Discovery of Natural Resources

Advances in exploration concepts and techniques offer hope for resource supply.

Philip W. Guild

Ore deposits result from igneous, sedimentary, metamorphic, biologic, and weathering phenomena; their sizes, shapes, and environments are extremely diverse. Finding those of substantial lateral extent, which usually are syngenetic (formed together with their enclosing rocks) or concentrated by supergene (weathering) action at or near the surface, commonly presents few problems, once their environment is recognized. This is not to say that the evaluation of their value—the delineation of reserves—does not require an extensive input of time and money, but rather that their existence can often be established by rather simple technology (or by none at all if they crop out at the surface and hence can be found by chance or by prospecting in the traditional sense).

Deposits of many metals and minerals, and, in particular, of the rarer and more costly ones, are epigenetic (formed later than their enclosing rocks) and hypogene (formed by solutions or gases ascending from deep sources that drop their metals in "favorable," commonly very restricted, locations somewhere near but below the existing land surface). If erosion has subsequently exposed these deposits and if they have not been hidden by younger rocks, deep soils, dense vegetation, or other cover, their discovery merely awaits recognition by an amateur or professional searcher. Few such outcropping deposits remain to be found, however, and exploration is rapidly turning to more and more sophisticated scientific techniques.

These techniques may be categorized as geologic—study of the total observable characteristics of the deposits and their settings; geochemical—measurement of traces of elements in rocks, soils, plants, water, or air that may suggest the proximity of a buried deposit; or geophysical—determination of anomalous values of magnetic, seismic, gravitational, electrical, or electromagnetic (radiation) properties that may be due to ore at depth. Modern prospecting combines many techniques, all of which have as their purpose the designation of target areas for the exceedingly costly physical exploration, usually drilling, that must follow if an actual discovery is to be made.

The hardware employed today ranges from scanning spectrometers carried by satellites to mass spectrometers and electron microscopes; computers are increasingly being used to evaluate the data collected.

Theory

Systematic exploration should be based on a genetic model:

1) How did the deposit form?
2) Where were the conditions favorable?
3) What ancillary features of broader extent might aid in zeroing in on the target?

Exploration based on a false model may be successful, for it is the work, not the theory, that leads to the discovery of ore, but, as deposits become more difficult to detect, it is inevitable that the discovery record should correlate positively with the correctness of the model.

On the global scale, plate tectonic theory has brought a degree of order into economic geology by providing a conceptual framework into which deposits of various types can be fitted and their known distribution explained. For example, most, if not all the porphyry deposits occur near converging plate margins on the overriding, continental or island-arc side (Fig. 1). Copper and other metals are known to be present at mid-ocean rifts where new lithosphere is forming; this observation suggests that the initial low concentration might have taken place there, subsequently to be intensified when the ocean lithosphere was subducted, fused, and introduced as magma to produce the extrusive and intrusive rocks with which the deposits are associated. Hence areas known to be situated over active subduction zones, marked by seismic activity (the Benioff planes), are favorable for prospecting, and successful campaigns have been conducted in several areas of the world since this principle was recognized. Older convergent margins can be deduced from the characteristic magmatic products and structural features; these also are useful general guides to the selection of areas for exploration.

Other deposit types, notably of lead, zinc, barite, and fluorite (the so-called Mississippi Valley and related ores), are formed in continental interiors, as are deposits of niobium, vanadium, titanium, the rare earths, and phosphorus-rich iron ores of igneous affiliation. At least some of these deposits seem to be associated with deep, persistent crustal fractures (lineaments) that may be related to the breakup or aborted past fragmentation of the continents. An intermediate group of deposits seems to have features, and plate positions, that combine aspects of subduction- and lineament-related ores. Some recent investigators (*1*) have drawn attention to apparent segmentation of the subducting oceanic lithosphere, which might be inherited from preexisting fractures, and have attempted to correlate ore distribution to the intersections of lineaments and Benioff zones.

Plate tectonics is thus stimulating, even revitalizing, the theory of ore deposition and promises to be increasingly useful as the details are worked out. However, except as a first-order guide for selecting prospecting areas, its role in the discovery of ore bodies is now, and probably will always be, of little practical importance. This conclusion derives from the matter of scale; even the largest epigenetic deposit is minute in relation to an orogenic belt, and understanding why a known deposit is located in a given region of the world does little to pinpoint a buried one. Far more exhaustive studies are required.

Application

Obviously, there is no universally accepted "best" method in exploration; the simplest, quickest, and least expensive method that finds ore is naturally the one to use. As mineral exploration is a highly competitive game in capitalist countries, details of current practices tend to be proprietary, especially as they reflect the exact "mix" of technologies employed. Modern ore search can be likened to a scientific ex-

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← *Courtesy Tilden Plant, Cleveland Iron Ore Company* periment in which one or more models (hypotheses) are compared with the observed facts to evaluate clues that will progressively restrict the volume of rock to be tested with the drill. New methods, combinations of methods, and, in particular, new tools are needed as the deposits remaining to be found become more elusive.

In practice, the explorationist begins by assembling and evaluating all the information available to him about the area under consideration. If this is small, as, for example, within or near a mining district, there may be a wealth of maps, drill hole data, and reports of previous investigators that will require only a fresh point of view to be "read" correctly. Thus Lowell (*2*) found the Kalamazoo porphyry copper deposit in Arizona with the first drill hole at a depth of 2500 feet (760 m) after reinterpreting evidence gathered from earlier studies of the nearby San Manuel ore body. The latter, which cropped out, had been tilted and broken into two approximately equal pieces; most investigators had believed the missing half to have been raised and eroded, or moved laterally an unknown distance, but Lowell correctly diagnosed both fault-plane geometry and the alteration pattern to find the deposit 8000 feet from its original position.

Although geologic maps are now available for most of the earth, those of many regions are at very small scales and give at best only a gross approximation of the actual situation; in any case maps cannot in themselves reveal concealed ore bodies but only suggest favorable places to look.

Remote Sensing

The selection of target areas for detailed ground investigation can be aided greatly by remote sensing from aircraft and satellite. Advantages include speed, the ability to cover areas having poor or no transportation facilities, the synoptic view of larger areas than can be seen from the ground, and the employment of sensors that are not practicable for field use. Most remote-sensing methods are "passive": they record reflected solar radiation (from ultraviolet to infrared) on film or by scanning devices, perturbations in the earth's magnetic field, or gamma-ray emission from radioactive elements. A few are "active": side-looking radar records the reflectance of microwaves ($\sim 10^9$ hertz) emitted from an airplane; the airborne electromagnetic method transmits very-low-frequency (100 to 4000 hertz) radiation from the plane to the ground and detects phase changes or decay times of currents induced in the earth (perhaps by ore deposits). Some may be considered as intermediate: natural fluctuations in electromagnetic fields generated by lightning discharges (100 to 500 hertz) or very-low-frequency (3 to 30 khz) radio transmitters can be measured in low-flying aircraft (*3*).

The Landsat [formerly Earth Resources Technology Satellite (ERTS)] satellites circle the earth in near-polar, sun-synchronous orbits 14 times per day at altitudes of about 910 kilometers. Multispectral scanners (MSS) record the energy reflected in four bands, two in the visible spectrum, 0.5 to 0.6 and 0.6 to 0.7 micrometer, and two in the near-infrared, 0.7 to 0.8 and 0.8 to 1.1 micrometers, across a strip 185 kilometers wide and transmit the data in digital form to receiving stations. Coverage is completed every 18 days. The digital data are converted to black-and-white images which resemble photographs and may be studied directly or converted in various ways and combinations to colored images that can greatly enhance contrasts and emphasize desired features. The satellites cross the equator on their southward passage at about 9:30 a.m. local time; hence, the rather low sun angle and resultant shadows reveal topographic features clearly. Seasonal variations (for example, light snow cover) also are very helpful. A resolution of about 80 meters is adequate for many geologic purposes, and the area that can be observed on a single scene (some 35,000 square kilometers) facilitates detection of linear and curvilinear features that were previously unknown even in well-mapped regions. Because many ore deposits are known or suspected to be localized by lineaments or by intersections of two or more lineaments, or to be near the periphery of circular features that may be of igneous origin, examination of Landsat imagery is being used increasingly as a first step in exploration (*4*). The selection last year of a site for drilling that coincided with the location of a medium-sized porphyry copper deposit in Arizona has been credited to the study of satellite data.

Further computer processing of the MSS data, already on tape, can reveal subtle differences not detectable by visual observation of the standard images. As reflectance is measured for each band of an area (50 by 80 meters) of the surface and recorded as a digital number, ratioing of the numbers for different bands will produce new sets of values. In this way albedo and topographic effects (brighter or darker slopes) are reduced, and response due to absorption bands (chiefly of ferrous and ferric iron, subordinately of other metals and of hydrous minerals) is enhanced. Because much of the critical information is contained in only part of the range of digital numbers, both the original and ratioed values can be "stretched" to increase the contrast still more. Black-and-white images produced from the ratioed, stretched, or ratioed and stretched data are then converted into color composites. Many rock types and, of particular interest for exploration, areas of alteration probably due to mineralizing processes have been distinguished by Rowan and his co-workers (*5*) in the Goldfield mining district, Nevada.

A digital-processing program that compared the spectral "signatures" in the four MSS bands obtained from an unexploited porphyry copper deposit in Pakistan enabled Schmidt (*6*) to make a computer-plotted "map" of the surrounding unexplored region that showed other areas giving similar responses. Of 19 sites subsequently visited, five were found to have sulfide-bearing, hydrothermally altered rock and seem to be parts of porphyry copper systems.

The direct application of satellites to mineral exploration has been most successful in arid, poorly known regions. Future improvements in methodology, and especially in the use of sensors designed specifically for geologic purposes, should greatly improve the already impressive record. Most future discoveries will undoubtedly require, however, the conjunction of several tools, deployed both by aircraft and on the ground.

Low-flying (100 to 300 meters above terrain) aircraft carrying or towing instruments capable of measuring changes as small as 1 part per million in the earth's magnetic field easily detect buried magnetite (Fe_3O_4) deposits, and, because many types of rock contain small but more or less characteristic amounts of accessory magnetite (or other, less magnetic minerals), maps made from the data are immensely useful for refining geologic knowledge, especially in poorly exposed areas. A few nonferrous deposits contain sufficient magnetite to be detected directly, but the principal value of aeromagnetic maps in exploration for most ores is in narrowing the search for favorable areas (which may be studied in greater detail by ground magnetic surveys).

Airborne gamma-ray spectrometers, which can be carried in the same aircraft with magnetometers, can distinguish radiation emanating from elements of the ^{238}U and ^{232}Th series and from ^{40}K, each of geologic significance. Only the uppermost surface materials contribute to this radiation because even very thin cover will effectively stop it; nevertheless, the method can detect exposed uranium deposits directly or suggest areas whose buried deposits are "leaking" daughter products. Monazite, a thorium-bearing mineral, frequently accompanies "black sand" deposits of titanium minerals; such a deposit was found recently in Georgia on the site of an anomaly discovered during the course of an aeroradiometric survey by the U.S. Geological Survey (*7*). Potassic alteration accompanies some epigenetic mineralization; theoretically, a ^{40}K anomaly could be a guide to exploration.

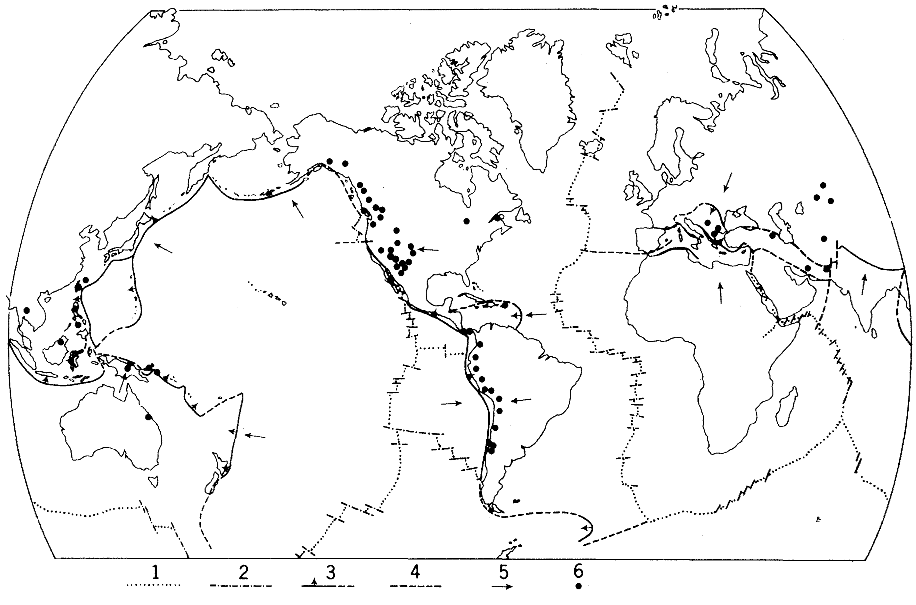

Fig. 1. Distribution of porphyry copper and molybdenum deposits in relation to the major lithospheric plates: *1*, accreting plate margin; *2*, transform plate margin; *3*, consuming plate margin showing the dip direction of the downgoing plate; *4*, margin of uncertain nature or location, or both; *5*, relative plate motion; and *6*, porphyry deposit. [Modified from (*18*), figure 4; courtesy of Springer-Verlag, New York]

Field and Laboratory Studies

As helpful as remote-sensing methods are, detailed ground studies are indispensable to all but the most fortuitous discoveries. These studies embrace too wide a range to treat even briefly here, but the chemical and physical nature, spatial distribution, and mutual relations of the rocks that hopefully contain ore must be worked out to provide the best guidance possible for the physical exploration to follow. Geologic mapping is fundamental; identification of rocks by inspection, chemical analysis, and study of thin sections of rocks in polarized light under the petrographic microscope is routine. Wet chemistry, atomic absorption, emission spectrometry, x-ray fluorescence, neutron-activation analysis, and electron diffraction are used as appropriate to determine the chemical composition of rocks and minerals. X-ray diffraction and both transmission and scanning electron microscopes are increasingly being employed for the identification of mineral phases.

Age determinations are particularly critical to the interpretation of the geology of any area. Paleontology, where applicable, can unravel complex structural situations and also provide clues to the depositional environment (shelf, shallow-water or deep-water marine, lacustrine, or whatever) that may assist in exploration for stratabound deposits. Radioactive age determinations, principally by the uranium-lead, potassium-argon, or rubidium-strontium methods, can often give good results on intrusive and volcanic rocks.

The information gained from field and laboratory is ordinarily plotted on maps; prediction of the third dimension is made on cross sections constructed from all available data. Gravity, seismic, magnetic, and electrical geophysical surveys may be especially useful at this stage to assist in choosing between alternative interpretations suggested by the geologic data.

The explorationist has another tool, geochemical prospecting, that involves systematically collecting hundreds or thousands of samples of rocks, soils, stream sediments, plants, water, or air, analyzing them for one or many elements in the field or laboratory, and examining the results by inspection or, more frequently, by computer-aided statistical methods for anomalous patterns that can guide further work (*8*). Anomalies may be primary, due to the same processes responsible for the ore deposit but extending greater or lesser distances beyond the deposit itself, or secondary, formed more or less near the present surface and completely unrelated to the original mineralizing processes. Both types can give clues to the presence of buried ore.

Primary halos or aureoles may consist of lower grade envelopes of one or more of the metals sought, or they may involve simple or complex additions or subtractions of any of many elements—silicon, potassium, magnesium, iron, sulfur, or others. Oxidation of iron sulfide (pyrite) produces the familiar red staining that led to the discovery of many near-surface deposits in the past; less obvious alteration effects require much more sophisticated geological, mineralogical, and particularly geochemical studies before interpretations can be made.

Studies of the dispersion halos around known districts are indispensable to an understanding of the behavior of the elements during the mineralization process. Analysis of about 2000 samples for each of 30 elements from the Robinson mining district near Ely, Nevada, and subsequent computer-processing of the 60,000 numbers obtained revealed a more or less concentric pattern outward from copper (the chief ore metal) and iron to lead, zinc, and silver, then the more volatile elements, namely, cobalt, mercury, gallium, tin, indium, and thallium. Robinson and his coworkers (*9*, p. 14) concluded that thallium and, to a lesser extent, indium have traveled farthest and may be sensitive indicators of concealed ore deposits.

Geologic events subsequent to mineralization can remobilize and redistribute volatile elements, complicating the patterns but also providing additional evidence for the unraveling of complex structural situations. Thus, halos of sulfur, tellurium, and cadmium are concentric around small intrusive stocks in the Coeur d'Alene district of Idaho that are known to be post-mineralization on the basis of lead isotope and other evidence (*9*, p. 14).

Most geochemical prospecting focuses on the search for secondary halos. These can be in situ, over a still buried body and due to groundwater percolating through or volatiles given off by the ore, or they may extend considerable distances downslope and be detectable in much of the drainage area. The latter situation may be due to partial erosion and subsequent covering of a deposit, to complete erosion of one or more deposits in the recent geologic past, or to some other combination of events. Placer deposits of gold, platinum, diamonds, and other heavy, chemically inert metals and minerals may be considered as classic examples of secondary halos, except that these have frequently been upgraded to economic status from original deposits too small or low grade to be minable, in contrast to most of those sought today, which are orders of magnitude lower.

Remote-sensing extends even to geochemical prospecting, for, although most sampling is done by field methods, airborne instruments capable of detecting mercury, sulfur compounds, halogens, and other volatiles are being developed and tested. Abnormal concentrations of metals in soils cause stress in certain plant species that may be detectable by spectral analysis. Research on these and many other fronts is going on in most of the world.

Fluid inclusions trap samples of mineralizing solutions during crystal growth and are potentially useful as prospecting guides (*10*). Although inclusions are tiny, averaging perhaps 10 micrometers and rarely as large as 1 millimeter in diameter, a surprising amount of information on composition, temperature and depth of crystallization, and source of the solutions can be obtained on heating and cooling microscope stages, by laser-excited Raman spectroscopy of solid, liquid, and gaseous phases (*11*), and by extracting and analyzing the minute quantities of liquid and gas contained in them. Liquids in quartz deposited during the mineralization phase that produced porphyry copper-molybdenum deposits have been shown to be more saline than liquids in other quartz; as quartz resists chemical breakdown during the weathering phase, a study of its fluid inclusions can suggest the existence of deposits even in soils or transported alluvium where metal ions might be completely leached and dispersed (*12*).

In spite of all the help that remote-sensing, geophysics, and geochemistry can provide, sheer geologic reasoning, persistence, and a degree of luck have been responsible for some of the spectacular discoveries of blind ore bodies.

An outstanding example is the Henderson molybdenum deposit in the Front Range 64 kilometers west of Denver, where Wallace headed a team that found ore worth several billion dollars at a depth of more than 3000 feet (*13*). The key was the deciphering of complex, multiphase intrusions and mineralizing events at the similar Climax deposit (*14*) 48 kilometers away and the application of criteria learned there over many years of study to exploration for a deposit suspected of underlying a small outcropping ore body on Red Mountain. The large, deep deposit was not a faulted segment but an entirely new one; the detective work that led to success would more than do credit to any fictional sleuth.

The application of virtually all the methods discussed heretofore to the appraisal of the mineral-resource potential of a large, relatively unknown region is exemplified by a series of maps and short texts on the Nabesna quadrangle, an area of south-central Alaska extending about 150 kilometers west from the Canadian boundary between latitudes 62° and 63°N and covering some 17,600 square kilometers (*15*). The results of sporadic geological reconnaissance studies dating back to 1898 were incorporated into systematic mapping of much of the area at 1 : 63,360 (1 mile to the inch) during the period from 1967 to 1974; this work was reduced to 1 : 250,000 ($\sim$ 4 miles to the inch) and completed with more reconnaissance work to produce the basic geologic map (MF-655 A) for the appraisal. Analysis of about 1350 stream-sediment samples collected during the mapping provided data for geochemical maps showing the distribution of copper, lead, gold, chromium, and cobalt (MF-655 B–F) on a simplified geologic base and for computer-plotted perspective diagrams that emphasize the anomalous areas. Perspective diagrams for silver, lanthanum, molybdenum, nickel, vanadium, yttrium, and zinc showing relationships of the anomalous areas to principal geologic features are on yet another sheet (MF-655 G). An aeromagnetic contour map and interpretation of the anomalies in geologic terms form another pair of maps (MF-655 H, sheets 1 and 2), and a gravity map with interpretation of Bouger anomalies yet another (MF-655 I). The ERTS-1 satellite imagery, computer-processed by ratioing, stretching, and both simulated true- and false-color compositing, was examined for linear and circular features and for color anomalies. The results are shown on both a map and a halftone reproduction of band 4 (0.5 to 0.6 micrometer) imagery with interpretation of the very numerous features detected in terms of their possible relationship to mineral occurrence.

The mineral-resource potential of the Nabesna quadrangle (MF-655 K) was estimated on the basis of known mineral occurrences (and production records, if any), geology, geochemistry, the geophysical and ERTS-derived information, and by assessment of the statistical probability based on the resources of geologically similar, better known regions. Some 25 areas were evaluated and ranked on the basis of criteria that included (i) known deposits, (ii) favorable rock types, (iii) observed surface alteration, (iv) color anomalies in ERTS imagery, (v) alteration suggested by aeromagnetic data, (vi) proximity to intrusives of ages (from isotopic dating) or compositions thought to be favorable, and (vii) the presence of faults or other structures suggested by ERTS, aeromagnetics, or outcrop pattern. Some exploration had already been done by private companies; portions of their results were made available for the government study, which should in turn be very useful for future exploration by industry. A final map (MF-655 L) shows the status of the land (national park or forest, state, native village, or whatever).

The Nabesna quadrangle study is only the initial unit of a program to be extended eventually to the entire state; it can be taken as one example of the nature and range of scientific studies required to provide the groundwork for detailed exploration.

Earth-science research does not have to be directed specifically toward mineral-resource exploration, however, as from time to time important discoveries are made during the course of investigations having entirely different objectives. Undoubtedly the best example in modern times was recognition of the metalliferous brines and muds in the Red Sea deeps (*16*), found during oceanographic work. An older similar discovery was that of the manganese nodules of the deep ocean floor found by the Challenger Expedition.

Summary and Conclusions

Mankind will continue to need ores of more or less the types and grades used today to supply its needs for new mineral raw materials, at least until fusion or some other relatively cheap, inexhaustible energy source is developed. Most deposits being mined today were exposed at the surface or found by relatively simple geophysical or other prospecting techniques, but many of these will be depleted in the foreseeable future. The discovery of deeper or less obvious deposits to replace them will require the conjunction of science and technology to deduce the laws that governed the concentration of elements into ores and to detect and evaluate the evidence of their whereabouts.

Great theoretical advances are being made to explain the origins of ore deposits and understand the general reasons for their localization. These advances have unquestionable value for exploration. Even a large deposit is, however, very small, and, with few exceptions, it was formed under conditions that have long since ceased to exist. The explorationist must suppress a great deal of "noise" to read and interpret correctly the "signals" that can define targets and guide the drilling required to find it.

Is enough being done to ensure the long-term availability of mineral raw materials? The answer is probably no, in view of the expanding consumption and the difficulty of finding new deposits, but ingenuity, persistence, and continued development of new methods and tools to add to those already at hand should put off the day of "doing without" for many years.

The possibility of resource exhaustion, especially in view of the long and increasing lead time needed to carry out basic field and laboratory studies in geology, geophysics, and geochemistry and to synthesize and analyze the information gained from them counsels against any letting down of our guard, however (*17*). Research and exploration by government, academia, and industry must be supported and encouraged; we cannot wait until an eleventh hour to mount a "crash program."

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Technological Insurance Against Shortages in Minerals and Metals

The Bureau of Mines has under way programs on recycling and more economical production of metals.

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The United States is faced with the challenge of producing more minerals and metals from lower grade resources.

The United States has an insatiable appetite for minerals. With but 6 percent of the world's population and only 6 percent of the world's land area, we consume 23 percent of the world's nonenergy minerals. In the last year and a half this pattern of usage has not changed appreciably. Stated in other terms, in the last 35 years we in the United States have consumed more minerals than all of mankind from the beginning of time up to about 1940. The forecast for the future is that in the next 25 years our mineral needs may triple. The supply is deteriorating steadily as demand increases, domestic high-grade ores are being used up, and other nations compete with us for world supplies. To meet this challenge requires a strengthening of U.S. metallurgical processing research and development efforts.

The nation has been a net importer of minerals since World War II. By the year 2000, we may be forced to get more than half of our nonfuel mineral requirements from foreign sources unless we move to increase their availability from domestic sources.

The United States is dependent on imported manganese, chromium, aluminum, platinum, and many other minerals and metals (Fig. 1). For example:

1) We import 90 percent of our aluminum needs, and yet there are unlimited aluminum-bearing resources in the United States in the form of clay and anorthosite. Economically viable processes for recovering the alumina from these resources must be developed to reduce our reliance on imported bauxite.

2) We import 25 percent of our iron and steel requirements, and yet billions of tons of nonmagnetic taconites lie virtually untouched.

3) We import 85 percent of our fluorine requirements, and yet in the processing of phosphate rock we discard more fluorine than we use.

4) We import about 70 percent of our nickel, gold, and silver, and yet we have domestic resources of these metals which also await the development of viable technologies for their exploitation.

5) We import 97 percent of our rutile requirements, and yet we have large deposits of ilmenite which could easily supply our titanium metal and TiO_2 pigment needs.

To overcome these dependencies, in part at least, it will be necessary to make real innovations and take major steps forward in exploration, mining methods and ore transport, processing low-grade resources, improved materials development, substitution and use, and secondary resource recovery. This will result in more efficient use of our resources and also will help ensure an adequate supply of mineral resources in the future.

Bureau of Mines Program

The metallurgy activity has been an integral part of the Bureau of Mines since its formation when Congress established in the Department of the Interior a bureau of mining, metallurgy, and mineral technology. The need for this work has been confirmed by subsequent legislation. To execute the primary charter, the general purpose of the current metallurgy program of the Bureau of Mines is to help improve the nation's minerals and metals posture. Research and development are directed toward providing the scientific and technical information necessary to encourage and stimulate the nonfuel minerals industry to make the expeditious advances in technology that will encourage the private sector to produce an adequate and continuing supply of mineral raw materials at accept-

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