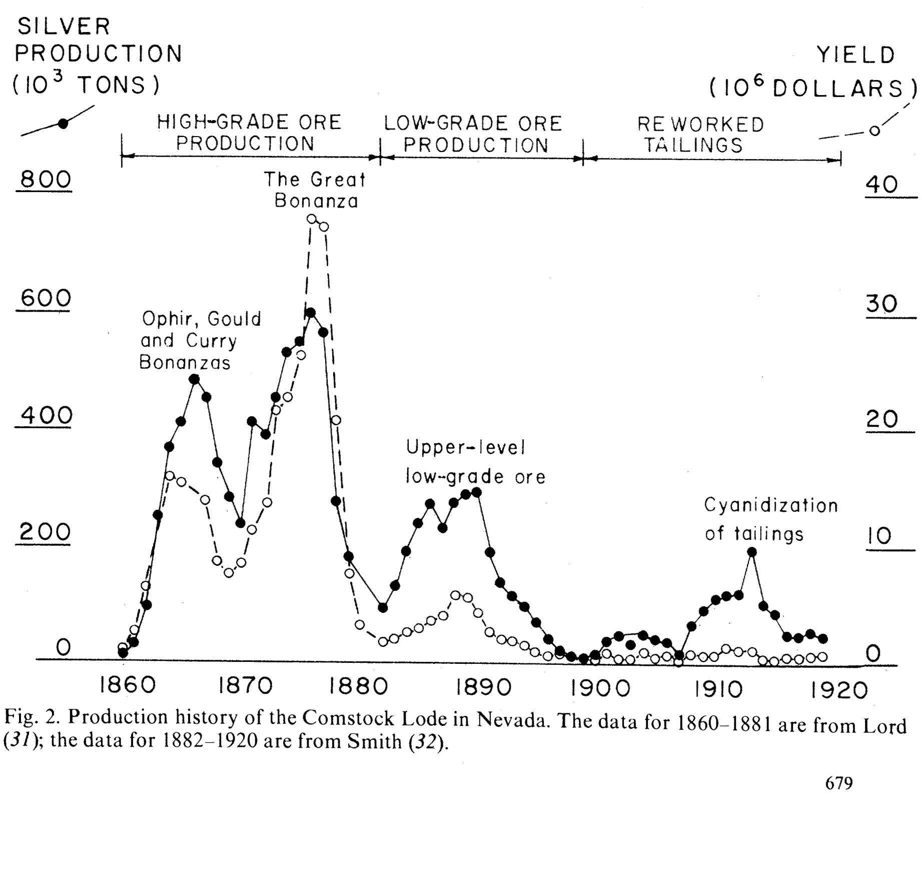

Fig. 2. Production history of the Comstock Lode in Nevada. The data for 1860–1881 are from Lord (*31*); the data for 1882–1920 are from Smith (*32*).

below which most copper is in solid solution in common silicate minerals and is not amenable to selective physical or chemical extraction (*22*, p. 129).

The basic question in forecasting earth-resource exhaustion is whether or not the energy-profit limit will be reached, or demand will cease, short of attempts to extract the desired resource from ordinary rock and seawater. For some resources, we can say with assurance that the energy-profit limit will be reached long before ordinary rock can be mined profitably. The fossil fuels are the best and most important examples. The energy potential represented by the average concentration of carbon in the earth's crust is 2.9 kilowatt-hours per metric ton, not nearly enough to crush and grind it to liberate the carbon for use. In large modern copper-ore mills, grinding and classification (separation) alone require about 26 kilowatt-hours (coal equivalent) per metric ton of ore milled. We can thus be sure that the sharp physical boundaries that characterize coal and petroleum deposits are also economic boundaries. In fact, for most petroleum deposits the economic limit of exploitation lies within the deposit rather than at its margins; oil clings so tenaciously to the pore walls of reservoir rocks that to flush it all out would require more energy than can be gotten from it. The curve of incremental recovery against energy cost is steeply exponential for so-called tertiary recovery techniques, and to achieve an average cumulative recovery ratio of even 40 percent from American reservoirs will require much higher prices for oil than can now be foreseen (*23*).

Table 3. Relations of ore grade, copper content, and mining and milling energy at Cuajone mine, Peru. Values in the last column are Δ per short ton of copper, where Δ is the energy required to mine and mill a short ton of 1.00 percent copper ore. To convert short tons to metric tons, divide by 1.1023.

Average grade (%)	Tonnage (short tons) ($\times 10^3$)	Copper content (short tons) ($\times 10^3$)	Energy needed to mine and mill (Δ/ton)
1.32	20,000	264	0.76
0.99	430,000	4,257	1.01
0.32	102,000	326.4	3.13
< 0.20*	1,057,000	66.6*	> 16,000

*Mostly barren overburden of post-ore volcanic rocks; calculated at crustal abundance for copper content and energy needed.

On the other hand, there are very large low-grade deposits of uranium in which the potential energy is more than sufficient to break, transport, and pulverize the rock, and then to recover the uranium. Breeder reactors converting 60 percent of the potential energy of uranium to thermal energy and 40 percent of that to electricity could produce more than 5500 kilowatt-hours per metric ton of average crustal rock, which might allow an energy profit to be returned. The question here is the amount of energy required for mining and milling very low grade ore. Not only does the tonnage of ore necessary to produce 1 ton of metal increase hyperbolically as the grade decreases (*24; 25*, p. 10) (Fig. 1), but the energy input per ton of ore ground increases as the size required to liberate small particles of ore decreases (*26*). As ore grade decreases, the percentage of the valuable metal recovered in milling decreases; this falling off in recovery efficiency has the effect of increasing the energy cost per unit of refined metal. Finally, the ore generally gets harder to break and more expensive to lift as mining goes deeper; therefore, the energy costs of mining (per ton of recovered metal) tend to increase as exploitation continues.

The energy required to produce refined metal from low-grade ores becomes extremely high at grades that, except for iron and aluminum, are well above the corresponding crustal abundances.

Except in the cases of strip-mined coal and Persian Gulf oil, the energy costs of obtaining useful energy are rising as found sources grow deeper, leaner, and more recalcitrant or refractory and as income

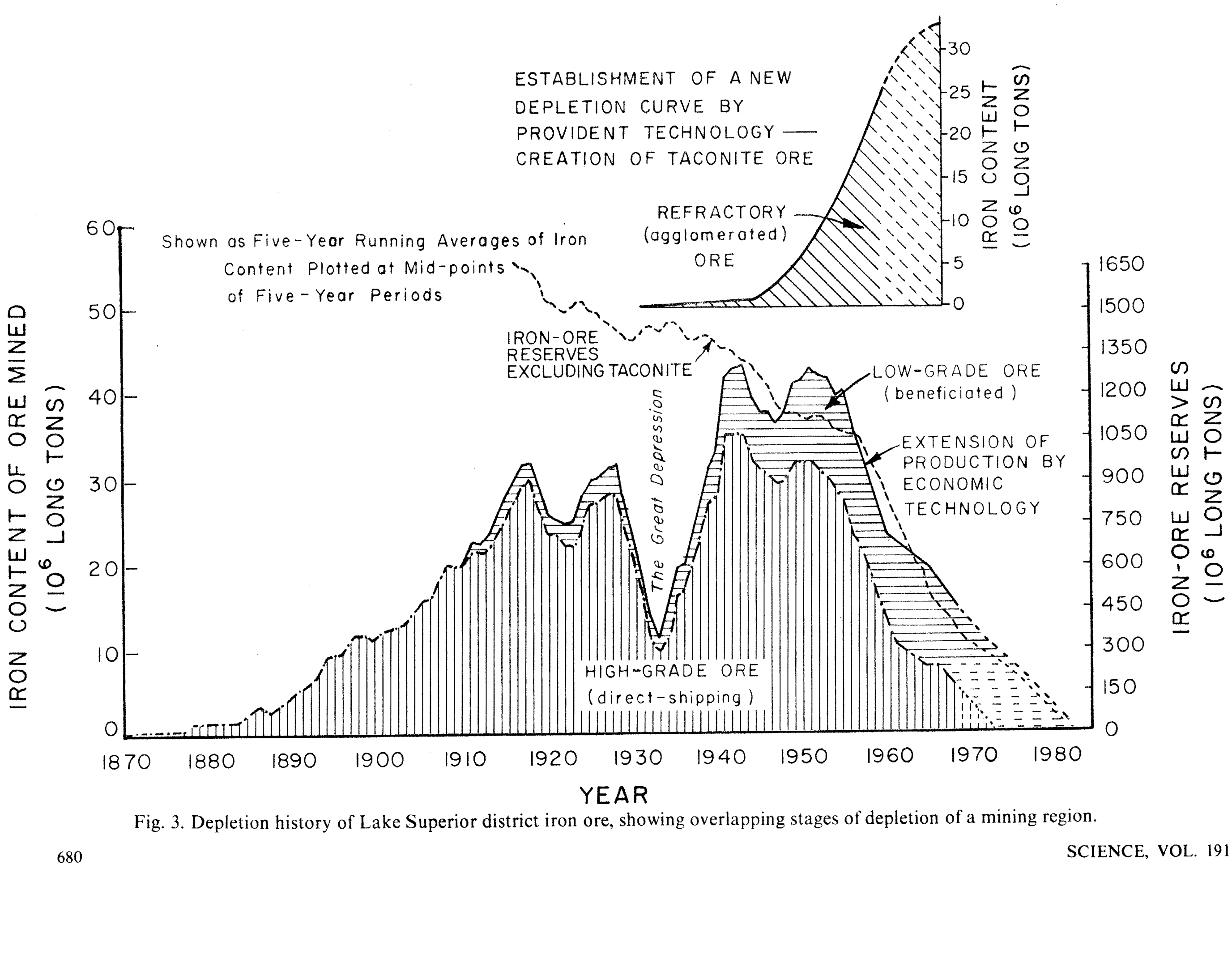

Fig. 3. Depletion history of Lake Superior district iron ore, showing overlapping stages of depletion of a mining region.

sources become limited. Coal exploitable by stripping and Persian Gulf oil are clearly finite, and production of both is likely to wane within 25 to 50 years. Increased costs of obtaining useful energy and higher work costs of exploiting leaner or more refractory materials will tend to raise present ore cutoff limits and thereby to reduce reserves, while technologists continue the struggle to lower cutoff grades and augment reserves. Only a breakthrough of provident technology that results in a substantial lowering of energy costs would reverse what appears to be a tightening of the drawstring on nature's bag of nonenergy resources. The breeder reactor may represent such a breakthrough.

Depletion Histories

The history of a mining district or of an oil field has a beginning and an end, separated by a productive period. Some histories end abruptly, others are drawn out. Resurrection is rare. The history of the Comstock silver lode (Fig. 2) illustrates a simple depletion pattern characteristic of high-grade, sharply bounded, vertically limited mineral deposits. The Comstock vein system, a candelabrum with tabular branches, is typical of fractures that fill with ore minerals at shallow depths; the system is rich and intricate near the surface, barren and simple a few thousand feet below. Its production history shows three distinct stages. In the first stage, during which the greatest part of the lode's total value was extracted, high-grade ore was mined at a fast rate. In the second stage, it became possible because of technological improvements to mine lower-grade material bypassed in the first stage. In the final stage, waste material and some very low grade ore were processed by a new technology, but little was added to the value already produced.

Somewhat different from the history of the Comstock is that of the Lake Superior iron district. Depletion of the rich "direct shipping" ores of that district is almost complete (Fig. 3). These ores, created by a geologic process related to groundwater levels and to the particular geologic configurations of the district, had sharp physical boundaries that coincided with economic limits. In the waning stage of production, upgrading of low-grade material into shippable concentrates added substantially to total production, but delayed exhaustion by only a few years. However, the Lake Superior district has been revived through a technological breakthrough that created a very large resource out of a previously worthless iron-bearing rock called taconite. Such provident technology can be effective only where there is a deposit, already concentrated by natural processes, characterized by a refractory host or reservoir rock. Taconite production, now in its youthful stage, will also pass through maturity to exhaustion.

Iron and aluminum are abundant elements in the earth's crust. For each, there are several kinds of geologic concentrations that represent actual or potential resources; consequently, for each we may expect the depletion history to consist of a series of production-history curves, as availability and cost dictate a steplike descent from high-grade hematite to taconite to iron-rich intrusive bodies, and from bauxite to alunite to high-alumina clays.

When we move in scale from an individual mining district to a country, we find fewer examples of complete production cycles. Mercury, however, is an essentially exhausted resource within the United States, and its production history shows some significant relations to price (Fig. 4). Exploitation of mercury went through three phases: a waxing phase, during which increases in production caused the price to fall; a mature phase, during which price and production were more or less in equilibrium; and a waning phase, during which successive surges in price evoked progressively weaker responses in production.

The waxing phase represents a period when real cost falls because of new discoveries, technological improvements, and economies of scale. The falling cost stimulates demand. Increased production hastens the exhaustion of high-grade, low-cost deposits and puts pressure on technology to counter increasingly adverse geologic and geographic conditions. When technology begins to lose the battle, real cost rises and the waning phase is entered. Prices rise with increasing costs of production and demand falls. Sharply rising prices stimulate the search for a substitute, either imports of the same substance or domestic production of a replacement material; if a substitute is found, domestic production of the resource ceases; if not, it is stretched out, diminishing slowly as demand wanes.

The relation of production and price curves for U.S. silver is similar to that for mercury (*19*, p. 21) and the curves for crude oil are developing in like fashion. During the waxing phase of U.S. oil production, gluts of oil drove the price down to or below the actual cost of production. Proliferation of automobiles and trucks was stimulated by cheap fuel, and demand grew. The passage to the waning phase, about 1971, was abrupt because of the large cost differential between domestic and foreign crude oil at a time of strongly rising demand, a differential that forced a rapid shift from domestic production to imports. Current, artificially high, world crude-oil prices have encouraged exploration for new domestic reserves and have stimulated new efforts to recover more oil from existing wells. It is almost certain, however, that we shall not see a production response equivalent to the price rise because the costs of finding and recovering crude oil (and natural gas) increase exponentially with depletion. If the present cartel of oil exporting countries collapses and world oil prices fall sharply, the end of the U.S. production curve will be abrupt. If the cartel does not collapse, but an adequate supply of substitute energy, say from coal or oil shale, is developed at or near the present price of crude oil, the end of U.S. crude production will be slower but similarly assured.

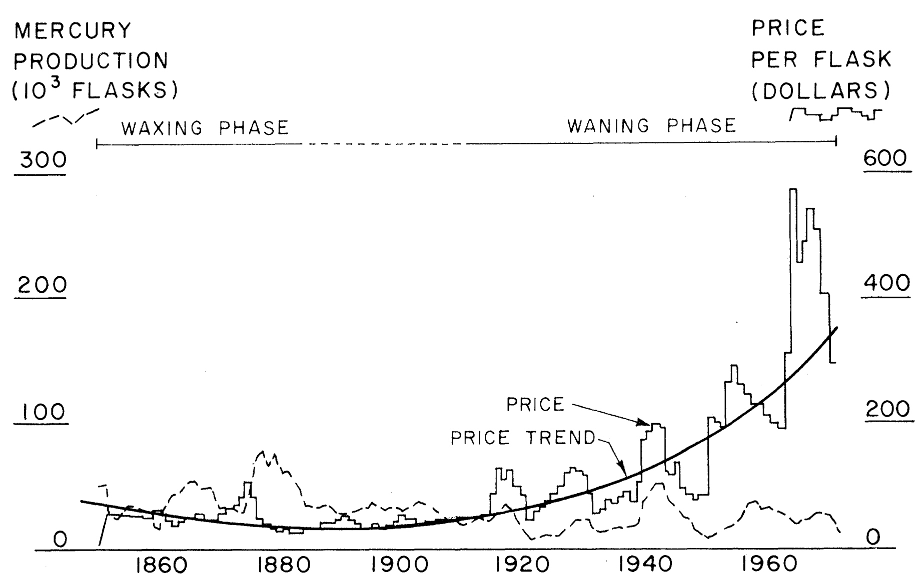

Fig. 4. Production and price history of mercury in the United States (*33*).

Conclusion

In view of the geologic and geochemical constraints on the occurrence of economic deposits of minerals and energy resources, and the advanced nature of present exploitation techniques, we must conclude that such resources are finite. The "endlessly retreating" interface between ore and almost-ore that some optimists have described could be validated only if the cost of useful energy would endlessly and acceleratingly decrease. On the other hand, the question "When will we run out?" bespeaks a misunderstanding of geologic resource limits. The world will not run out of geologic resources. They will merely become more expensive. As they become more expensive their utility will diminish, either by human decision or by failure to achieve an energetic profit. How expensive a geologic resource becomes, and how fast its real cost rises, will depend on a combination of geologic and technological factors. Depletion (rise in cost) is swift for those materials found mainly in sharply bounded, highly concentrated deposits—especially swift if they cannot be recycled after use. Depletion is slow for abundant materials found mainly in deposits of relatively low geochemical concentration with gradational boundaries—especially slow if they can be recycled after use.

Summary

Despite the fact that strongly positive geochemical anomalies are relatively small and rare and appear to be restricted to the outermost part of continental crusts, the history of economic exploitation of nonrenewable resources over the past 200 years is, in general, one of decreasing costs and increasing reserves. However, the direct energy or work costs of recovery have been rising, slowly for a long while, then more rapidly as the number of tons of ore required to produce a ton of refined metal has started to rise more steeply with decreasing ore grade. The seeming paradox of decreasing total costs and increasing work costs is explained by a long record of decreasing real costs of the energy used to extract and process nonrenewable resources. Now that energy resources themselves are beginning to cost more in work, now that the efficiencies of energy conversion appear to be nearing limits dictated by the strength of materials and the laws of thermodynamics, and now that the work costs of recovery, at least for some resources, are moving up the steeper parts of exponential curves, the nature of the limits to exploitation of nonrenewable resources is beginning to be recognized.

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