RESOURCES
FOR THE FUTURE

"EXPLORING THE RESOURCE BASE"

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Exploring the Resource Base
(Notes for an after-dinner talk)

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I want to thank R.F.F. for inviting me to attend this workshop on The Long-Run

Availability of minerals. I am particularly grateful because it gives me a chance to present some

geological concepts that tend to be overlooked when we start talking about that difficult-to-

define term "Sustainable Development."

It was only when I read John Tilton's very nicely written position paper "Depletion and

the Long-Run Availability of Mineral Commodities" that I discovered that R.F.F. and I share a

common bond in our past. R.F.F. apparently came into being as a result of the Paley

Commission. The reason that I am here tonight is also because of the Paley Commission. As I

understand it, the Paley Commission's conclusions led the U.S. Geological Survey to expand

their research program into the genesis of mineral deposits. Somehow, they located me in

Australia, invited me aboard, and in late 1958 I joined the U.S.G.S., then located downtown at

17th and F in Washington, D.C.

I suppose that Barnett and Morse were also in Washington at that time, working on their

seminal study of scarcity and growth; unfortunately I did not know of the study and I never met

them. But I did start to think about some of the issues with which they were concerned.

However, my stimulus for doing so did not come from RFF. In the U.S.G.S. in the 1950s and

1960s there were a few people actually working on aspects of the magnitudes of resources—one

was Vince McKelvey, and another was M. King Hubbert. I don't know, but I suppose they may

have been influenced to do so by the Paley Report too. I did not actually work with either

Hubbert or McKelvey, but I knew them, and I heard them give talks on their work, most of

which dealt with rates of discovery rather than the science of how the resources formed. I

wondered a bit about how their work could be tied back to the underlying science of how, where,

and why mineral deposits form, but I did little more than wonder and become convinced that if

we understood all aspects of the chemistry of ore formation, we could eventually understand all

aspects of the supply of resources..

I left the U.S.G.S. in 1966 and joined the faculty at Yale. Those were heady times for

geologists because the race was on to collect samples on the Moon, and I spent quite a few years

deeply involved in the lunar sample program. Time spent thinking about the magnitudes of

resources would have stopped right there had it not been for a fortunate circumstance. I was

invited to speak about mineral and energy resources in Yale's School of Organization and

Management, and then the late Tjalling Koopmans asked me to speak on some aspects of the

topic to his class in economics. People in the class asked thoughtful questions about the

magnitude of resources and that brought the topic back to me again. I have continued to think

about some of the resource issues from a geological viewpoint and I want to talk about a few

geological aspects tonight.

Let me start by making clear what I intend to talk about. We live on a planet that is a wonderful mixture of 92 chemical elements. Five of those elements are so scarce as to be undetectable for all practical purposes. The remaining 87 elements all find a use somewhere in our technological society. What technology has done, and continues to do, is exploit the special atomic properties of these 87 elements, either singly or in combination—that is, as elements or as compounds. (FIGURE 1)

One of the traps one can fall into is to treat all resources in the same way—that is, if we have a use for them, we sometimes seem to think we should be able to treat issues of supply in the same way regardless of the commodity. To avoid that problem, I am only going to talk about a subset of the elements—those with metallic or semi-metallic properties in the ranges of temperature and pressure reached in technological processes on the earth's surface and, in addition, those that are minor constituents of the crust, which means less than 0.1 percent by weight. This amounts to about half of the elements, and includes all those metals like tin, tungsten, copper, zinc, and many others that have such special uses they are sometimes called the enzymes of industry.

I have made this restriction because the geological processes that control the distributions of these elements are similar. The chemical processes that form copper and mercury deposits are nearly identical, for example, but they are quite different from the processes that form oil and natural gas deposits. It may make sense to lump oil and gas together with copper and mercury

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from an economic viewpoint, but it makes no sense to do so from a geological point of view.

Let me stress an important point. The reason we have deposits of most of the special metals on the Earth is that Earth has a hydrosphere; and as a result water circulates deeply into the crust. The most important discovery from the deep drill holes in Russia and Germany is that water circulates at hydrostatic pressures down to at least 12 km. That water, and of course water that reaches even greater depths, is heated by Earth's internal heat. Hot water and rocks interact and the products of those reactions are the ore-forming solutions that create most of our ore deposits.

Lacking water, the Moon and the asteroids give no hint that they harbor useful deposits of anything other than iron and a little nickel.

The Future

I will be talking about the future, not the past. I realize that geological time scales are not appropriate for a discussion concerning sustainable development, but surely a century is not too big a chunk of time to grasp. When we discuss trends of the past—or perhaps I should say "long-term" trends—we often consider durations of a century or more. Looking forward we should surely try do the same.

Over the century ahead we may need to discover and produce three or four times more of

the metallic elements than have been produced throughout all of history. The forces driving

demand that will require such amounts will be a population scheduled to double, the continuing

spread of technology from the developed to the less developed world, and an increasing per

capita consumption of material on a global scale. (FIGURE 2)

I don't wish to elaborate on this demand conclusion but it is important to what I want to say,

because I use the conclusion as an entry point to what John Tilton refers to as the McKelvey

diagram. If production is to continue it is pertinent to ask where it will come from, and that

means we must look at the resource base. (FIGURE 3)

The McKelvey diagram is an adaptation of an old and long-used way to classify mineral

reserves by the U.S. Bureau of Mines. McKelvey extended the concept to include all of the

undiscovered deposits that might be out there. Further adaptations produced the diagram that is

now used by geologists and economists alike. There are two categories—*reserves*, which are

simply measures of the amount of discovered commodities. *Resources*, the second category, is

less definite. The definition used by most geologists is that of the U.S.G.S.—*"beyond reserves,*

all other mineral deposits that may eventually become available, by which is meant either known

deposits that are not economically or technologically recoverable at present, or unknown

deposits, rich or lean, that may be inferred to exist but have not yet been discovered." What

does that term *mineral deposit* mean to geologists? The standard definition, and the one the

U.S.G.S. means in their definition of the term resource, is *any volume of rock containing an*

enrichment of one or more minerals.

Geologists specializing in mineral exploration have been spectacularly successful over the past 100 years. They have found, and engineers have mined, an extraordinary flow of material. I say 100 years for a good reason—although a great many deposits were found in the 19th century and earlier, they were either found accidentally, as in the case of the great nickel deposits at Sudbury in Ontario, or they were found by prospectors who scratched every surface and knapped every rock to see what was inside. That is how places like Tonopah, Nevada, and Butte, Montana, were discovered. The special profession of mineral exploration, trained geologists who specialized in the discipline, started about 1900 but really got under way following World War I, when small-time prospectors and accidental discoveries could not meet the demand. Exploration geologists certainly scratched the surface, but they also developed techniques for looking for deposits beneath soil cover of a few tens of meters, and that expanded their horizons far beyond those of the traditional prospector. This time coincides with the big decline in production costs, starting in 1919, noted by Barnett and Morse.

Using data derived from studies of the details of mineral deposits this new breed of geologists found that they could narrow their searches, and increase their chances of discovery by geological reasoning. Some new tools were also developed. Examples are diamond drilling, aerial photography, geophysical measurements of magnetism, electrical fields, and gravity, and rapid inexpensive analytical procedures that allowed sampling of vast numbers of rock and soil

samples. But most importantly, it became possible to travel quickly and relatively inexpensively anywhere on earth. People no longer were experts of a small geographic area, they became experts of classes of geological terrains, or experts on specific kinds of deposits, and they could quickly carry their expertise from one place to another.

But there are some soft spots in the success story of mineral exploration and they deserve closer attention. Over the past 200 years the locus of successful mineral exploration has moved steadily westward, away from Europe. We tend to forget that the industrial revolution was nurtured on materials produced from the mines of Europe and the eastern half of North America. Those mines are now exhausted, as are many of those still farther west, and both exploration and production have now moved to regions that played little, if any, role in the industrial revolution.

The 20th century tools that speeded up mineral exploration have not been of much use in the discovery of new mineral districts in the older mining areas. Where new, unexplored ground is concerned, the tools seem to let us find what is present fairly quickly, and while going back over previously explored ground may turn up a missed orebody or two in a known mineral district, the tools have not helped us to locate many new mineral districts. Indeed, in that part of Europe occupied by the Romans, no new mineral districts have been discovered since the empire collapsed.

Where, then, are all of the undiscovered deposits that should be included in the category of resources? The answer is not hard to find. They are, first of all, in those parts of the world that have not been intensively explored because they are politically unstable, topographically

inaccessible, or for one reason or another withdrawn from access by social or political acts. But much more importantly, many resources lie beneath a cover of younger barren rocks and are sufficiently deep so that today's prospecting technology cannot detect them. This still untested, but surely mineralized region amounts to 50 percent of the continental area, and most of it could be mined because the cover depths are only a kilometer or two thick and mines have already reached depths of 5 kilometers or more. The exploration challenge here will be technical, but will also be a challenge to the political will. To make prospecting beneath deep cover possible, governments will need to empower their geological surveys to prepare three-dimensional maps at a level of detail that starts to approach the two-dimensional maps that have been available and used in exploration for about 150 years. If prospecting beneath cover is eventually achieved, there is every reason to believe that the rocks below will be as richly mineralized as those we have been prospecting since mining began. (FIGURES 4 and 5)

We can conclude from these remarks that the magnitude of conventional mineral deposits is sufficiently great so that for the century ahead, and probably for more than a century, scarcity need not be an issue unless we make it so for other reasons, such as environmental concerns or a total breakdown in trade arising from nationalistic forces. The one assumption in this conclusion is that scientific advances will allow us to discover deposits at much greater depth than we can do today.

The Resource Base

Let's now take a closer look at the rest of the resource base. Our greatest body of knowledge concerns the mineral deposits that we actually mine. For the moment, let's forget about them as ores and consider what these deposits are in a scientific sense. They are anomalously high, localized concentrations of one or more chemical elements in the earth's crust. The crust is not chemically homogeneous; geological processes have made it heterogeneous. But even though heterogeneity does not deviate far from the mean, there are nevertheless some small volumes of rock that are highly anomalous in their enrichment of one or more elements, and it is the most anomalous of these concentrations that we mine. An obvious question that we need to ask is "what is the actual range of concentrations in the crust?" Or, as a miner might say, "what are the grade-tonnage relations?" Or, "how does tonnage change as the grade is dropped?"

Curious as it may seem, we know a lot about some aspects of this questions, but very little about others. In particular, there are many gaps in our knowledge of tonnages at grades just below mineable levels. This lack of information was pointed out by John in his paper, quoting work by Don Singer. We know, of course, that low-grade concentrations exist, because one of the most successful techniques used in mineral exploration employs chemistry to detect low-level chemical anomalies as a way to identify a possibly mineralized region. But once an anomalous area is identified, all testing is directed toward a search for high-concentration centers, and little or no attention is paid to testing the low-grade halo. As a result, there is no solid body of data on which to draw, and we therefore have to rely on more anecdotal material. There we run into a dichotomy of thought. Miners and prospectors are eternally optimistic and

they will tell you that tonnages of metal in low-grade deposits are huge. They do so because

most mines have a cut-off grade below which material is unprofitable but they don't test the

magnitude of the unprofitable stuff. To the optimist the material below cut-off is a huge resource

waiting to be tapped. Sam Lasky was one of these optimists and he used data gathered in the

1920s and 1930s as porphyry copper deposits were being studied and mined. Lasky's results

suggest that as grade declines arithmetically, tonnage goes up geometrically. His data all came

from ore grades. Subsequent work suggests that as we go to grades far below ore levels, the

relationship breaks down. People who study the way mineral deposits actually form tend to be

pessimists and are led to conclusions that differ from Lasky-type adherents. They conclude that

the big tonnages of metal are highly localized in high-grade deposits and that low-grade tonnages

are small—they conclude this because ore formation involves focused, or channeled flow of

solutions, rather than pervasive flow, which might give a Lasky-type distribution.

    Many years ago I embodied this thinking in a diagram in which I suggested that a tonnage-

grade plot for a given metal would not have a normal distribution, but rather would have a

bimodal distribution. (See FIGURES 6 and 7) The only test ever made of my suggestion was by

Denis Cox of the U.S.G.S. He turned to the one metal where he thought sufficient data might be

available, copper. The data support, but do not prove my contention. Proof awaits much more

rigorous testing and that is not likely to be done until it becomes necessary to do so.

The Mineralogical Barrier

I don't want to replow too much old ground, but I would like to close with a brief discussion of another point that is all-too-often overlooked—what I call the *Mineralogical Barrier* in the two figures just cited.

When we look closely at any common rock, and the example I use is granite – see FIGURES 8 and 9 – the most common igneous rock of the continental crust, we see that there are only five or six minerals present. And no matter how many granites we look at we always see the same five or six minerals. Those minerals are, quartz, K-feldspar, plagioclase, biotite, muscovite, and magnetite. Note that in these six minerals there are nine chemical elements, Si, Al, K, Na, Ca, Fe, Mg, O, and H. These elements collectively account for 99 percent of the mass of the crust. Now, if we have the rock carefully analyzed we are in for a surprise. The analyst will report the presence of at least 50 or 60 elements, and maybe more if a very sensitive analysis is requested. Most elements will only be present in trace amounts, and search as you will you will not see a mineral containing one of these trace elements.

The reason this happens is that certain atoms resemble each other in size and electrical charges so that they can substitute for each other. (FIGURE 10) For example if we selected biotite for analysis we would find that small amounts of Cu, Zn, Ni, Co, and other elements substitute for the Mg, so the formula would be K(Fe,Mg,Cu,Zn,Ni ...). By this process of atomic substitution essentially all of the scarcer metals in the crust are hidden away in common minerals. In effect, most of the resource base is just common rock.

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There are limits to atomic substitution and those limits are controlled by temperature,

pressure, and chemistry. For each chemical element, and for each mineral, there is a separate

limit, but we can generalize by saying that for conditions attained in the crust, most of the limits

probably fall between 0.1 and 0.01 percent of the element by weight. When the limit is

exceeded, a new mineral will form and that new mineral will contain the element under

discussion as a major constituent.

For example if the limit of copper is exceeded in biotite, it is likely that chalcopyrite,

$CuFeS_2$, will form. This limit of substitution, then represents a sort of barrier to technology.

Above the limit we will find separate ore minerals. Below the limit ore minerals disappear. As

we use up the rich ores, then the buried ores, and then start using the low-grade material, we will

eventually run into a barrier where we have to contemplate pulling a rock apart chemically,

rather than separating it into concentrates of copper minerals and valueless silicates as we do

today. That limit is the mineralogical barrier. It is a very good question to ask what fraction of

an element in the crust is above the mineralogical barrier. There has never been a rigorous test

but geochemical evidence suggests it lies between 0.01 and 0.001% of the amount of an element

in the crust—not much, in other words. Many experiments show that it is feasible to break down

a common rock and recover the chemical elements present, but at what cost? Based on

experiments done by the former U.S. Bureau of Mines we can calculate that just the energy cost

of jumping the barrier in order to process common rock for copper is a factor of 10.

But consider what we will produce. In order to break a mineral apart to get the metals

present by solid solution we will have to degrade the entire mineral. Processing the minerals in a granite this way will produce metals in the proportions present. By taking copper as 1 we can compare what we would obtain from ordinary rock compared to what we use today. Note that we finish with vastly more iron and aluminum than we need relative to copper. (FIGURE 11)

There are many more things we know about the way chemical elements are distributed in the crust and we don't have time to discuss them all, but I hope my remarks tonight give you a flavor of what we geologists think might lie ahead, and why we think so.

Let me summarize:

Firstly, we believe the mineral potential is large enough to satisfy needs under any scenario of growth for the century ahead provided that technology is developed for subsurface prospecting.

Secondly, as we move from conventional ores to the unconventional, low-grade ores will be less in quantity than we might hope; and

Thirdly, as we proceed ever deeper into the resource base we will face discontinuities that prevent smooth expansions, and require instead the development of new techniques and probably large step increases in costs.

USE OF CHEMICAL ELEMENTS

YEAR	ELEMENTS KNOWN	ELEMENTS USED IN SOME FORM
1700	14	14
1900	83	32
2000	87	87

FIGURE 1. Historical use of the chemical elements.

GLOBAL CONSUMPTION OF COPPER AND ZINC

(UNITS: KG/PERSON/YEAR)

YEAR	COPPER	ZINC
1900	0.1	0.1
1999	2.0	1.2
2050	9.5 ?	5.0 ?

FIGURE 2. Comparison of global per capita consumption of copper and zinc for 1900 and 1999. In North America today, per capita consumption is 9.5 kg and 5.0 kg of copper and zinc, respectively. If the global consumption of rose to those levels while the population doubled to 2050, production of new metals would have to be many times larger than all the copper and zinc mined in the world to date.
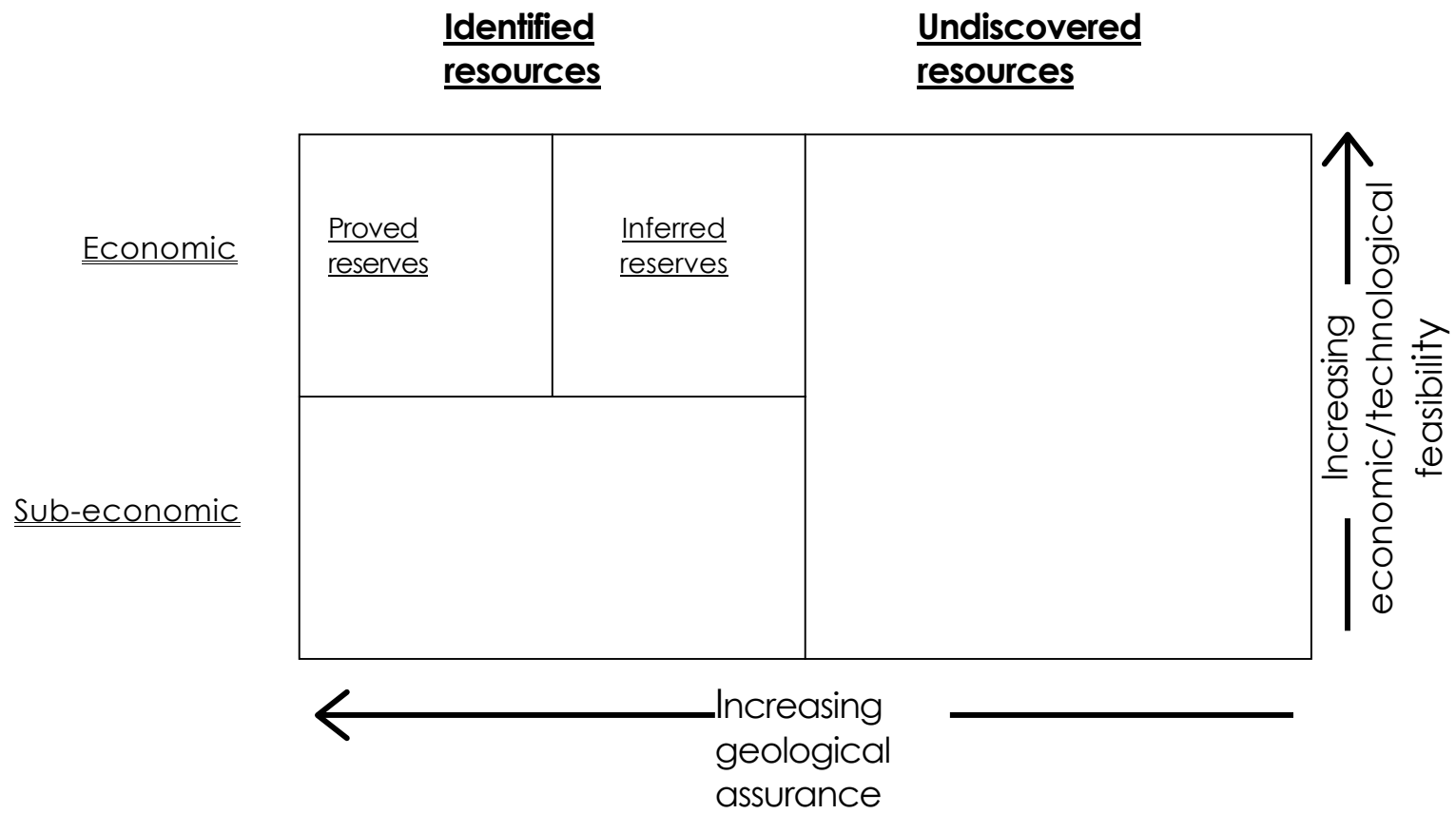
FIGURE 3. Mineral resource classification: simplified version of McKelvey diagram.

FIGURE 4. Map of Central North America showing the outline of the Canadian Shield (dashed line.) Exposed Precambrian rocks in the shield have yielded a great many rich deposits. Below the top dashed line the shield is covered by a barrier of younger sedimentary rocks. The potentially rich shield rocks are within 2 km or less of the surface in the shaded areas.
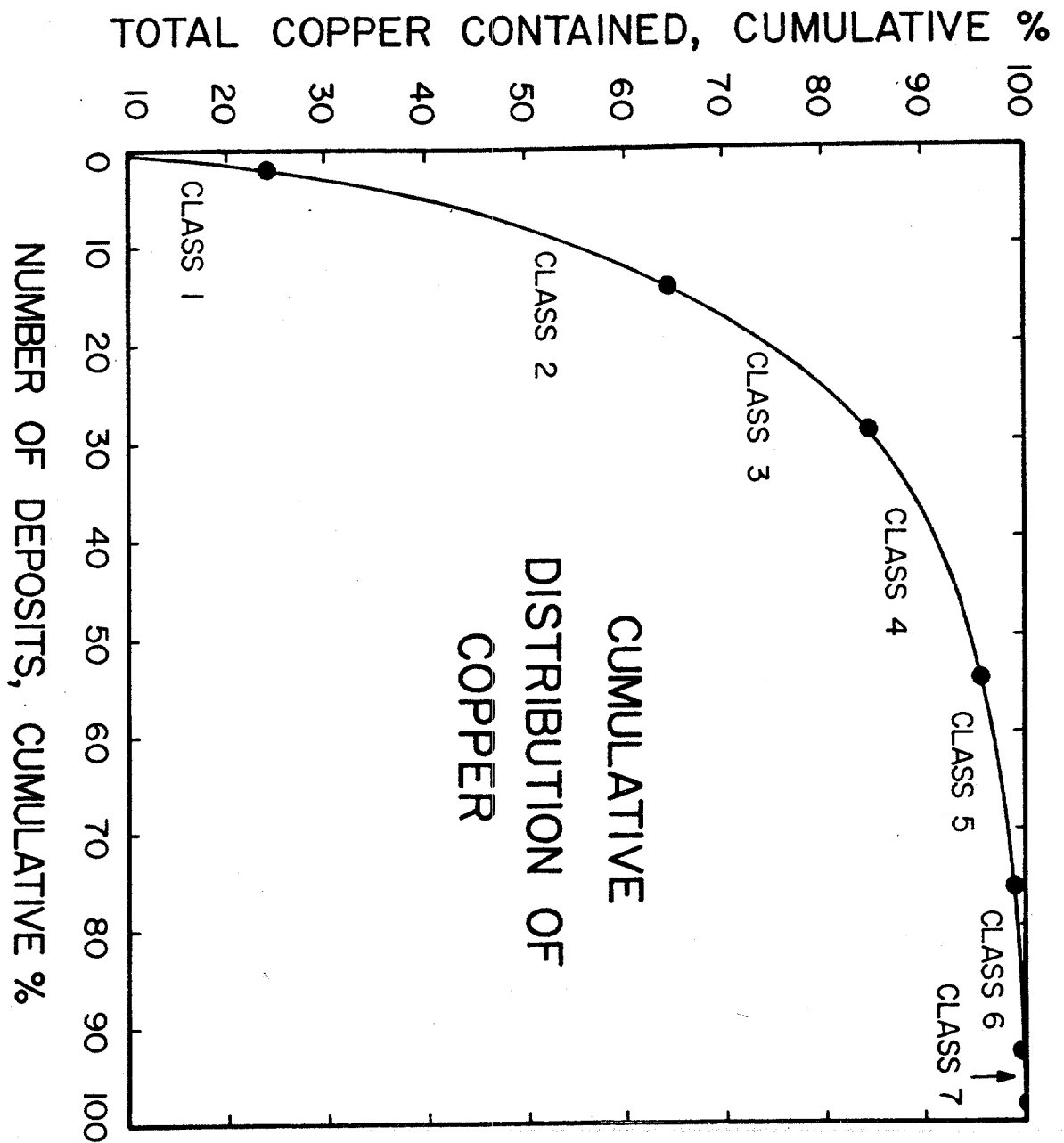
FIGURE 5. Cumulative curve of copper production versus deposit class. Note that 85 percent of the copper is contained in only three classes of deposits (30% of all deposits). It is the largest three classes that would be sought beneath cover.
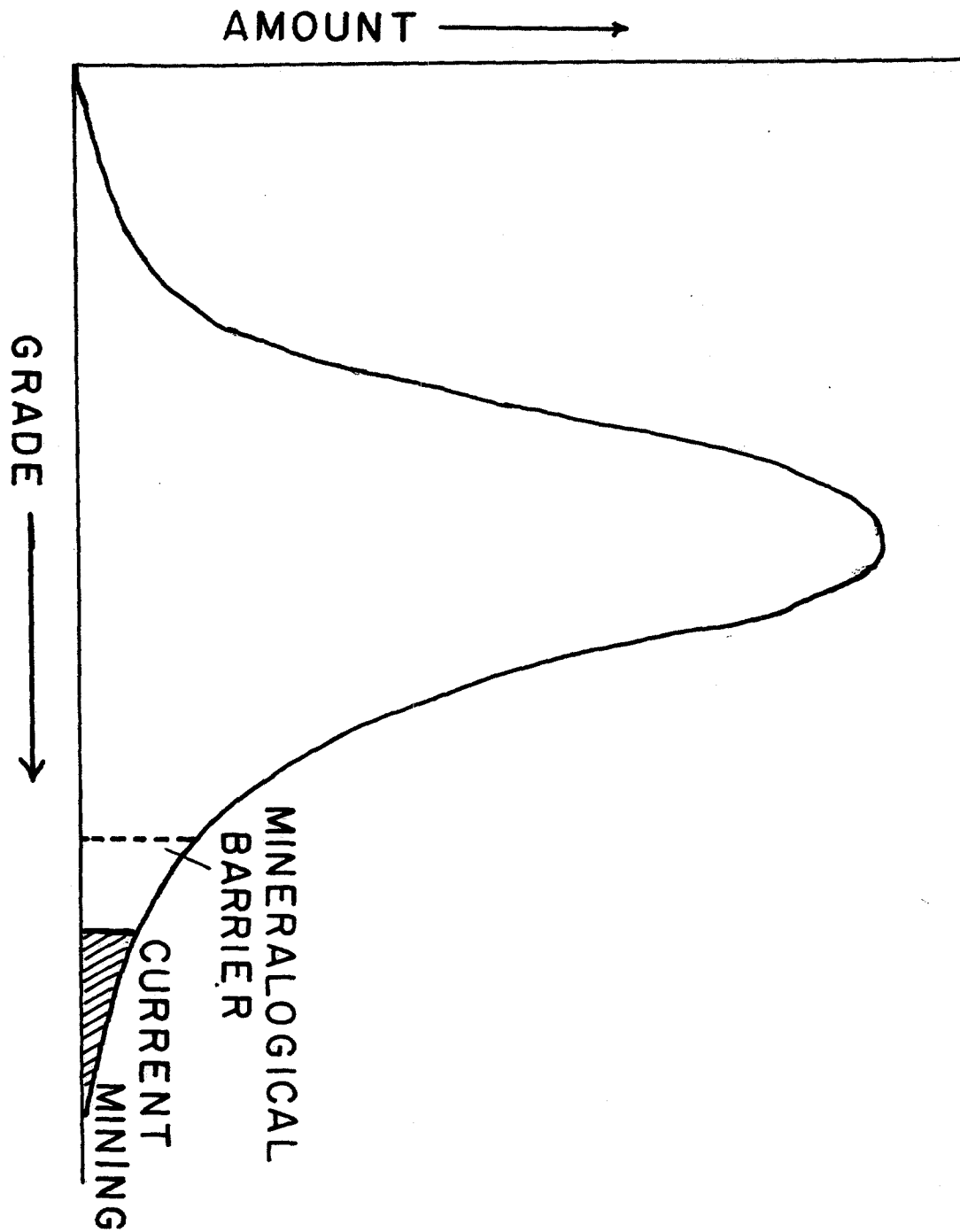
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FIGURE 6. Normal distribution of grade and tonnage. Such a distribution is found for all major metals in the crust—that is, those present at levels greater than 0.1 percent of the crust by weight.
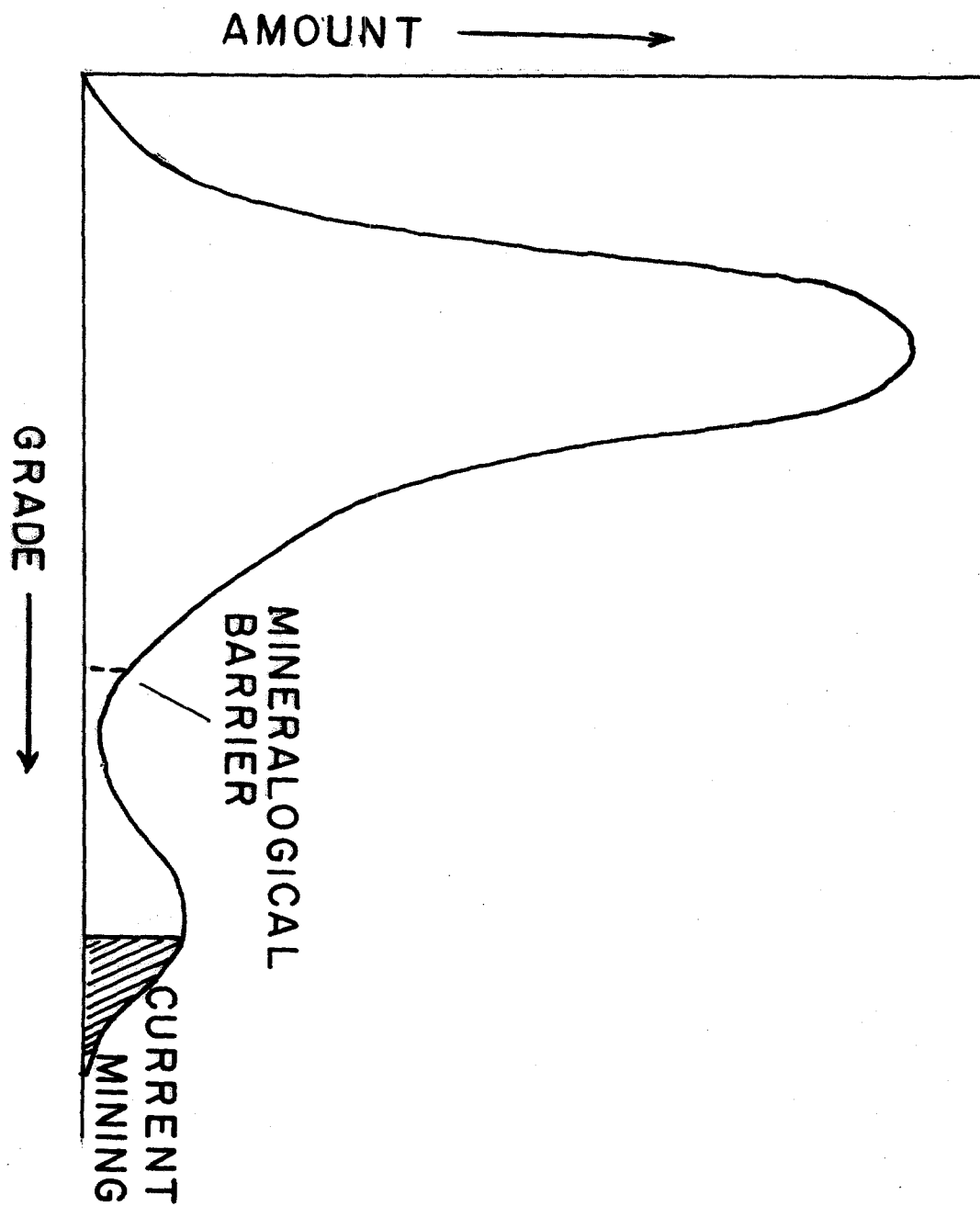
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FIGURE 7. Postulated bimodal distribution of a minor metal (less than 0.1% of crust by weight) that is concentrated as a result of leaching, transport, and deposition by ore-forming solutions.

MINERALS IN GRANITE

Quartz	SiO_2
Potassium Feldspar	$KAlSi_3O_8$
Plagioclase Feldspar	$(Na,Ca)Al(Si,Al)Si_2O_g$
Biotite	$K(Mg,Fe)_3AlSi_3O_{1o}(OH)2$
Magnetite	Fe_3O_4
Elements Present	Si, 0, K, Al, Na, Ca, Mg, Fe, H

FIGURE 8. Common minerals found in granite.

COMPOSITION OF GRANITIC CRUST

ELEMENT	WEIGHT %
Oxygen	45.2
Silicon	27.2
Aluminum	8.00
Iron	5.80
Calcium	5.06
Magnesium	2.77
Sodium	2.32
Potassium	1.68
Titanium	0.86
Phosphorous	0.101

FIGURE 9. Abundance of major chemicals in the earth's crust.

ATOMIC SUBSTITUTION

Biotite $K(Fe,Mg,Cu,Ni,Zn ...)_3 AlSi_3O_{10}(OH)_2$

Potassium Feldspar $(K,Pb) AlSi_3O$

FIGURE 10. Example of atomic substitution of minor metals in common minerals.

PROPORTIONS OF ELEMENTS IN CRUST

(BY WEIGHT)

COPPER = 1

Aluminum	1170	1.85
Iron	850	46.2
Zinc	1.22	0.64
Nickel	1.05	0.07
Copper	1.0	1.0
Lead	0.15	0.25
Tin	0.02	0.017
Silver	0.001	0.0013

FIGURE 11. Proportions of useful metals in average crustal rock (granite), by weight. Proportions are relative to a unit mass of copper. The current global use rates are given for comparison.