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Selected Mineral Deposits and Their Role as Research Locations for Innovative Mining Techniques

BY Roy H. Grau III and Noel N. Moebs



UNITED STATES DEPARTMENT OF THE INTERIOR



UNITED STATES BUREAU OF MINES

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Information Circular 9445

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cgs	centimeter gram second	Mt	million metric tons
cm	centimeter	nT	nanotesla
Gt	billion metric ton	st	short ton
kHz	kilohertz	t	metric ton
km	kilometer	Ω	gamma
kt	thousand metric tons	%	percent
m	meter	°	degree
m/s	meter per second	°C	degree Celsius

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

SELECTED MINERAL DEPOSITS AND THEIR ROLE AS RESEARCH LOCATIONS FOR INNOVATIVE MINING TECHNIQUES

By Roy H. Grau III¹ and Noel N. Moebis²

ABSTRACT

This U.S. Bureau of Mines (USBM) study examined abandoned mining sites within the United States to determine their potential as mining research locations. The deposits discussed are podiform chromite deposits located throughout the United States and hard-rock titanium deposits of Virginia. Maps detailing preliminary geophysical traverses are presented. These deposits can reduce our dependence on foreign ore supplies and decrease deficiencies during national emergencies.

This report also addresses a recently completed USBM project in innovative mining called "Selective Borehole Slurry Mining." The technique is founded because many mines must mine, transport, and process large amounts of material relative to a small amount of valuable ore. The method incorporates advantages such as selective ore extraction, reduced capital costs, and relocating workers from hazardous conditions. A needed component of the innovative mining system is a measurement-while-drilling system. This system will provide a path for the slurry miner to follow while pinpointing the areas of highest mineral concentration in the borehole. Its applications will also provide mine operators with instantaneous data on what lies immediately ahead of the present mining location.

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INTRODUCTION

The U.S. Bureau of Mines (USBM) compiles data on 87 important nonfuel mineral commodities (1).³ Seventy-four of these mineral commodities are either mined in the United States in enough quantity that we do not import them or they are obtained by reliable foreign sources. Of the remaining 13 minerals, chromium, cobalt, manganese, and platinum have a major influence on our economy. Over 70% of the world's production of these minerals is from the Republic of South Africa or a politically unstable source (2). Individually, no single technological approach can solve our dependency on strategic minerals from foreign countries. Depending on the mineral, many solutions such as stockpiling, recycling, substituting, and developing other mineral sources will help. In addition, by providing favorable economic mining conditions, the exploitation of domestic reserves will increase.

In recent years, the USBM has been investigating various novel mining methods to replace standard drill and blast operations. This work supports the USBM mission to develop innovative technologies to make better use of domestic mineral resources. The need for this is clear as portrayed in several past studies. Some time ago, the U.S. House of Representatives Subcommittee on Mines and Mining of the Committee on Interior Affairs concluded that for certain minerals our dependency results from domestic mineral industries no longer being competitive in world markets (2). The report concludes that domestic mineral industries are burdened with several disadvantages. One leading problem is that domestic companies must adhere to stricter environmental restrictions. Several of these same issues were also addressed by the USBM in "Issues, Trends, and Needs in the U.S. Mining Industry: A Mining Research Perspective"⁴ and in "Project 2000."⁵ The former report focused on 11 issues that hampered the U.S. metal/nonmetal mining industry. The top issues were complying with environmental regulations, the need for innovative mining systems, and the need to develop large mineral reserves present in public lands. The report states: "The environmental issues of mining are not going to leave; the mining industry must comply with regulations in the most cost-effective manner and use mining systems that minimize environmental impacts."

Both USBM reports emphasize that the USBM must conduct research to develop new mining technologies that reduce damage to the environment. The reports also

emphasize the need for industry to lower production costs and become more competitive with international producers. The USBM reports also emphasize the importance of gaining access to restricted public lands for exploration and development purposes. A major research effort is needed to study mining systems that minimize environmental impacts and promote complete land restoration. Such a system would justify opening restricted areas for mining.

The subcommittee study and the two USBM reports prove that the U.S. mining industry needs technological advances to economically produce minerals, especially strategic minerals, in an environmentally safe manner. Domestic production aimed at eliminating foreign sources would be difficult, if not impossible, to achieve. However, it would be beneficial to have a means to exploit domestic ores during a national emergency.

This Information Circular describes locating, investigating, and performing the preliminary evaluation of test sites at eastern U.S. mineral deposits for novel mining experiments. The proposed test experiments on these sites involve selective borehole mining and remote in-hole mineral identification during drilling. Many deposits were carefully evaluated locations to be considered for a test site. Literature searches and correspondence with industry and government officials were conducted concerning dozens of prospects and mines. The most promising sites were selected, and preliminary field studies were performed. Two restrictions were placed on site selection. First, the deposit needed to be small, but high-grade. In current markets, minable deposits are large, whereas smaller deposits are usually ignored. Although large deposits are often unavailable in the United States, the combined tonnage of small deposits is significant. Second, although not essential, priority was given to mineral deposits formally considered strategic and critical. A strategic mineral can be defined as a mineral for which the quantity needed for essential civilian and military use exceeds the source domestic and foreign supplies as the acceptable substitutes are not available within a reasonable time.

From the deposits reviewed, 16 cases resulted in field trips to the sites in the Eastern United States (figure 1). The deposits contained the strategic and critical minerals of cobalt, chromite, rutile, manganese, and beryl, as well as gold, lead/zinc, zirconium, topaz, and tantalum. Certainly, there are many other sites that have not been investigated, particularly in the Western United States. The authors believe that the most important sites visited for this study were chromite podiform and rutile/ilmenite deposits.

³Italic number in parentheses refer to items in the list of references at the end of this report.

⁴U.S. Bureau of Mines. *Issues, Trends, and Needs in the U.S. Mining Industry: A Mining Research Perspective*. Sept. 1987, 106 pp.

⁵U.S. Bureau of Mines. *Project 2000, A Strategic Plan for the USBM*. 161 pp.

During the field studies, ore samples were taken, ownership records were found, landowners were contacted, and some geophysical electromagnetic (EM) and very low

frequency (VLF) field surveys were conducted. This enabled USBM researchers to better understand the problems in fully delineating these sites.

SELECTED STRATEGIC AND CRITICAL MINERAL DEPOSITS

VIRGINIA RUTILE AND ILMENITE DEPOSITS

Titanium dioxide is an important source of pigment and whiting agent in paper, plastics, and rubber manufacture. The coatings industry is by far the largest user of titanium dioxide, followed by the paper and plastics industries. Approximately 93% of the rutile consumed in the United States is for titanium dioxide pigment. Titanium is a valuable alloy for aircraft metals because of its strength-to-weight ratio and high-temperature stability. Welding rod coatings as well as miscellaneous applications, including titanium metal, consume 7%. Titanium is obtained from either the titanium oxide rutile or the lower-grade iron titanium oxide ilmenite. Rutile is used to produce both

titanium sponge and pigment; ilmenite is used chiefly to make pigment. Ilmenite substitutes are available, but they are not as desirable a product and their cost is restrictive. The United States imports nearly 60% of its titanium needs from Australia. The imports are in rutile, ilmenite, and synthetic rutile derived by processing ilmenite. Titanium is also imported from Sierra Leone, Canada, and the Republic of South Africa. Rutile and ilmenite imports during the 1989-93 period ranged from 226 to 310 kt and 462 to 615 kt, respectively, as shown in figure 2.

U.S. titanium mineral production comes almost exclusively from placer deposits at Trail Ridge, Green Cove Springs, and Highland, FL. A similar placer deposit approximately 80 km south of Richmond, VA, is being developed, and ilmenite mining could begin within 2 years. Titanium processed from rutile results in far fewer environmental problems than from processing ilmenite. For each ton of titanium dioxide produced, a rutile feed creates approximately 0.2 t of waste, whereas ilmenite produces approximately 3.5 t of waste. The environmental consequence of converting ilmenite to pigment is much greater than separating the ilmenite from the quartz sands during placer mining. During placer mining, waste sand can be readily returned to the mined-out void and the area can be regraded and seeded. However, even with this reclamation record, there is continual pressure to curtail this type of mining.

An area of interest for mining test purposes is the Roseland anorthosite-titanium belt of west-central Virginia (figure 3). At one time, this district supplied the world with titanium. All mining operations in the district ceased

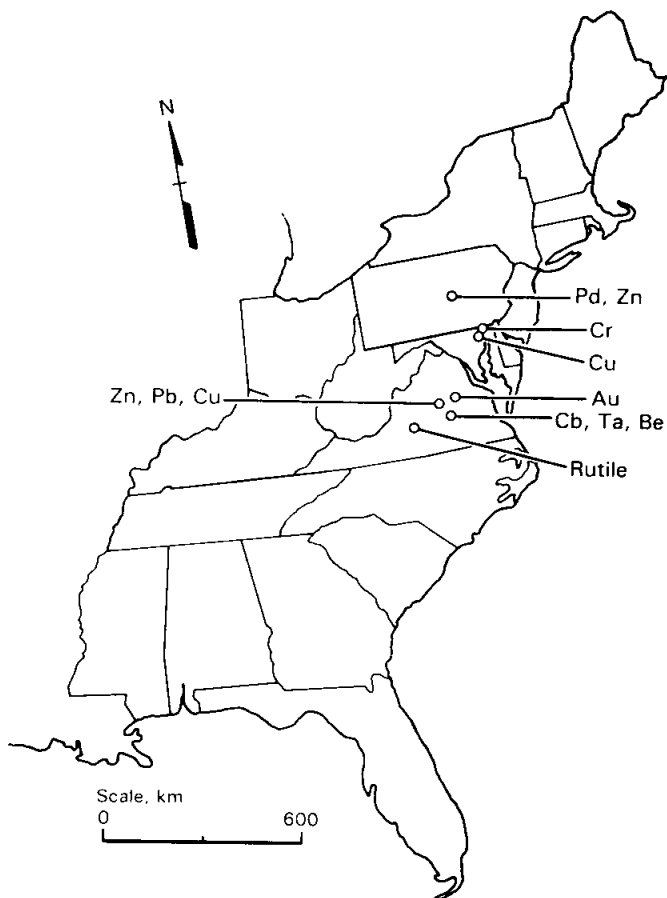


Figure 1.—Field sites investigated by the USBM for this study.

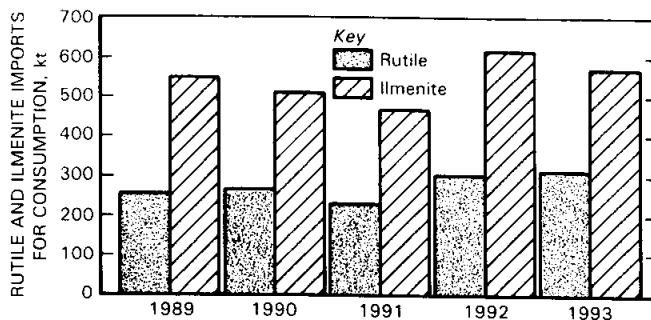


Figure 2.—Domestic rutile and ilmenite imports for consumption from 1984 to 1988.

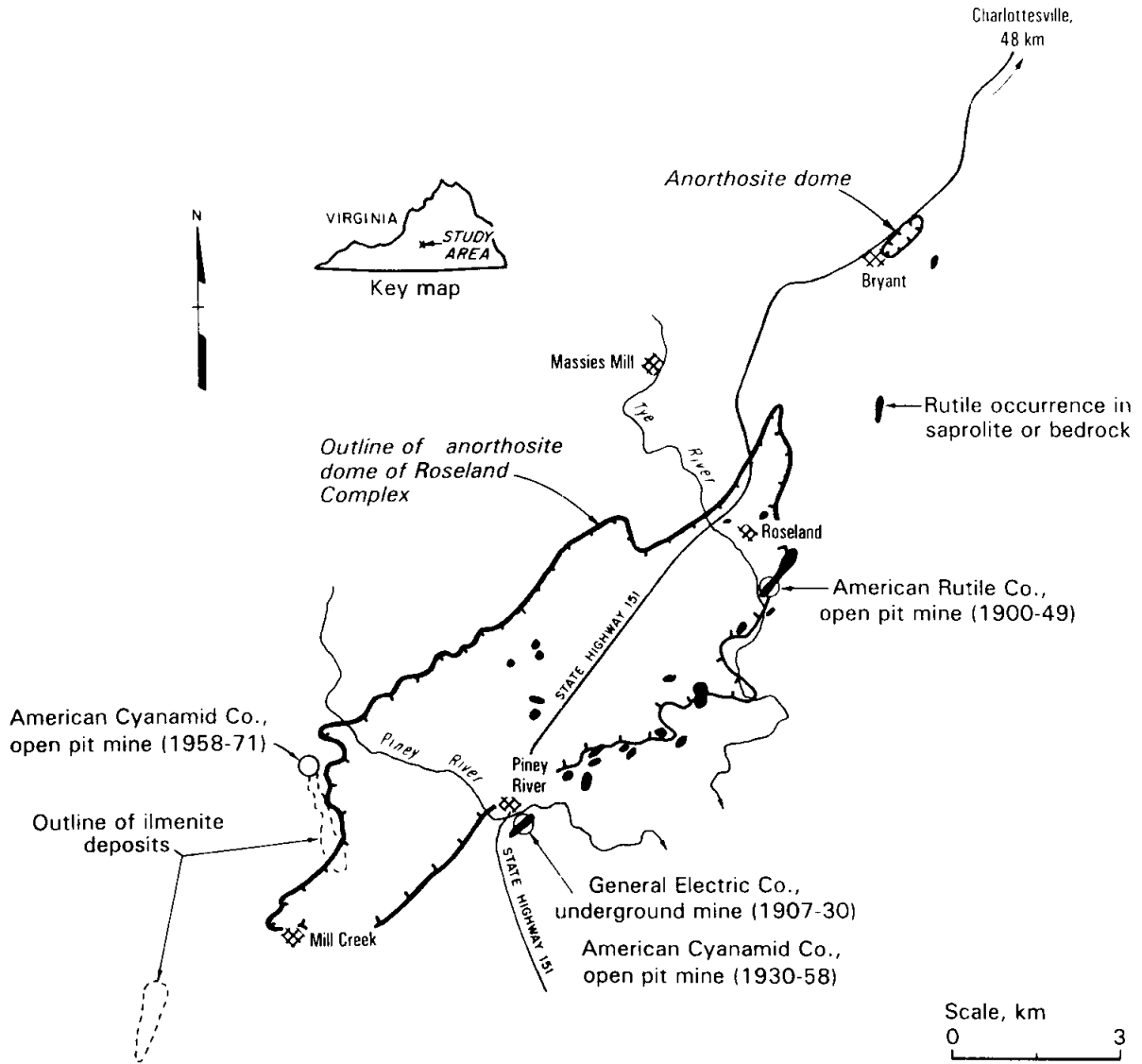


Figure 3.—Extent of Roseland anorthosite-titanium belt with Virginia index map.

in 1971 because of competition from Australian beach sands. Although the district is currently inactive, its titanium resources may at some time be feasible to exploit under favorable conditions. The area is located in the foothills of the Blue Ridge Mountains in Nelson and Amherst Counties, VA. It lies approximately 145 km west of Richmond, VA, and 55 km southwest of Charlottesville, VA. The district lies along the boundary between the Blue Ridge physiographic province to the northwest and the Inner Piedmont physiographic province to the southeast. The area is easily accessible by State Highway 151, which runs through its center. A large portion of the land is cultivated; most of the remainder is second-growth timber. The belt is approximately 26 km long, with a

maximum width of 5 km. The Virginia Blue Ridge Railroad had its northern terminus at Piney River near the center of the district, but was dismantled in 1985.

Lying along the southeast margin of the Blue Ridge Mountains, the district's rocks are predominantly Precambrian age. An elongate northeast-trending anorthosite dome approximately 14 km long by 3 km wide is the district's major structure. The anorthosite is made up chiefly of andesine with minor oligoclase, microcline, and quartz. The anorthosite dome's outline is irregular. It is bordered on the northwest by the Shaeffer Hollow granite consisting of blue quartz, microcline, and plagioclase. The dome is bordered on the southeast by a banded granulite gneiss containing garnet, graphite, and blue quartz.

Locally, the dome is bordered on the southeast by the Roses Mill rock unit consisting of a biotitic augen gneiss. Foliation and banding are common in nearly all rocks bordering the anorthosite dome.

A thick mantle of saprolite and colluvium obscures much of the underlying geology and covers the district. Rock outcrops are rare and are generally found only along the major streams, road cuts, and quarries. The anorthosite country rock is nearly pure feldspar and was quarried for many years near Piney River. The processed rock was called apalite and was used to manufacture glass container and glass wool insulation.

In 1913, Watson and Taber (3) published one of the first comprehensive reports on the district's titanium deposits, most of which is still valid. Studies were conducted independently in this area by the USBM in 1963 and the U.S. Geological Survey (USGS) in 1987. The USBM performed a reconnaissance of at least 20 titanium-bearing mineral deposits in or associated with the Roseland anorthosite (4-5). The studies revealed that the Roseland District's nelsonite deposits vary in grade and are small deposits for mining. Many of them are lenticular and pinch out at shallow depths, although some may extend to greater depths. Reserves of the area excluding placer deposits are estimated at 1.1 Mt of rutile and 12.2 Mt of ilmenite (6).

The titanium in the district is generally found in four forms:

1. *As course-grained disseminated rutile near the southeastern border of the anorthosite dome.* A deposit such as this was mined by open pit at Roseland by the American Rutile Co. in 1900-49 (figure 3). The ore grade averaged 2.4% rutile and 4.9% ilmenite according to Fish (4) and Herz and Force (6).

2. *Occasionally, as rutile in narrow, steeply dipping dikes.* Some rutile-rich dikes at Piney River were mined by the General Electric Co. in 1907-30.

3. *Occurring in saprolite, which overlies the higher-grade portions of the gneiss and anorthosite.* Ilmenite mining from these type deposits accounts for most of the titanium produced in the past from this district. There has been little transportation of this material, which ranges from 3 to 37 m thick. Overburden is seldom more than 3 m thick. Fish (4) estimated an average grade of 7.0% titanium dioxide for this ore type. There were two major saprolite mining operations in the district. The American Cyanamid Co. had an open pit at Piney River (1930-58) near the anorthosite dome's eastern border. The second open pit was at St. Mary's Church (1958-71) near the western border of the dome (figure 3).

4. *In ilmenite nelsonite dikes.* The term "nelsonite" is primarily used to describe ore bodies composed of a granular mixture of ilmenite and apatite. The term is also applied to granular mixtures, which include apatite,

magnetite, hornblende, rutile, biotite, zircon, and ilmenite. The name was derived from Nelson County, VA, where the ore was first identified.

Nelsonite is a heavy, dark ore with an even-grained "salt and pepper" texture (figure 4). The ilmenite nelsonite has a black and white spotted appearance that contrasts to rutile nelsonite, which has a similar, but darkish brown appearance. Ilmenite nelsonite analyses range as high as 70% ilmenite (5). Upon weathering, this ore develops a characteristic pitted surface. The dikes occur chiefly near the anorthosite margins and in the surrounding gneisses and granulates. The nelsonite dikes are generally tabular, but may be very irregular, lenticular, and steeply dipping. The dikes have been traced along strike up to 460 m, and the widths range from centimeters to 15 m. Occasionally, nelsonite contains zirconium in substantial amounts. The dike at USGS locality No. 26 (6) showed 0.18% zirconium. The Zion Hill Church dike, described later in this report, contained 0.02% zirconium.

Nelsonite dikes are more resistant to weathering than most of the country rock. Float rock occurs along the crests of several low topographic ridges. This suggests that narrow dikes underlie and form the core of the resistant ridges. Nelsonite dikes were prospected by trenches, shafts, and an occasional drillhole earlier in the 20th century, but none were exploited except those at Piney River. Here, the small rutile-rich dikes were mined underground, whereas the upper weathered portion of a large ilmenite nelsonite dike was mined by open pit.

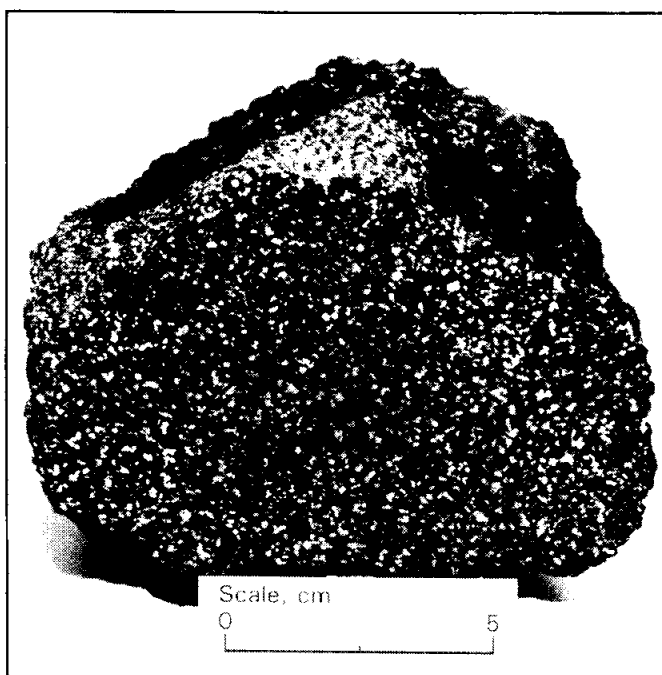


Figure 4.—Ilmenite nelsonite sample showing typical "salt and pepper" texture.

GEOPHYSICAL INVESTIGATIONS

The USBM performed surface geophysical measurements at two sites in the district to find their potential for delineating nelsonite dikes. The two sites selected were the Johnson dike on State Highway 151, 14 km north of Piney River, and the Zion Hill Church (or Boyd) dike at Bryant on State Highway 151, 13 km north of Piney River (figure 5). The Orchard Hill dike, also shown in figure 5, was not studied in detail, but illustrates the typical diversity in strike of nelsonite dikes within a small area. At the Zion Hill Church dike (figure 6), geophysical surveys of ground resistivity, very low frequency (VLF) electromagnetic and magnetic, were performed. Only a magnetic survey was conducted at the Johnson dike because of the favorable results obtained by this method at the Zion Hill Church site. This coincided with an extensive literature search and laboratory tests performed on nelsonite samples. Both suggested that a magnetic method is most appropriate for detecting ore. The results of the laboratory tests on granulite gneiss, anorthosite, and nelsonite ore samples from the sites are shown in table 1. The contrasts

in magnetic susceptibility and resistivity are apparent. Although ilmenite is nonmagnetic, it often contains small magnetic intergrowths that impart magnetic properties to the ore. This creates the likely scenario that the dikes can be outlined by magnetic surveys.

RESISTIVITY METHODS

The electrical resistivity method for subsurface studies has proved itself to be among the most effective means of shallow subsurface investigation. Resistivity is a fundamental property of earth materials determined by introducing electrical currents into the ground using two electrodes. The resistivity is calculated from the potential gradient measured between the electrodes. Because the electrode spacing can be held constant when moving from station to station along a traverse line, lateral changes at the same depth can be determined. Because the electrical conduction in rocks is essentially electrolytic, the formation resistivity depends on the percent moisture saturation and the nature of the electrolyte. Saturation depends widely on the deposit's porosity and the presence of joints. The nature of the electrolyte can also vary widely.

The resistivity equipment used in this study consisted of a portable Soiltest R-50 Stratameter designed for 183-m maximum penetration. During this study, the depth to bedrock was shallow, so a resolution of a few meters probably was achieved. In the Roseland area, the nelsonite dikes are seldom covered by more than 3 m of weathered overburden, except under valley fill material.

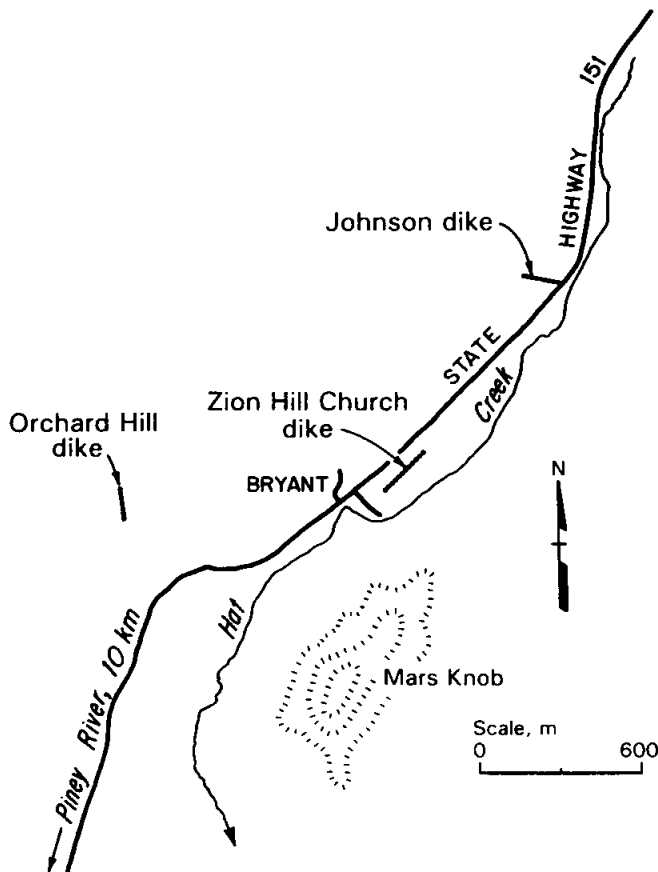


Figure 5.—Ilmenite nelsonite dikes in a portion of the study area.

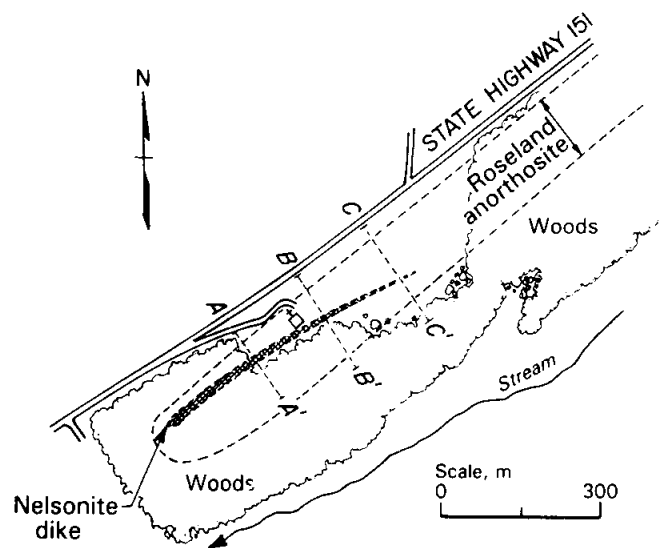


Figure 6.—Zion Hill Church ilmenite nelsonite with geophysical traverses.

Table 1.—Laboratory results from geophysical tests performed on rock samples from Virginia anorthosite-titanium belt

Material	Shore hardness	Magnetic susceptibility, 10×10^{-6} cgs	Specific gravity	Resistivity, $\Omega \cdot m$	Sonic velocity, m/s
Anorthosite	74	0	2.8	50,000	4,306
Granulite	—	0.07	2.7	40,000-170,000	5,455
Ilmenite	38	0.27	4.6	4	8,420
Nelsonite	11	0.33-0.44	3.8	35,000-55,000	4,086

VERY LOW FREQUENCY METHODS

The very low frequency (VLF) electromagnetic method of study uses radio transmissions from a worldwide naval submarine communications network. These transmissions induce secondary electromagnetic fields in and around subsurface conductors, such as some ore bodies, aquifers, and pipelines. Faults can be detected where rock on one side of the fault is more conductive than on the other or where a fault or fracture zone has conductivity different from adjacent units. Reportedly, even individual shear zones or joints filled with wet clay are detectable at shallow depths. Buried pipelines and cables are easily detected and are often unexpectedly encountered in the Appalachian region, even in seemingly remote areas. Elevated power transmission lines induce strong signals in the VLF equipment within 60-m proximity.

The VLF method provides a high resolution of subsurface conductors to depths of about 45 m, a far greater depth than required for the current study. The VLF unit used in this study, a Geonics Ltd. EM-16, is a portable receiver with two built-in coils—one with a vertical axis, the other horizontal. These are used to measure the in-phase and out-of-phase components of the secondary electromagnetic field. A null in the signal from the vertical coil is attained by tilting, and the tilt angle is read on an inclinometer. A quadrature (out-of-phase) component of the signal from the horizontal axis is measured by adjusting a control knob. The operating frequency of this unit ranges from 15 to 25 kHz.

MAGNETICS

Magnetic methods have a long history. They have been used to investigate a large variety of geologic features, including ore bodies. Therefore, the capabilities of the method and equipment are well established, and references on case studies are plentiful. However, unless adequate geologic control or other independent information is available, no data interpretation can provide a unique, foolproof conclusion. Fortunately, in the Roseland District, the nelsonite dikes outcrop, so depth determination was unnecessary, although some project beneath shallow valley fill. The existence of dikes that do not outcrop is conjectural, but could be a major factor in attempting to assess the district's nelsonite ore reserves. In addition to outcropping, the Johnson dike was partially core-drilled approximately 60 years ago. This information was helpful and provided the geologic control for magnetic data correlation with the dikes's subsurface character. The Zion Hill Church dike, although never core-drilled, was trenched and mapped. That information provided some measure of geologic control for the present study. The equipment used in this study for measuring the total magnetic field was a Scintrex Omni IV portable proton precession magnetometer. The Omni IV operates in a dynamic range of 18,000 to 110,000 nT with an absolute accuracy of 2 nT over total temperature range.

GEOPHYSICAL TRAVERSE RESULTS

ZION HILL CHURCH (BRYANT) DIKE

The Zion Hill Church dike trends N. 40° E. and is bordered on each flank by anorthosite (figure 6). The ore body is plotted where it was observed. Three geophysical traverses were conducted across the dike and were oriented perpendicular to the dike's length using magnetic,

resistivity, and VLF methods. These results are summarized in figure 7. During traverse A-A', the nelsonite dike's outcrop was observed, and the magnetometer responded with a magnetic anomaly of about 800 nT above background. This was near the dike's widest portion. The total field magnitude returned to near normal background approximately 30 m on either side of the peak. Resistivity

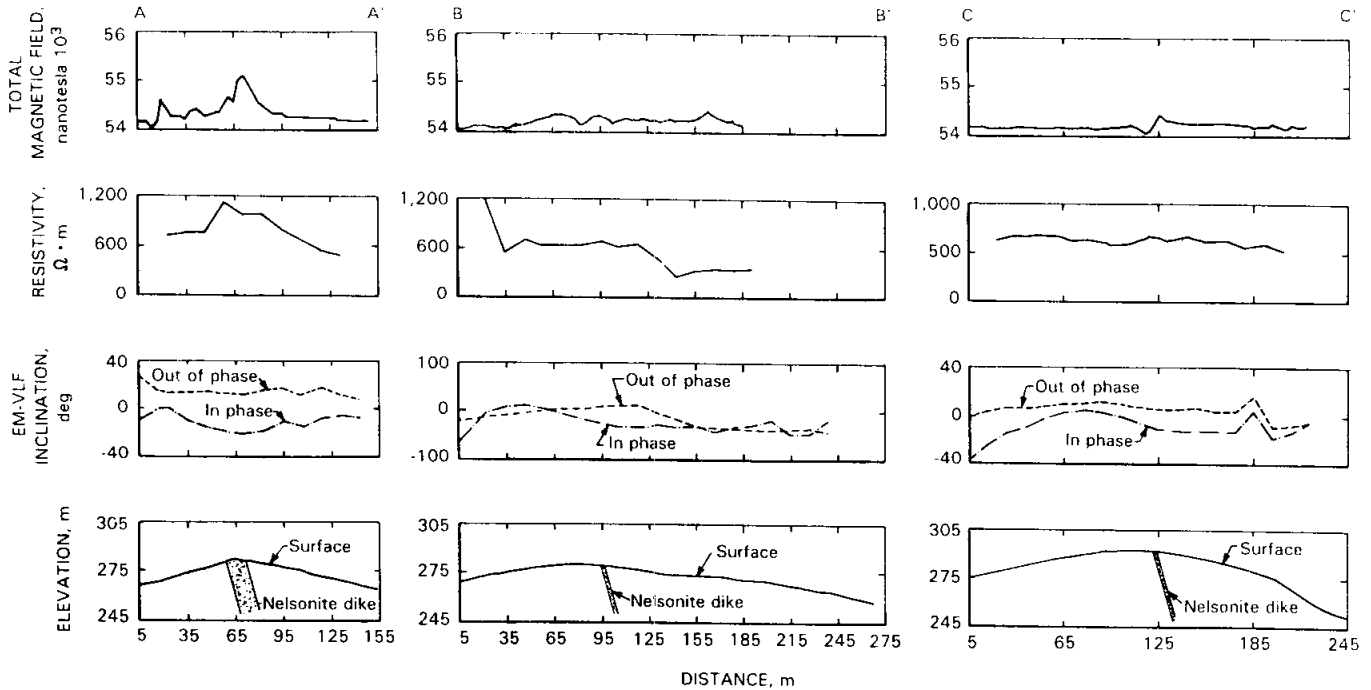


Figure 7.—Zion Hill Church geophysical profile A-A', B-B', C-C'.

showed a broad anomaly on traverse A-A' of about 400 $\Omega \cdot m$ magnitude above background. The VLF results were largely inconclusive, but suggest the absence of any conductive material closely associated with the dike. The results along traverse B-B' were almost entirely insignificant probably because at that portion the dike had narrowed considerably and split into several narrow dikes. On traverse C-C', only the magnetic results give an indication of an underlying dike despite apparent thinning. Furthermore, the shape of the curve is what is expected for an isolated magnetic body at this latitude—a small magnetic low just north of the magnetic high. It is interesting that the average magnetic field was greater on the left portion of the survey (from the ore body to C'). This may suggest a different type of country rock. From this survey, we believe the ore body was starting to pinch out at the C-C' location. A steep southeastward dip also is suggested by these measurements and agrees with field observations. Laboratory studies (table 1) show that the country rock anorthosite has a much higher resistance than the nelsonite. However, data from the resistivity survey show that the resistance is actually higher on the dike. This can be attributed to the fact that the anorthosite is in an advanced state of weathering and thus a much finer matrix that contains moisture. The nelsonite, by contrast, is weathered only to the point of large fissure, like cracks due to freeze-thaw action.

These cracks allow for high permeability in the ore body, good drainage, and thus high resistivity. This

indicates that resistivity has potential for detecting the ilmenite-nelsonite dikes in anorthosite country rock. From this data, we can conclude that the ilmenite-nelsonite ore bodies will provide a discernible response for geophysical equipment measuring resistivity and magnetics. As previously indicated, the magnetic response is due to the magnetite intertwined with the ilmenite and not the ilmenite itself. The resistivity difference is believed to be due to the difference in moisture content.

JOHNSON DIKE

The Johnson nelsonite dike was discovered and partially core-drilled early in the 20th century by the Burgess Titanium Co. A 12-m shaft was sunk on the dike (figures 8 and 9), and some exploratory trenches were dug to expose the dike. The dike trends N. 80° W. (figure 8) and cuts across a northeast-trending contact between a banded granulite and a granite gneiss, which both contain abundant blue quartz. The dike dips steeply to the north. It is thickest near the shaft, thins to the west, and pinches out to the east near Hat Creek. The depth extension is unknown. Several meters of residual soil and nelsonite float cover much of the dike.

Magnetic measurements at 3-m intervals were conducted across the dike along four traverses. The results are summarized in figure 10. Magnetic profile C-C' shows a pronounced anomaly of over 1,500 nT directly over the outcrop of the dike near the shaft. A weaker,

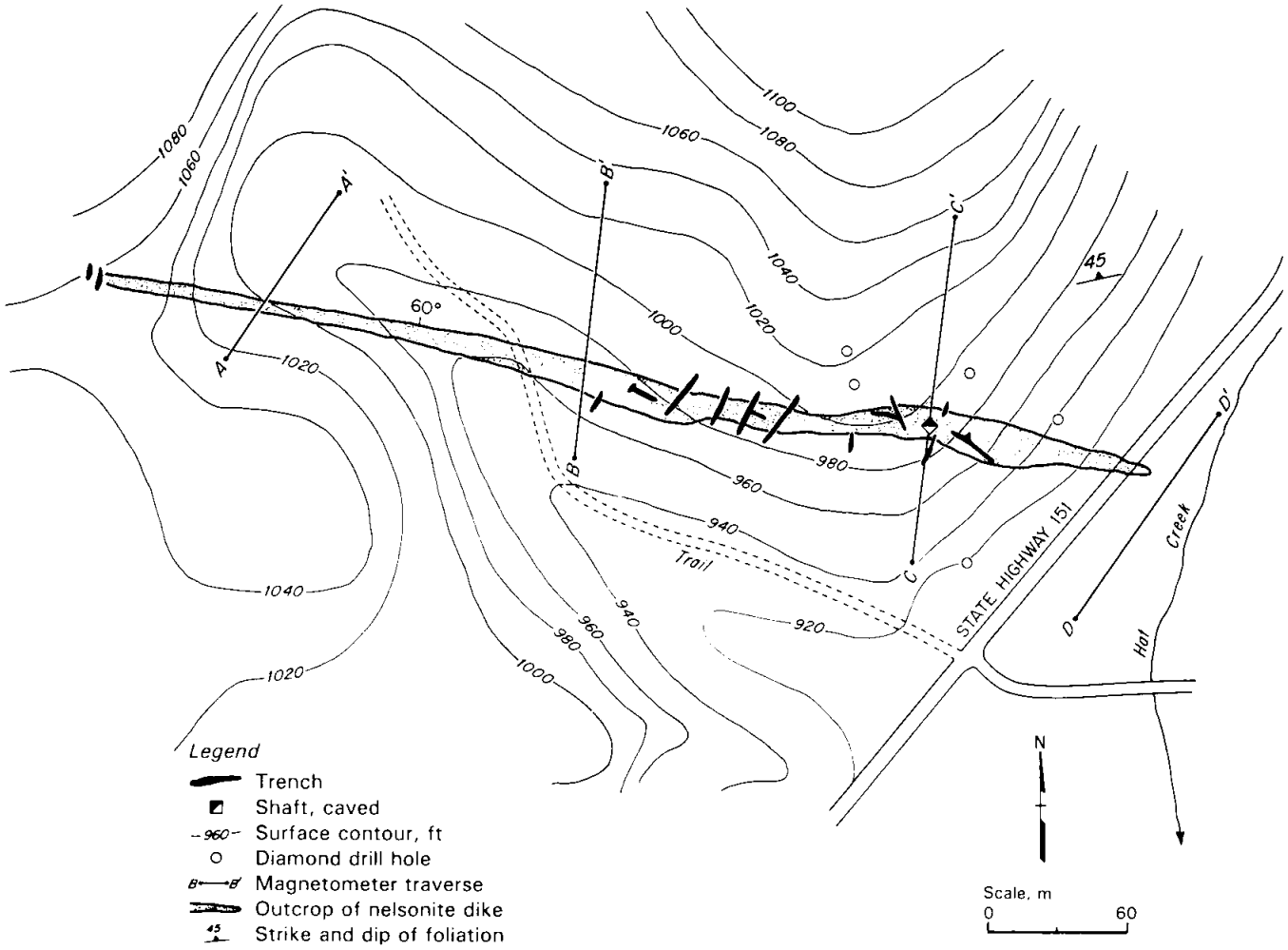


Figure 8.—Johnson ilmenite dike with traverses.

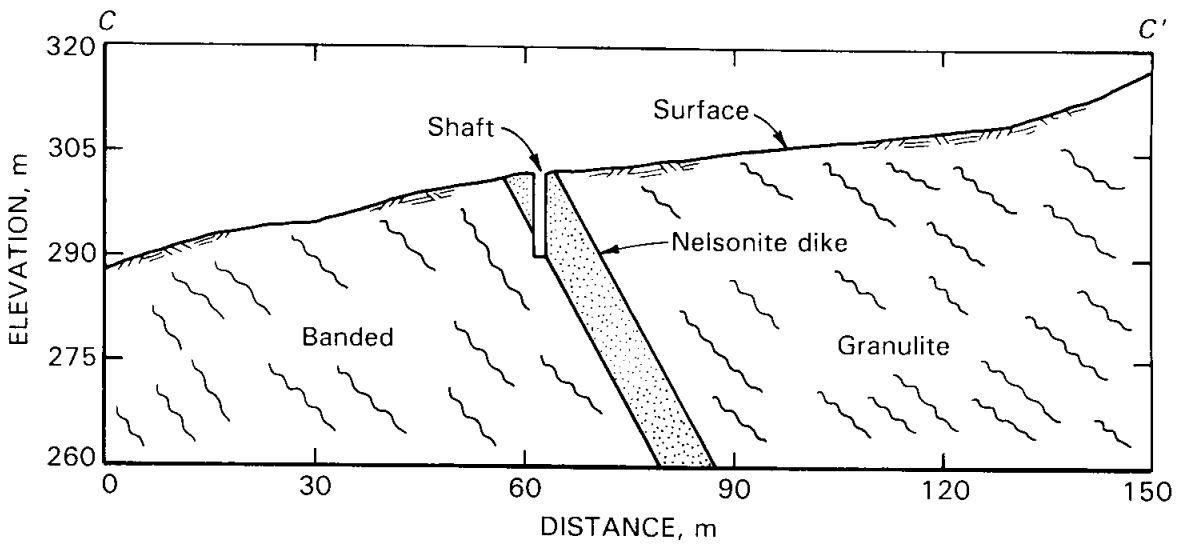


Figure 9.—Johnson dike and shaft profile.

unexplained anomaly of 500 nT occurs approximately 40 m east of the dike.

Profile B-B', located 150 m west of C-C', shows a broad, but weak anomaly of about 400 nT centered on the dike. However, no evidence of the anomaly that was detected east of the dike on profile C-C' was found. Evidence of the main dike was again detected along profile A-A', 150 m, as indicated by a broad, weak anomaly of about 200 nT.

Profile D-D', between State Highway 151 and Hat Creek, showed no anomalous readings, indicating that the dike pinches out slightly east of State Highway 151. At that location, it is exposed on the west bank of the road cut.

The authors conclude that VLF was of little use in delineating the nelsonite ore bodies. Nelsonite has a specific gravity approximately 1.5 times that of anorthosite; therefore, gravimetric surveys conducted on the contact between anorthosite and the gneiss country rock might outline concealed deposits.

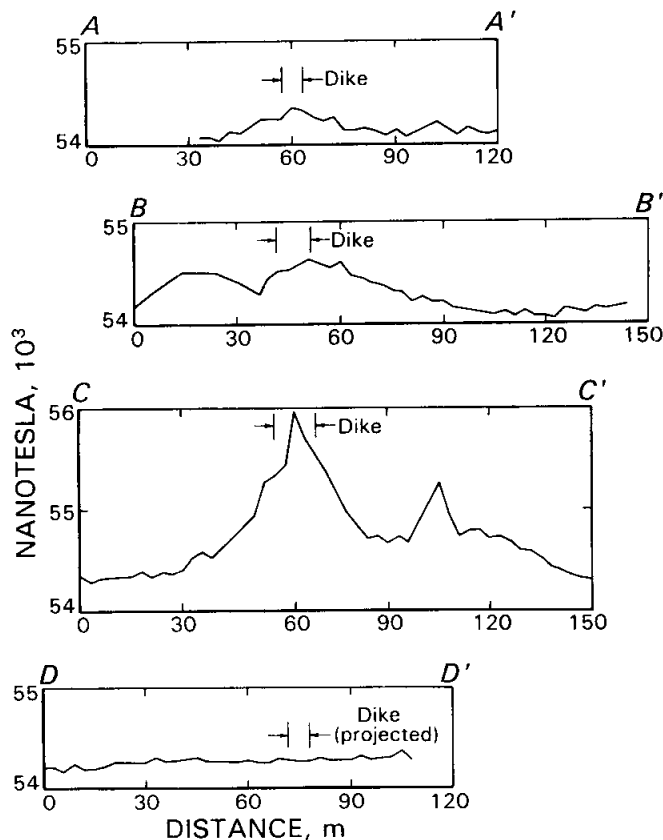


Figure 10.—Johnson dike magnetic profiles.

CHROMITE

Importance of Chromite

Chromium enhances steel by imparting properties of hardness, wear, and corrosion resistance and of high-temperature strength. Chromium's largest use is in stainless steel manufacturing, and it is strategically important as a superalloy. There are no chromium substitutes for either of these uses. Figure 11 summarizes chromium usage in the United States. Stainless steel is common because it is abundant, reasonably priced, and has an excellent historical performance. Stainless steel consumption could be reduced because it is utilized in many applications that do not require its superior performance. Because of its widespread acceptance, there are few incentives to replace stainless steel. Therefore, most potential substitutes remain at the laboratory development level.

Chromite Sources

The last chromite mining in the United States occurred in 1961. During the 1985-94 period, chromite oxide imports ranged from 87 to 270 kt, as shown in figure 12. From 1989 to 1992, the chromium import sources contained in chromite and ferrochromium were the Republic of South Africa (48%), Turkey (13%), Zimbabwe (10%),

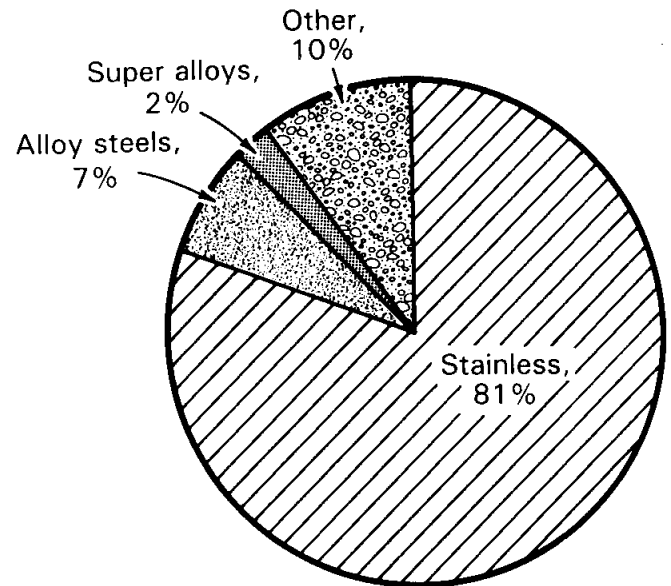


Figure 11.—Chromium applications in the United States.

and the former Yugoslavia (8%), with other countries accounting for the remainder (1) (figure 13). Turkey was the source of high-grade metallurgical chromite; the Republic of South Africa supplied the chemical chromite.

In 1992, world shipping grade chromite resources totaled 11 Gt, and world shipping-grade chromite reserves totaled 1.4 Gt (1, p. 47). Countries with the most reserves are listed in table 2. The Republic of South Africa has the greatest percentage of chromium resources.

Table 2.—Countries with the most chromite reserves (see reference (1))

Country	Reserves, Mt
South Africa, Republic of	960
Zimbabwe	140
Kazakhstan	130
India	59
Finland	29
Brazil	8
Turkey	8
Philippines	7

Domestic Reserves

Domestic chromium deposits are small or low-grade. The known domestic deposits are not exploited because associated mining costs and transportation costs exceed the ore price currently available from foreign sources. Domestic chromite deposits are remote from consuming plants; therefore, ore cannot profitably be transported to consumers. The largest known U.S. chromite resource is in the Stillwater complex in Montana (7). The Stillwater chromite occurs as layered stratiform and eluvial-alluvial lathyrctic deposits. Other domestic chromite deposits, called podiform deposits, occur in scattered small deposits in Alaska, California, Pennsylvania, Maryland, and North

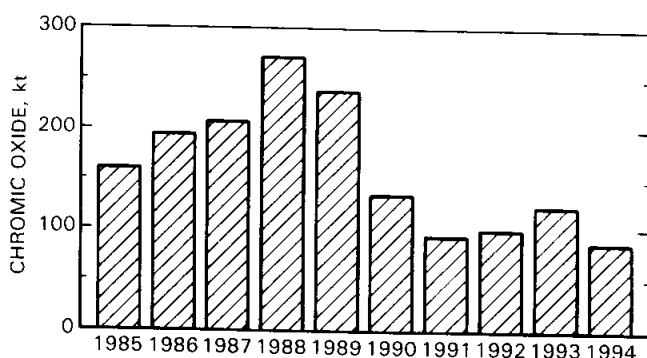


Figure 12.—U.S. chromic oxide imports from 1985 to 1994.

Carolina. California and Alaska contain the most podiform chromite reserves, as indicated in table 3.

Podiform deposits have the most potential for innovative mining techniques. They contain both massive and disseminated ore and are generally magmatic segregations that form lenses and irregularly shaped masses in dunite and peridotite rocks. Although singularly these deposits are small, when combined they represent 26% of U.S. chromite reserves (figure 14). Most of these deposits

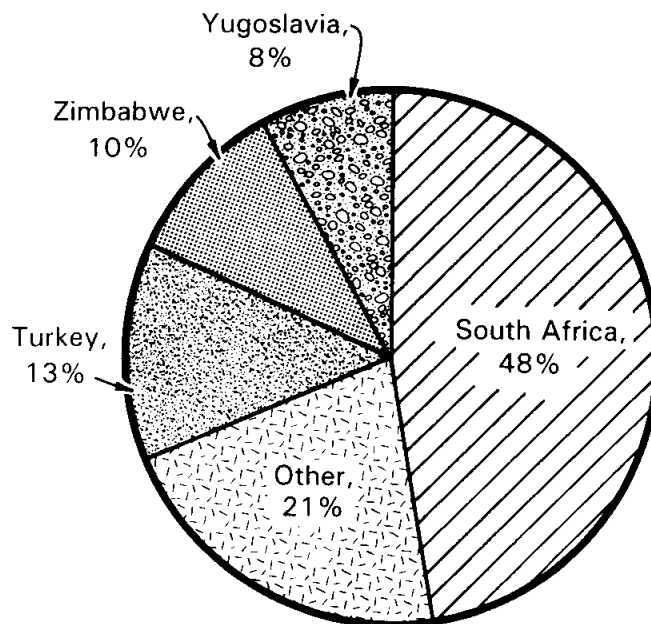


Figure 13.—Import sources of chromium contained in chromite ore and chromium ferroalloys from 1989 to 1992.

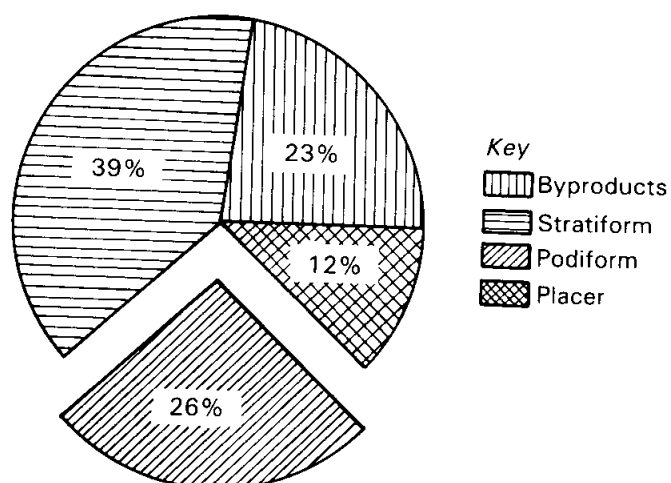


Figure 14.—Domestic chromium resource by deposit type.

Table 3.—Contained Cr₂O₃ from podiform-type deposits located in the United States (Mt)

State	Disseminated		Massive		Total		Total Cr ₂ O ₃ , Mt
	Low Fe	High Fe	Low Fe	High Fe	Low Fe	High Fe	
California	1.4	2.384	0.62	0.0	1.462	2.384	3.846
Alaska ¹	NA	NA	NA	NA	NA	NA	2.230
Oregon	0.059	0.042	0.019	0.042	0.078	0.042	0.121
Montana	0.0	0.036	0.0	0.0	0.0	0.036	0.036
Washington	0.015	0.0	0.0	0.0	0.015	0.0	0.015
Pennsylvania/Maryland	NA	NA	NA	NA	NA	NA	NA
Total	1.474	2.420	0.081	0.042	1.555	2.463	4.018

NA Not available.

¹Alaska indicated and inferred values from reference (8), remainder from reference (7).

are too small to mine by conventional mining methods. Innovative mining techniques are required to make mining these deposits economical.

Alaska

Estimates of chromite reserves in Alaska total 3.1 to 3.9 Mt contained Cr₂O₃ (8-9). The estimated reserve potential for Alaska podiform deposits ranges from 2.6 to 3.4 Mt. The reserves are in 132 subeconomic deposits scattered throughout 8 separate regions (9). The regions are defined by geology, geography, and physiography. The estimates are conservative because they include only known deposits containing greater than 900 t Cr₂O₃. From surface observations, additional unmeasured resources are present in deposits of unknown size. The regions have not been completely explored; therefore, potential exists for additional reserves to exist in undiscovered buried deposits and covered extensions of known deposits.

The lack of adequate transportation to much of Alaska's ore makes it out of easy reach for mining claims for many years. Therefore, a more realistic reserve value is the contained Cr₂O₃ in the Chugach Trend in accessible southern Alaska. The region stretches over 965 km in southern Alaska and has chromite podiform deposits containing 2.0 Mt Cr₂O₃. Alaska's only chromite production has been from this region. Production occurred during World War I, World War II, and the Korean conflict and has totaled approximately 27.2 kt chromite with grades between 38% and 43% Cr₂O₃. Only the Chugach Trend is large enough (9) and close enough for emergency needs in case of foreign supply interruption.

Conterminous United States

Previous USBM studies have reported the total quantity and quality of identified domestic Cr resources in the conterminous 48 States and southern Alaska (7-9). The total available chromite in the conterminous United States is 22 Mt Cr₂O₃ (7). However, podiform resources within the conterminous United States contain 123 kt of massive contained Cr₂O₃ and 3.9 Mt of disseminated contained

Cr₂O₃. Chromite deposits are located at the Pennsylvania-Maryland border, Delaware, North Carolina, California, and Oregon. Although these deposits are geographically different, their geologic characteristics are quite similar. They are all associated with ultrabasic rocks, such as peridotite, dunite, saxonite, or its alteration product serpentine. These deposits range from alternating zones of disseminated to massive chromite. They are within dunite or serpentine, depending on whether alteration occurred. This presents a distinct advantage because an economical mining method in one locality would likely work in others.

If the United States used its chromite reserves for supplying its consumption, the reserves would be depleted in a decade. Competing against the Republic of South Africa, which has such a large supply of chromite, would be difficult. On the other hand, because chromium is a strategic mineral, it would be beneficial to have a means to exploit domestic ores during a national emergency.

Pennsylvania/Maryland Chromite

In the mid-19th century, the State Line District on the Pennsylvania-Maryland border supplied the world with a high Fe podiform chromite of excellent chemical grade. The ore produced in this region has both a high iron content and high chromium content. Thus, the ores were used as metallurgical grade chromite during World War II. No refractory chromite occurs in this district. The reported production from 27 of the 40 known mines was 227 to 254 kt of lode chromite ore (10). The ore ranged from less than 30% to 55% Cr₂O₃.

The decline of chromite mining in Pennsylvania and Maryland was hastened in 1848 when large chromite deposits in Turkish Asia Minor were discovered. By 1860, this source virtually controlled the entire European market. Additionally, in the early 1860's, chromite was found in California. As deposits were discovered in the West, the eastern U.S. mines slowly began to close. The Pennsylvania and Maryland mines were experiencing mining problems for various reasons, including ore exhaustion, mining depth, inadequate pumping facilities,

mining rights, and price decline. Production from the area ceased in 1882. Interest was revived during both World Wars, but little or no mining occurred.

The Pennsylvania/Maryland chromite (figure 15) occurs in the geologic province known as the Piedmont Upland. The Piedmont is a metamorphosed rock belt that trends from Alabama northeast to New Jersey. In Pennsylvania and Maryland, the province is approximately 260 km long and 80 km wide. The Piedmont is characterized by rolling hills with gentle slopes, except along major streams, where steep-walled valleys exist. The State Line Chromite District consists of an east-west trending, irregular belt of ultramafic rocks that intrude mica schists and Precambrian gneiss. These rocks included peridotite, pyroxene, olivine, and dunite, but are now largely altered to serpentine and talc. Morgan (11) concludes that dunite, a rock consisting almost entirely of olivine, is the parent rock for much of the State Line area serpentine. The podiform chromite deposits occur only within the altered dunite. Serpentine composite samples collected from a large active rock

quarry in the State Line District contained 0.028% chromium and 0.24% nickel. This suggests the element's relative abundance in the ultramafic rock belt.

The areas underlain by serpentine are distinctly different in appearance from those underlain by schist. Soils created from serpentine decomposition are rich in magnesia, but low in lime and potash. This has led to sparse vegetation consisting of grasses, cedars, and scrub pines. These locations are thus called serpentine barrens. These are the areas that were explored for chromium ore. The podiform deposits vary from massive to disseminated chromite. The massive chromite ore is a dense aggregate of pure or almost pure chromite ranging from 48% to 63% Cr_2O_3 . In contrast, the disseminated ore contains chromite grains embedded in the serpentine averaging approximately 35% Cr_2O_3 . The grains are distributed fairly uniformly throughout the serpentine, and they often form boundaries between massive ore and barren rock. Very often they are concentrated to form separate irregular lenses in relatively barren serpentine.

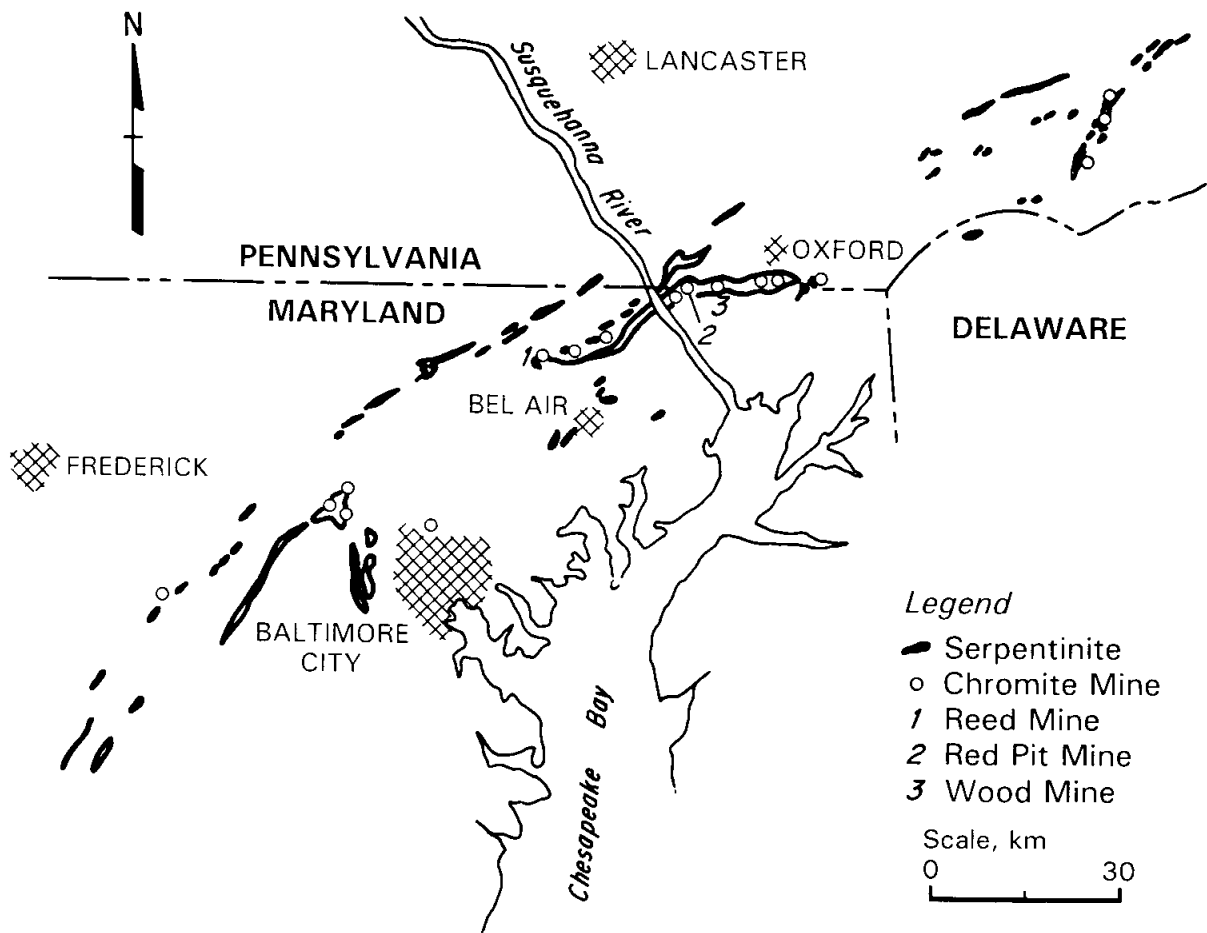


Figure 15.—Serpentine belt of Pennsylvania and Maryland.

The geologic composition of the chromite deposits in Pennsylvania and Maryland is not well understood. They are extremely variable in size and distribution. Thus, like most mineral exploration, it is difficult to estimate an ore body's magnitude and to locate other ore bodies when outcrops are not present. Although the deposits may lie only a few meters under the serpentine cover, they are difficult to find without applying sophisticated exploration methods.

In 1989, USBM personnel examined the Wood, Line Pit, Reed, and Red Pit abandoned mine sites (figures 15-16). These were probably the largest mines in their time. The areas surrounding all of these mines were either wooded, remote, and infested with green briar vegetation or cultivated farmland. Local inhabitants report that large ore dumps were removed from all of the mines; the material was used for road surfacing. Pits and trenches near all four mines were located and, in some cases, hazardous water-filled shafts were discovered.

RED PIT MINE

The Red Pit Mine is located approximately 300 m north of the Pennsylvania-Maryland border in Fulton Township, Lancaster County, PA (figure 16). The mine is a short distance west of Pennsylvania Route 222. The Red Pit Mine was selected from other mines and prospects in the district as a possible advanced mining test site. The Red Pit Mine's geographic characteristics of low relief and accessibility are more favorable compared with others in the district. It was hoped that a magnetic signature would be detected that would correlate with the chromite occurrence. The present study was limited to a brief surface reconnaissance consisting of magnetometer traverses across the site.

Information on the history of the Red Pit Mine is limited. The mine was owned by Isaac Tyson, who discovered and operated several other chromite mines in the district, including the Wood Mine. In 1867, the mine was permanently closed because of an explosion and cave-in. Total production has been estimated at 18 to 140 kt, averaging over 50% chromium oxide. The mine was reported to be large and unusually deep, perhaps 150 m. Unfortunately, as with many other local mines of the 19th century, virtually nothing is known about the underground workings. No records are available that indicate whether any test holes were ever drilled on the property or whether any geophysical or geochemical surveys were conducted. The mine probably was discovered from chromite float at the site because outcrop is virtually nonexistent. The name Red Pit was evidently derived from the abundance of red gossan type of siliceous, disseminated ore scattered about the surface. Fresh specimens exhibit grains and bands of chromite imbedded in a dense, highly siliceous jasperlike material (figure 17). This association has not

been reported from other mines in the district and appears to occur only with Red Pit disseminated ore. Access to the underground workings presumably was by means of three shafts (figures 16 and 18). A long trench and many pits attest to the former activity at this site. Outcrop no longer can be found at the site, although scattered rock fragments found nearby suggest that bedrock is close to the surface. In 1955, Pearre and Heyl (10) found exposed ore in the shaft and pit walls; these are now covered with soil and vegetation. Both massive and disseminated ore specimens can be found in the remaining dumps.

Geophysical Exploration

Applied geophysical exploration methods depend largely on the country rock homogeneity and ore and on the contrast in physical properties between the two. One should attempt to determine both by physical measurements of ore and rock samples and by test surveys whether or not a particular method is practicable. Many variables must be considered using this approach, including the detection equipment, type, and sensitivity, as well as the chromite's extent in depth and size and the normal variation in almost all natural material properties. Even those samples collected from the same area or from different parts of the same deposit can range widely in character. Hawkes (12) discussed in detail the pitfalls of attempting to prospect directly for chromite using magnetics only. However, at the same time, he explains how valuable host rock information can be found from magnetic surveys. Consequently, the present study was conducted. Any particular host rock magnetic signature that is detected in the mine vicinity could be useful in further exploration. The USGS has conducted extensive research on the chromite geophysical signatures (13). These studies highlight the importance of a laboratory research phase to obtain preliminary physical property estimates that might contribute to a distinctive geophysical signature. Laboratory evidence from these studies suggests that mineral assemblages found in association with the chromite are responsible for a geophysical signature rather than the chromite itself. It was concluded that a multiple physical property approach is required when using geophysical techniques in the exploration for non-base-metal minerals. In particular, magnetic results alone can be misleading. In some districts, magnetite is found in close association with the chromite; in others, the chromite ore is distinguished by an absence of magnetite.

Laboratory Tests

To determine the Red Pit's geophysical character, laboratory tests were performed on serpentine host rock and the chromite ore samples. Representative results are shown in table 4.

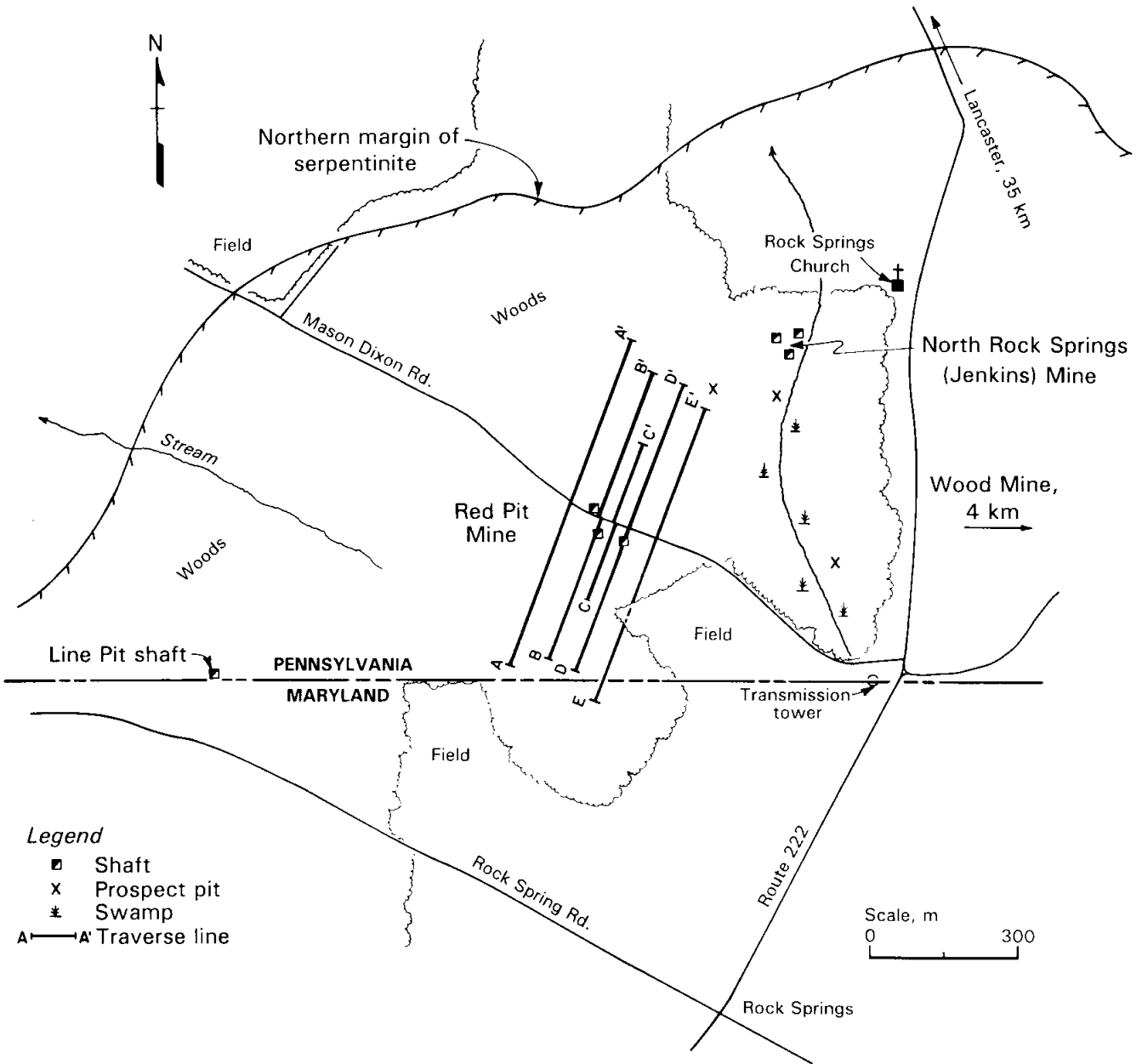


Figure 16.—Plan view of the study site and vicinity.

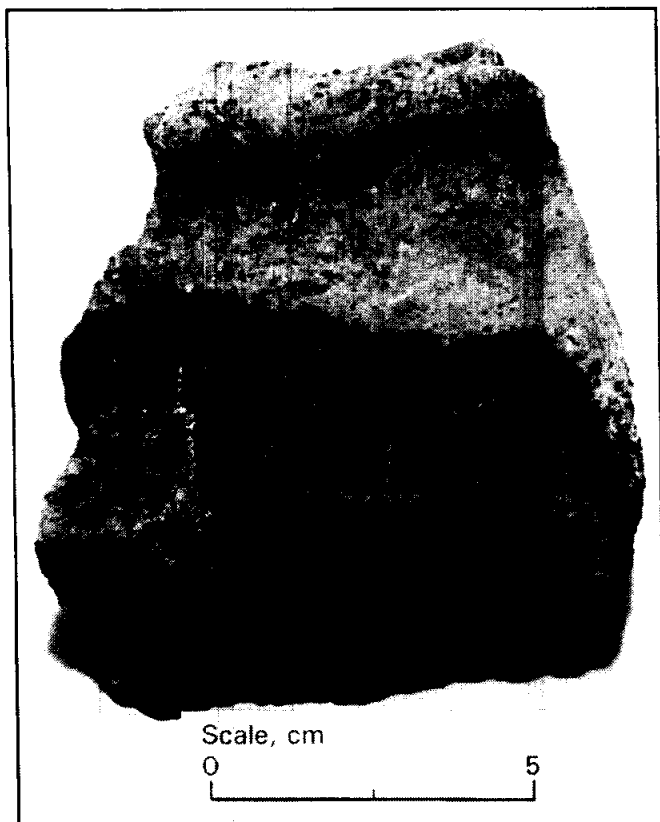


Figure 17.—Disseminated chromite in highly siliceous jasper-like matrix.

Table 4.—Laboratory test results from serpentine host rock and chromium ore samples

Parameters	Serpentine	Chromite
Magnetic susceptibility in cgs units $\times 10^6$	840	430
Specific gravity	2.8	4.1
Resistivity, Ω	500	120
Sonic velocity, m/s	4,550	2,728

The magnetic susceptibility values for chromite fell within the lower range of 57,000 to 94,000 in cgs units $\times 10^6$, as reported by Hawkes (12); the values for serpentine were 247 to 5,967 in cgs units $\times 10^6$, as reported by Sharma (14). Direct detection of a chromite ore body using only a conventional magnetometer survey is difficult. The low susceptibility values and relatively small contrast between serpentine and chromite, along with the highly variable character of natural materials, are among the reasons.

Magnetics

Prospecting for iron ore with magnetic methods has been used for more than 100 years. In the 20th century, magnetics have become valuable tools in the search for

many other ore types. Many theoretical and field studies of rock magnetism have been conducted. However, as with most geophysical applications, data interpretation may be ambiguous. Rock magnetism can be attributed chiefly to the presence of magnetite, ilmenite, or pyrrhotite. Magnetite is by far the most prevalent because it is a common constituent of most igneous rocks. Five magnetometer traverses extending well outside the Red Pit mined area were conducted to detect any anomalies associated with the chromite occurrence. This information would be used as a guide in further prospecting the area. Measurements were made at 6-m intervals along the traverses with an Omni IV proton precession magnetometer with an accuracy of 2 nT at an ambient intensity of 50,000 nT at 23 °C. All stations were within the serpentine belt. The measurements ranged from 55,722 to 58,444 nT, which is typical for these latitudes. The proton precession magnetometer measures the total field magnetic intensity in nanoteslas. This will change depending on the global location, so that anomalies in the northern or southern latitudes will differ from those near the Equator. However, within local geographic districts, anomalies generally can be compared after the appropriate corrections have been applied.

Approximately 4 hours were required to complete each traverse across the Red Pit Mine area. On completion of each traverse, measurements were repeated at the initial station to find diurnal variations. Because these variations were small, no corrections were necessary.

Magnetometer Survey Results

The five magnetometer traverses locations are shown in figures 16 and 18. A rough contouring of the measurements obtained is illustrated in figure 19. The contouring did not reveal any strong trends or patterns that could be associated with the Red Pit Mine workings. However, a weak low was shown approximately 60 m south of the Mason Dixon Road and just south of the workings. According to Doyle (15), magnetic depletion is characteristic of some types of ore deposits and might serve as a guideline in some chromite deposits.

These profiles were translated into smoothed curves (figure 20), all of which indicate an overall slope or decrease from south to north. Some local variations in the ore zone vicinity are shown. More significant, perhaps, is the leveling off and general slope reversal within 150 m of the ore zone. This could be part of a regional trend, but no detailed aeromagnetic maps were available for this site.

The smoothed profiles were divided into two groups: one group (traverses B-B', C-C', and D-D') transects the mine workings (figures 18 and 21); the other (traverses A-A' and E-E') lies outside the workings (figures 18 and 22). Although no pronounced contrast between the two groups is apparent, traverse lines B-B' and C-C' track

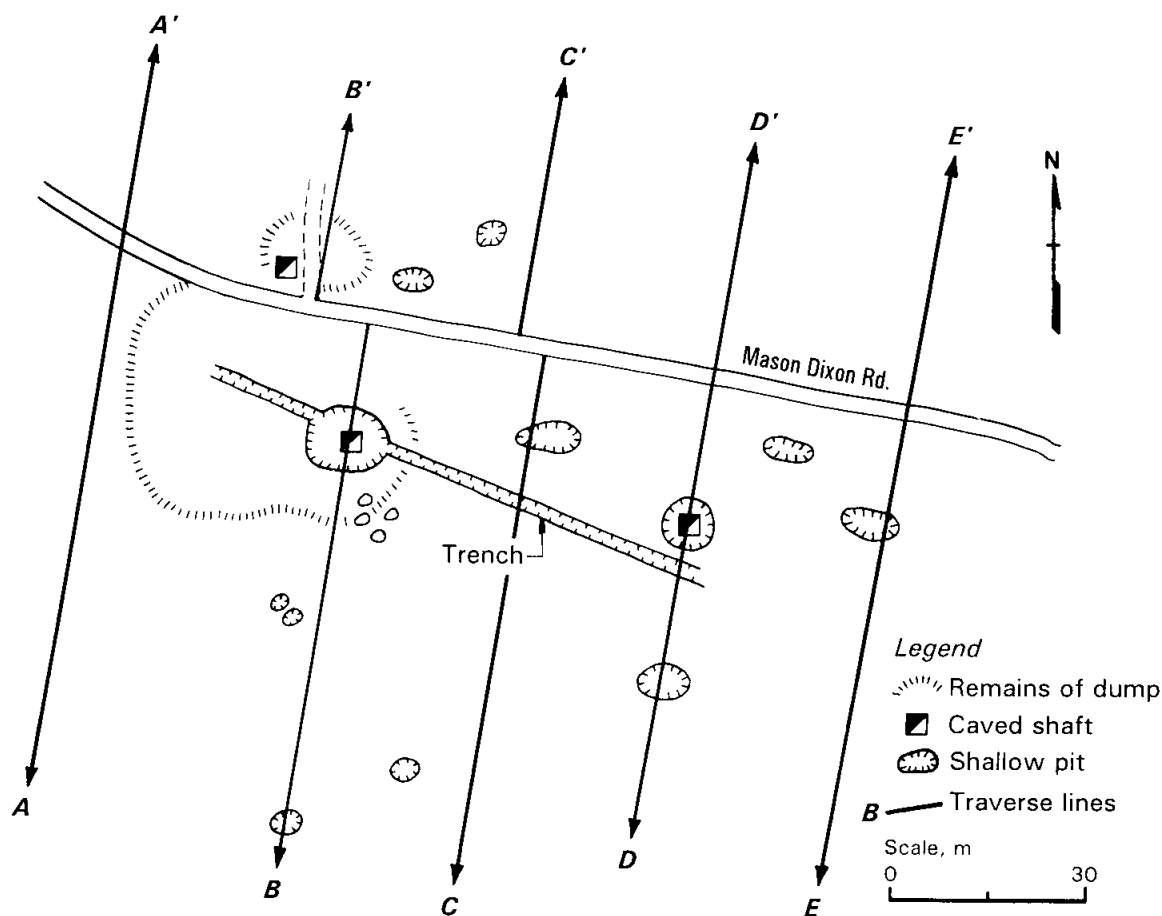


Figure 18.—Red Pit Mine area detail showing traverse locations.

closely over the workings and show a sharp trough in the ore zone. Traverse line E-E' is located outside the workings, but also shows a trough in the same area. Although these local variations may be significant, it is impossible to properly interpret the magnetometer survey results. Before this can be accomplished, more must be learned about the size and distribution of the Red Pit ore deposit and adjacent lithology. Other magnetic methods, such as vertical gradient measurements or data processing techniques, might have enhanced certain features.

Very Low Frequency Electromagnetic Fields

One traverse across the mine area was conducted with an EM-16 VLF electromagnetic unit (figure 23) using the Annapolis, MD, transmitting station. This traverse eliminated the possibility that some conductive mineral assemblage might be associated with the chromite zone that could provide a guide or target for further exploration. However, only relatively small in-phase angles of tilt were recorded. A broad zone of about -6° tilt was associated

with the mine area; however, a very broad zone of -6° to -15° occurs to the mine's north. These are difficult to explain because of the lack of subsurface information on the site. The tilt may be related to a conductive constituent of the serpentine, such as pyrite. The out-of-phase suggests virtually no shallow effects. The results were inconclusive, and further tests should be conducted to determine the measurement value.

Other Chromite Mining Districts

Chromite mining in California began in the late 1860's and operated sporadically through the 1940's. Chromite ore occurs in both pod and disseminated deposits. The pod deposits contain clean chromite masses that can be mined, sorted, and shipped as lump ore. The disseminated deposits consist of dunite-containing scattered chromite grains comprising up to 80% of the rock mass. Although the pod-type deposit has produced the most ore to date, the disseminated ore deposits contain the largest known reserves.

The North Carolina chromite ores occur in small, isolated peridotite outcrops that lie in a district that is 8 to 40 km wide and 320 km long. The prevailing rocks of the region are hornblende and mica gneiss (16). Chromite production began in 1918 because of the war efforts, but ended after a short time. Only small amounts of chromite were produced. The total production of chrome ore in North Carolina was 356 t, of which 56% was from massive ore in lenses and pockets. Prospecting was again conducted in the early 1940's. Small chromite amounts are known to occur in ultramafic rocks of the slate belt; however, only two deposits have been prospected. The deposits are the Adam Mountain area in Wake County, NC, and the Perry deposit near Wilton, Granville County, NC. The deposits were drilled around 1950, but were of too low grade to be mined profitably.

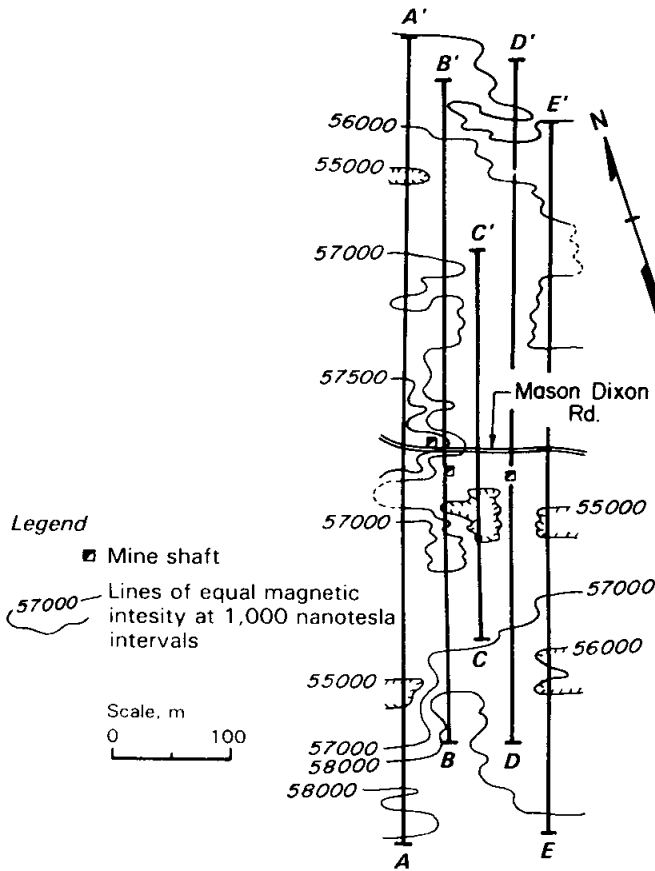


Figure 19.—Magnetic intensity contours near traverse lines.

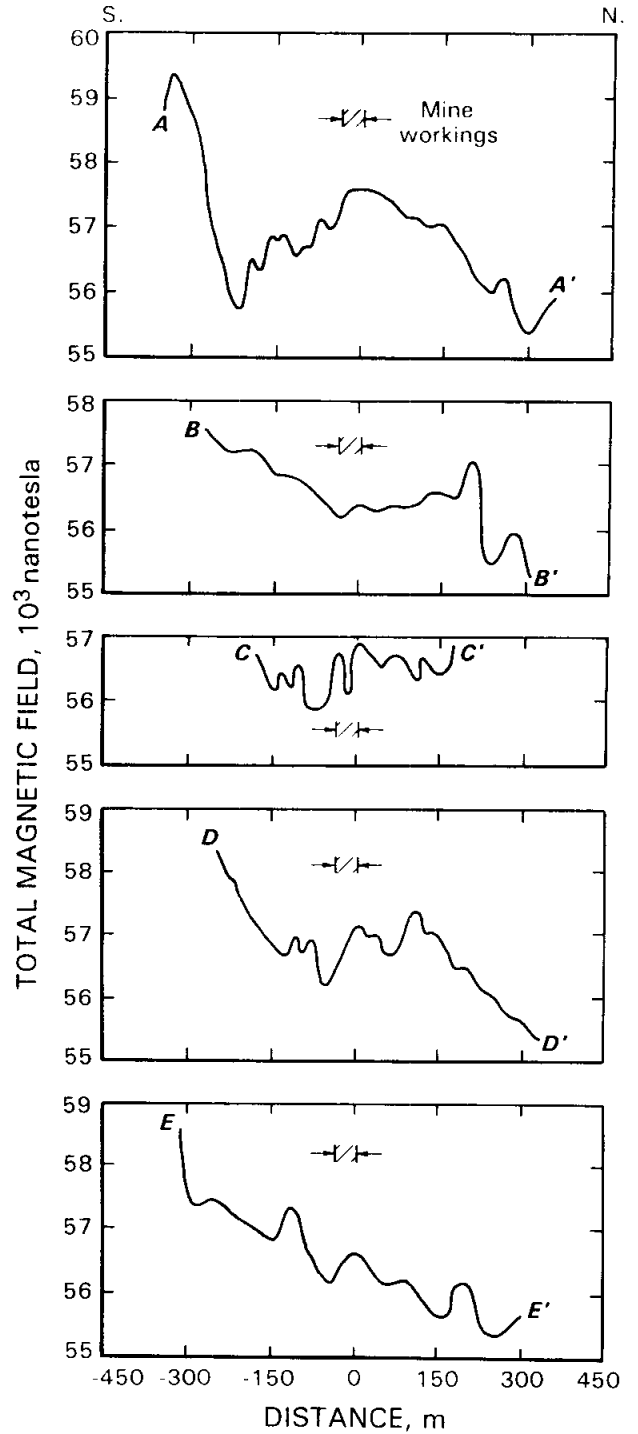


Figure 20.—Smoothed magnetic intensity profiles, A-A' to E-E'.

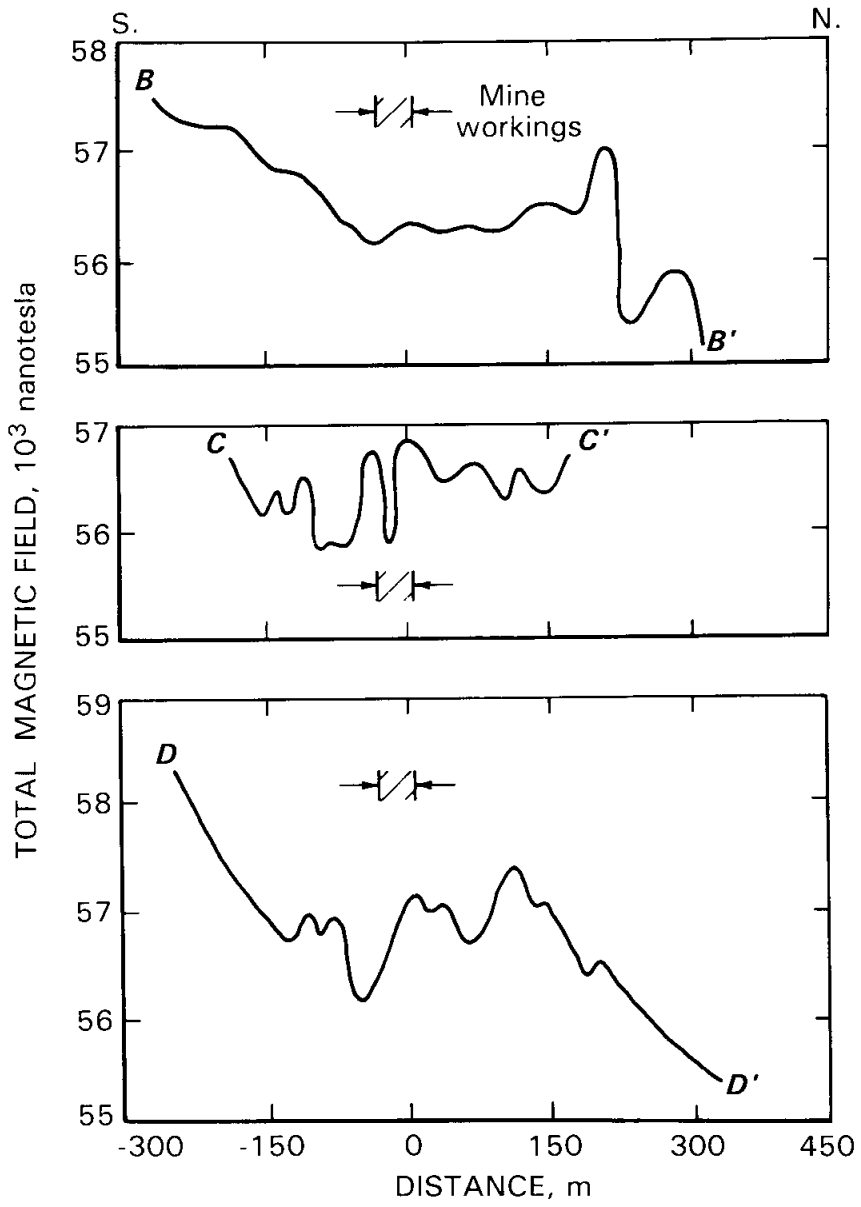


Figure 21.—Smoothed magnetic intensity profiles across mine workings.

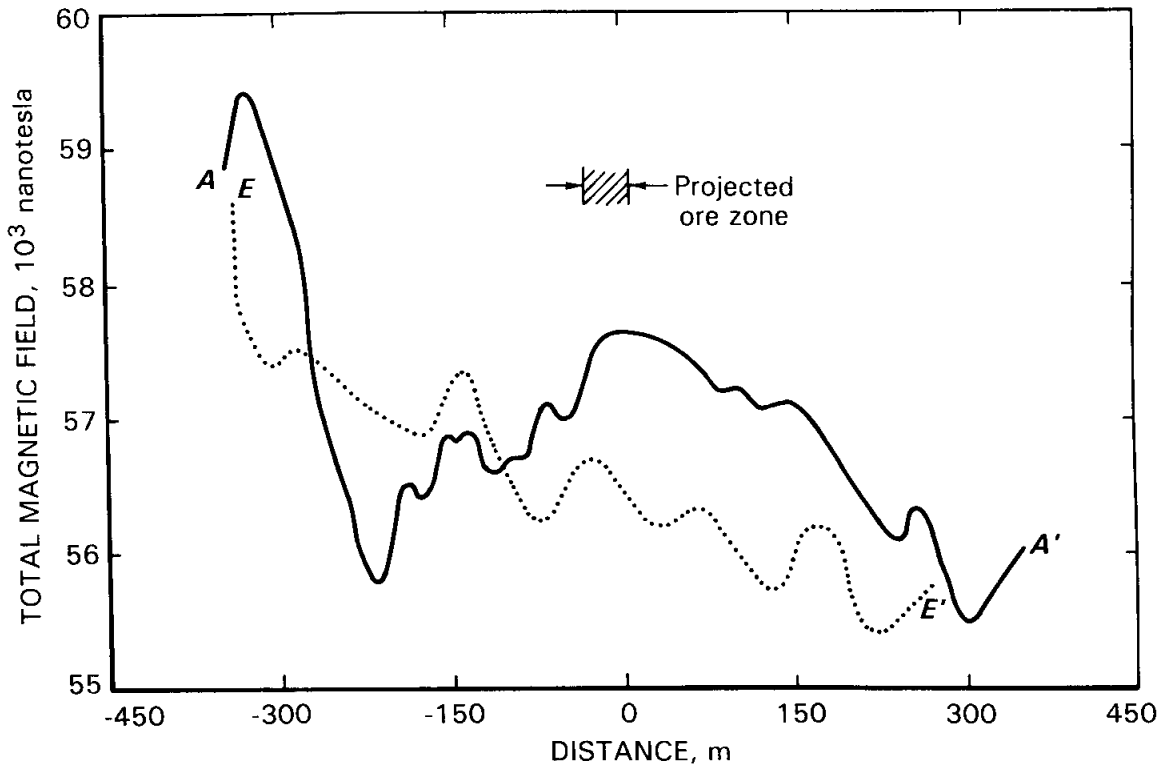


Figure 22.—Smoothed magnetic intensity profiles outside mine workings.

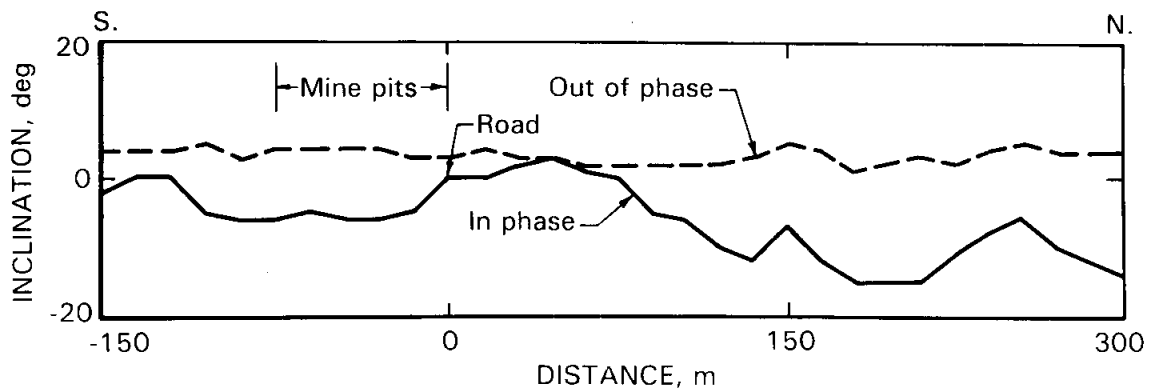


Figure 23.—VLF-EM traverse results across Red Pit Mine area.

MINING AND MINE DEVELOPMENT CONCEPTS

SELECTIVE BOREHOLE SLURRY MINING

Mineral recovery by mining subsurface deposits requires bulk extraction of material using large openings to provide access for workers and equipment. The actual mineral

vein may be much smaller than the excavation. Large amounts of material must be mined, transported, and processed relative to the valuable ore. This results in considerable capital, labor, and environmental compliance costs involved in mining even a small ore amount. There

is a definite need for an innovative mining system that could mine thin vein deposits without removing the surrounding host country rock. One mining technology developed by the USBM is called *selective borehole slurry mining* (SBSM). This method has the potential for extracting ore from either small deposits or thin vein deposits. The method incorporates several advantages, including selective ore extraction, small capital costs, and relocating workers from hazardous conditions (17).

The system is based on the theory that an underground ore deposit could be mined using an abrasive water-jet-cutting technique (figure 24). Water jets fragment the borehole wall and slurry the fragmented minerals to the surface via the main borehole. This slurry would then be collected and processed at the surface. The system would alternate between directionally drilling a pattern of accurately placed boreholes along ore veins, mining the ore, transporting the ore to the surface, and transporting the waste material back down for backfilling. Numerous

boreholes, possibly an entire pattern, could be directionally drilled from inside a one-pilot borehole. The abrasive water jets would be remotely positioned in the boreholes precisely where high mineral concentrations exist. The system is dependent on placement of accurate directionally drilled holes and verifying the location of high-concentration ore zones.

MEASUREMENT-WHILE-DRILLING SYSTEM

Technological advances through concentrated and directed research efforts are required to successfully implement the SBSM system. A research area that must be investigated to successfully apply the system is the development of a state-of-the-art measurement-while-drilling (MWD) system applicable for mineral exploration. Additionally, to effectively design SBSM equipment, resource characterization of various ore bodies is needed. This will provide detailed geologic information, such as the

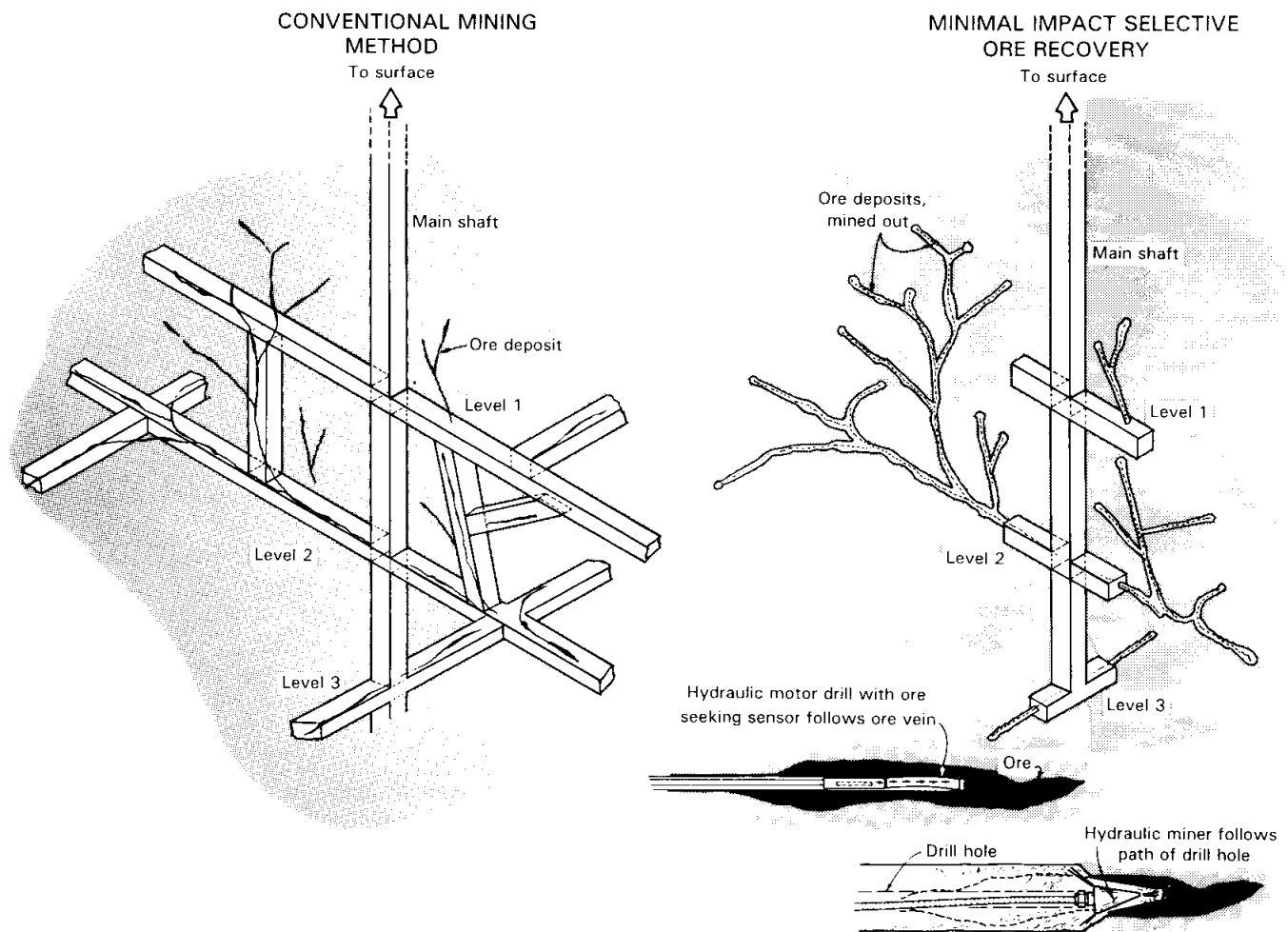


Figure 24.—Schematic showing conventional mining method and minimal impact selective ore recovery.

ore body's size, geometry, and distribution of high-concentration ore zones. It is also important to know the country host rock's structure and lithology changes. Because drilled coreholes provide the most comprehensive geologic and mineral information, cooperation with mining companies is essential because they often have this information on hand.

A MWD system has many uses besides SBSM. It is particularly applicable for two other drilling applications: exploration and mine development. These drilling types are distinctly different. Exploration drilling follows a reconnaissance exploration program and narrows the mineral search by pinpointing interesting mineralization areas. The methods used for the reconnaissance vary from airborne geophysics to ground reconnaissance and geochemical prospecting. If an attractive deposit is located, the ore must be delineated by exploration and development drilling. During these stages, it is extremely important that ores are assayed and minerals are characterized along with core descriptions and classifications. These data are then used to determine the ore body's shape, size, thickness, depth, and orientation. The drilling characteristics such as hole spacing, size, pattern, and drilling type used strictly depend on the target's nature and the host rock characteristics. During exploration, the most favorable targets are first selected and tested by a minimum of widely spaced holes. The hole spacing is reduced until enough information is obtained.

Development drilling starts when it is fairly certain that an economic deposit is present. The developmental drilling may require core drillholes. The pattern is designed to define the ore body's size and orientation so that the optimum mining plan may be developed. It is extremely important to get the most out of this drilling time as possible. If methods such as MWD are available to reduce coring and assaying cost, they should be employed.

The drilling method selected is often based on cost and includes diamond drilling, percussion, and rotary. The most important factor is the percentage of core recovery in the mineralized zone. Although diamond drilling may be the best method for core recovery, it often is the costliest. An alternative to diamond drilling is rotary drilling with reverse circulation. Under certain conditions, this method can provide good chip samples, but in other cases its use is questionable (18). The reverse circulation drill was originally designed for drilling alluvial formations. It is capable of drilling and sampling highly fractured or void-filled formations. It is particularly useful for drilling through old mine workings. Accurate geologic sampling can be accomplished using this system. However, there are a number of problems. Heavier ore is often trapped in voids within the drillhole. Additionally, errors defining the mineral depth can result because of uncertainty as to the origin of the samples. The latter problem is somewhat reduced because the samples are expelled rapidly enough

so that changes in geologic formations can be pinpointed. Often during production demands, time is not available to drill a face and conduct core analysis. The ore may not be blasted, or ore may be stockpiled until a grade for the ore is determined. This often results in handling ores several times and in delays.

The purpose of the MWD system is to obtain as much information as possible about the ore body using drilling and geophysical sensors. The system also provides a path for the borehole slurry miner and delineates high-grade ore areas. This idea requires combining several different downhole identification techniques presented in figure 25.

Methods using advanced technology are needed to accurately evaluate every drilled hole increment. Consequently, methods to determine mineral type and concentration, host rock lithology and structure, and borehole position must be refined. The capabilities must be packaged in a wireless logging/surveying system that can provide information on a near real-time basis.

The concept of measuring drilling parameters is not new, and there are several reasons for measuring drilling parameters (19-21). Among them are optimum placement of blasting load in a hole to increase blasting efficiency, diagnosis of roof conditions, and improvement of drill performance to reduce costs. Although there is no substitute for drilled core, there are drilling parameter recording methods that will reduce coring and assaying. This will save considerable time and cost in the mining production schedule.

Most studies that address these recorders are qualitative because recording of data is usually in a graphical form. Knowledge and exploitation of drilling parameters must be improved using quantitative interpretation of the results. For the actual drilling operation, convenient measurements such as footage and drill rod number are recorded. Additionally, items that should be recorded are bit weight, rotation speed, drilling fluid properties, and circulation velocity. The most important parameters are those related to the ground response from drilling, i.e., drilling fluid pressure, reflected vibrations through the drill rod, advance rate, and torque. These parameters are functions of the strata's resistance to drilling. Such information would enable the geologist to better locate strata with different material strengths, thicknesses, and voids. Although experienced drillers can differentiate such parameters, the matter is usually subjective.

MINERAL DETECTION

One ore detection method that is gaining in popularity is x-ray fluorescence, which has been investigated by the USBM and many companies. Every element known has a characteristic x-ray spectrum. The wavelength of these x rays is proportional to the square of the atomic number. The method works by exciting a rock sample using an

MEASUREMENT WHILE DRILLING SYSTEM

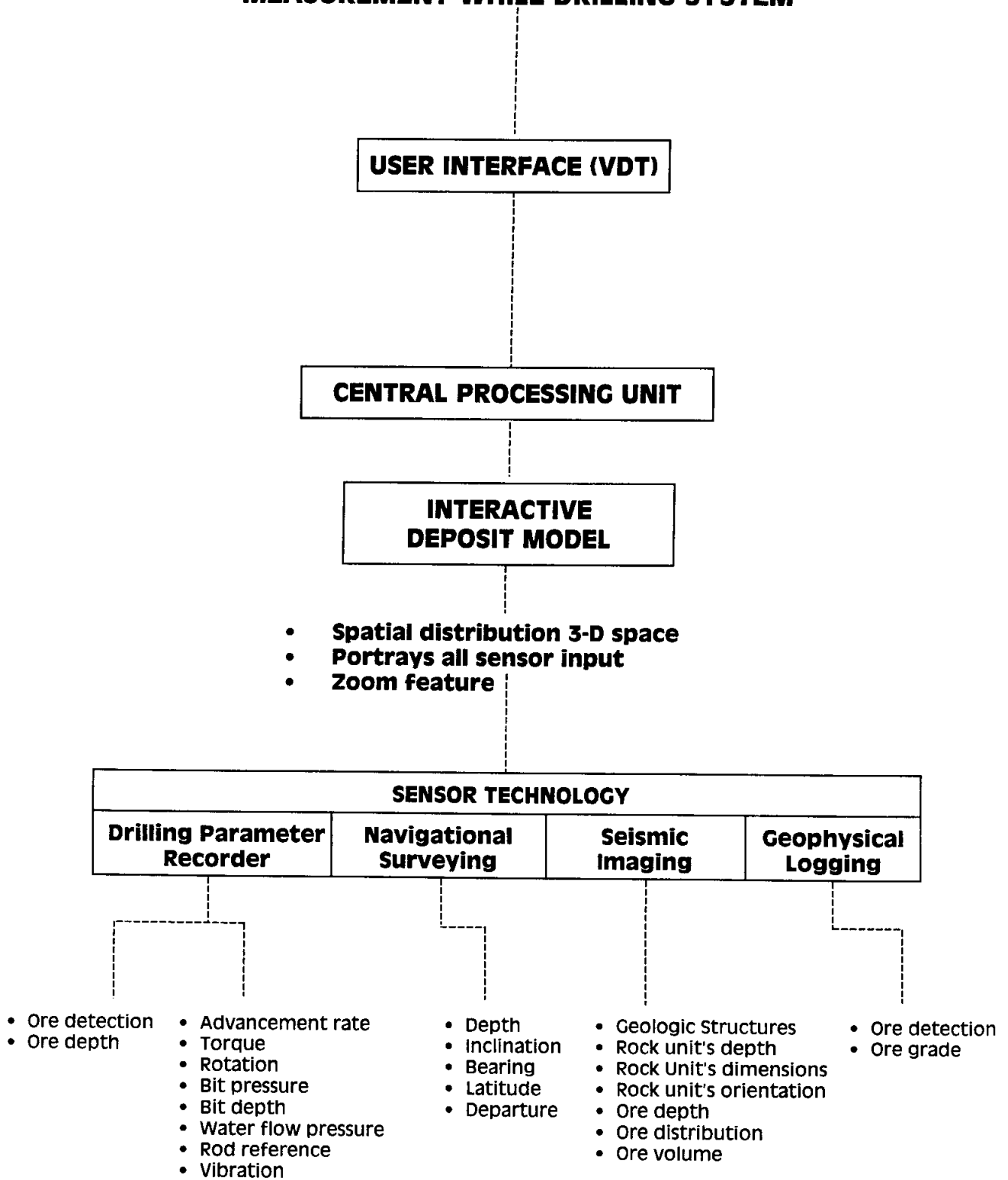


Figure 25.—Measurement-while-drilling system.

external radioactive source and measuring the characteristic x-radiation of the desired elements that is emitted back. If the x-radiation of a particular mineral can be isolated and its intensity measured, the element can be identified and its concentration determined. However, there are a number of problems. A quantitative analysis of element concentrations from the x-ray spectrum is not straightforward because the incident photons are scattered. Different mineralogy and physical properties such as porosity, grain size, and rock crystal distribution cause the scattering and the energy adsorption of the x-ray spectrum to vary. Additionally, the rock matrix may contain other elements that absorb the x-rays of the desired elements. Therefore, the unit must be calibrated to the respective mineralized material, and the x-ray source used must be appropriate for the target. For instance, americium is appropriate for silver and molybdenum, and cobalt is the choice for lead and platinum. Although the technique has limitations, with proper software many problems are reduced. Technology has progressed far enough to use the method in a borehole probe. Commercial instruments using the state-of-the-art microchip and microprocessor technology allow for high-speed, high-resolution signal and data manipulation.

Other methods that may work for mineral identification are magnetic and electrical geophysical techniques. Magnetic differences within the Earth can be attributed to structural changes in rocks or magnetic susceptibility. Additionally, sedimentary rocks generally have a much lower magnetic susceptibility compared with igneous or metamorphic rocks. Magnetic methods could be used to directly locate ores containing magnetic minerals, such as

magnetite. Intrusive bodies such as dikes can often be distinguished on the basis of magnetic observations alone. However, it remains questionable whether specific areas of an ore zone could be delineated from country rock using this method.

Many electrical prospecting techniques are available, each measuring some different electrical property. Resistivity is often used to map boundaries between layers having different conductivities. It has been used to map bedrock and in ground water studies to determine salinity and the water table depth.

Seismic reflection is an important parameter to identify host rock and ore structure, particularly faults and folds. This technique is probably better than any other technique for painting a subsurface structure picture aside from drilling many boreholes. One seismic reflection technique under development is using the drill bit as a downhole energy source for seismic profiles. Logs can be made available when required because no downhole instruments are needed. For the drilling parameter recorder, information from all of the sensors will be electronically entered on a personal computer. There, through sophisticated software, the operator could analyze the entire spectrum of results from the initial drilling stage to the final mining and backfilling operation. The computer's function would be to store, organize, retrieve, and analyze data. The capabilities of the machine should enable it to project mineral veins and to display and correlate any number of drillholes, geophysical logs, or cross sections. This system needs the capability to model complex geology where faulted and folded deposits exist.

SUMMARY

This USBM study found that deposits exist within the United States that individually are small, but collectively could contribute to U.S. resources. Although these resources will not eliminate our dependency on foreign ore supplies, they could reduce deficiencies should shortages occur. Unfortunately, because of their size, grade, and location, an unconventional method of mining the deposits must be developed. One method to mine these deposits is advanced drilling techniques in combination with borehole slurry mining techniques. These methods may be

applicable for chromite and titanium. The podiform chromite deposits in Pennsylvania, Maryland, North Carolina, California, Oregon, and Alaska contain approximately 26% of chromite in the United States. Other sites where this mining method may be applicable are rutile-ilmenite deposits in Virginia. The Pennsylvania chromite site and the Virginia titanium deposit were investigated with geophysical tools and are determined to be excellent test locations for advanced mining techniques.

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