MINNESOTA GEOLOGICAL SURVEY

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MINERAL DEVELOPMENT IN MINNESOTA

PAST HISTORY, PRESENT TRENDS, AND FUTURE POSSIBILITIES

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CONTENTS

MINERAL DEVELOPMENT IN MINNESOTA

By

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ABSTRACT

Mineral development, like all development in Minnesota in the 21st century, will occur within the principles of sustainable development. However those principles are not entirely applicable to the extractive-minerals industry inasmuch as mining depends on the utilization of nonrenewable resources. Because mineral deposits once mined are gone forever, sustainable development in mining can be achieved and through continuous replacement of the commodity consumed. The rate at which many mineral resources must be replaced can be reduced by careful conservation measure and by the use of substitutes. Recycling contributes to our current supplies or most metals, but recycling alone cannot meet all of our societal demands for metal products. Thus for mineral resources, "replacement" to a large extent means discovering new mineral deposits. Minnesota has had a long history of metal mining extending back to 1884 when iron ore was first shipped from the Vermilion range. Since then, Minnesota has produced nearly 3.5 billion tons of iron ore for the United States steel industry. Iron mining will continue to be of considerable importance in the foreseeable future. The Mesabi range contains more than 170 billion tons of crude or 36 billion tons of iron-ore concentrate that will be recoverable for more than 200 years using current open-pit mining methods. Geologic studies also show that a vast, but low-grade copper-nickel resource consisting of 4.1 billion tons of material that has an average copper value of 0.7 percent and a copper to nickel ratio of 3.33 to 1. Other commodities, including low-value, large-volume industrial materials also are important to the state's economy. Industrial materials mined and used include construction aggregate (sand and gravel or crushed stone) dimension stone, clay, silica sand, and peat.

Geologic studies started in the mid-sixties have defined a modern conceptual framework that has established that the state has a large economic potential for a variety of commodities including gold, zinc, copper, nickel, and uranium. Many technical problems stand in the way of a discovery, but Minnesota has considerable potential for future mineral development. Therefore given enough effort, the probability of finding a new mineral deposit is fairly large.

The discovery of a mineral deposit of sufficient size and grade is the first step toward developing a mine, but a discovery will not in itself lead to mining. For a mineral deposit to be mined requires that the commodity can be extracted profitably with existing technology and under current economic conditions. Thus in the end, the decision to develop a deposit turns on economic and public policy factors. Economic decisions depend on specific factors such as taxes, royalities, environmental costs, and interest rates, as well as on less specific questions regarding potential impacts on the quality of life. In the end, a program leading from discovery to mine depends on a strong working relationship between the public and private sectors. The partnership like all partnerships require confidence based on mutual respect and understanding. Each sector has a role to play and each must freely contribute to the process.

Mineral development like sustainable develop in general will occur only when we take a long-term view. Mineral development from discovery to mine typically takes a long time and involves large sums of money. It is the public sector's responsibility to provide geologic maps at regional and intermediate-scales and other kinds of geologic information that will support the exploration process. It is the private sector's responsibility to explore and develop diligently. In the final analysis, both sectors must recognize that a mining company profits today must provide the capital for tomorrow's exploration ventures.

INTRODUCTION

With the approach of the 21st century, Minnesota is embarking on a far-reaching initiative that will expand its commitment to the concepts of sustainable development. In essence, sustainable development involves meeting the needs of the present generation without lasting damage to environmental resources and without sacrificing the ability of future generations to meet their own needs. However, the principles of sustainable development are not entirely applicable to the extractive-minerals industry inasmuch as mining depends on the utilization of nonrenewable resources. Because mineral deposits once mined are gone forever, sustainable development in mining, in common with all extractive industries, can be achieved only through continuous replacement of the commodity consumed. For mineral resources, "replacement" to a large extent means discovering new mineral deposits (Fig. 1).

The rate at which mineral resources must be replaced can be reduced by careful conservation measures and by the use of substitute materials. Recycling also has been championed as one way of replacing part of our mineral resource base without degrading the environment. Recycling contributes substantially to our current supplies of most metals. Although nearly all metals can be recycled, we must recognize that recycling alone cannot meet all of our societal demands for metal products. Consequently, sustainable development in the metals sector can be achieved only through continuous exploration for new deposits, through technological innovations to mine and extract metals more efficiently, and through careful planning for environmental rehabilitation once a mine or mineral deposit is depleted.

Minnesota has considerable potential for future mineral development. Geologic studies that started in the mid-sixties and culminated in 1972 with the publication of Geology of Minnesota: a centennial volume, defined a modern conceptual framework that established that the northern part of the state had large economic potential for a variety of commodities including gold, zinc, copper, nickel, and uranium. Exploration activity increased even more in the late eighties, particularly after the results started to become available from a high-resolution aeromagnetic surveying program that began in 1979. The aeromagnetic surveying program has been completed since 1989 and there is now optimism that every part of the state has at least some economic potential for mineral deposits. That optimism has been articulated several times, first in a 1988 report submitted by the Blandin Foundation of Grand Rapids, Minnesota to the Minnesota Legislature, and most recently in a report published in early 1995 in Skillings Mining Review by members of the Department of Natural Resources, Division of Minerals.

All of the published reports have emphasized that Minnesota is a difficult place in which to explore for metallic minerals or for the high-value, low-volume industrial minerals such as diamonds or rare earth elements. Many technical problems stand in the way of discovery. The technical problems are complicated by a view held by many that the government and mining sectors must have an adversarial relationship. On almost a daily basis, we are told that miners exploit the land and ruin the environment, and must therefore be strictly regulated; we are told by mining interests that government over-taxes and over-regulates the mining industry. In reality, a successful exploration program requires a close working relationship between the public and private sectors. This partnership, like all partnerships, requires mutual confidence based on mutual respect and understanding.

This essay describes what I believe to be the infrastructure in which mineral development occurs, and thus describes how government and the private sector must work together if new deposits are to be found. I make no claim as to originality. This essay is a synthetic work that brings together ideas from a number of different authors and traditions—altogether too many to mention by name. I also have dispensed with most reference citations, which would number in the hundreds and interfere with the flow of ideas if they were inserted in the text in traditional academic style. However, I would be remiss if I did not make special reference to the publications of Roy Woodall[1] and Lewis B. Gustafson[2], whose ideas and words are incorporated throughout the text. Their work should be required reading for anyone interested in the institutional and intellectual infrastructures in which mineral exploration programs succeed.

A BRIEF HISTORY OF MINING IN MINNESOTA

Mining is the extraction of a mineral commodity from the earth because of its perceived value or usefulness. Well before the time of European settlement, Native Americans in Minnesota mined clay, flint, copper, and other geologic materials. Indeed they mined materials that are sparsely distributed or difficult to extract even by today's standards. By A.D. 1200, and possibly as early as A.D. 900, they quarried blocks of quartzite in southwestern Minnesota to extract thin layers of claystone, which they used to produce ceremonial pipes and other religious objects. Native Americans also utilized copper float from along the St. Croix and Kettle Rivers in east-central Minnesota, and flint from near Gunflint Lake in northeastern Minnesota. The European settlers of the mid-1800's used many of the same mineral resources. They used flint for their flint-lock rifles and clay for their pottery. Later they searched for and found large clay deposits they used to produce brick. Their need for varied construction materials in the mid-nineteenth century led to the development of an extensive stone-quarry industry in east-

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[1]Woodall, Roy, 1984a, Success in mineral exploration: A matter of Confidence: Geoscience Canada, v. 11, p. 41-46.
Woodall, Roy, 1984b, Success in mineral exploration: Confidence in prosperity: Geoscience Canada, v. 11, p. 83-92.
[2]Gustafson, L. B., 1989, SEG distinguished lecture in applied geology—the importance of structural analysis in gold exploration: Economic Geology, v. 89, p. 987-993.

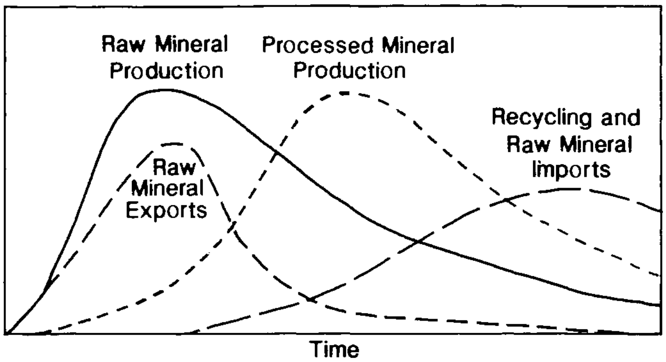


Figure 1. Classical relations between the availability of a particular commodity and its economic utilization. These relations, first elucidated by J. Foster Hewitt in 1934, show that because any given mineral resource is present in only finite quantities production will decline over time. To maintain the same production level, the resource must be replaced by recycled material or material from other sources.

central Minnesota and along the Minnesota River Valley; this produced a wide variety of dimension and cemetery stones that were used throughout the upper Midwest and ultimately throughout the world. In addition, the early settlers explored for copper and silver in east-central Minnesota and along the North Shore of Lake Superior in northeastern Minnesota. Considerable effort also went into a search for lead and zinc in southeastern Minnesota. Most of the reported finds were small and of no economic importance. A small mine that produced hand-picked ore assaying 6.2 percent copper was worked briefly on Susie Island off Grand Portage in Cook County on the shore of Lake Superior. Also several small copper mines were developed along the North Shore just north of Duluth and in Pine County, but none produced meaningful amounts of ore. In the early 1800's, small lead mines operated for a short time at Dresbach, in southeastern Minnesota in Winona County, and at two other localities along the Zumbro River in Wabasha County. To further enhance mineral exploration during the late 1800's, the state offered rewards to discoverers of salt and fossil fuels, such as coal and natural gas. Unfortunately, no deposits of economic size were ever found and no significant rewards were paid.

In 1865, the first major attempt to develop minerals in the northern part of the state was organized by several companies during the time of the Vermilion gold rush. The rush was started when H.H. Eames, the State Geologist at the time, claimed to have found a sizable gold deposit near Lake Vermilion in St. Louis County. During the next two years several mining companies were formed and thousands of dollars were spent in the search for Eames' gold. Unfortunately, gold was never found in commercial quantities and the rush collapsed. Subsequently, sub-commercial quantities of gold were discovered in 1893 on Little American Island in Rainy Lake, about 10 miles east of International Falls. The mine yielded slightly more than $5,500 in bullion from ore that assayed at about $12.50/ton. The mine closed after about one year of operation.

Despite its disappointing return of precious metal, the 1865 gold rush had important ramifications for the state because it indirectly led to the discovery of the Vermilion iron-mining district, from which ore was first shipped in 1884. During the next several decades, other iron-mining districts, including the Mesabi range in 1892 and the Cuyuna range in 1911, came on-line and produced major quantities of iron ore. Although now nearly forgotten, the so-called Fillmore District, in southeastern Minnesota, also produced nearly 8.1 million tons of iron ore from 1942 to 1968.

By the late 1950s the iron-mining industry in Minnesota was on the decline. Reserves, thought to be sufficient for 100 or more years of mining, had been depleted during World War II. Consequently, the Minnesota and U.S. Geological Surveys, as well as various private companies undertook a major exploration program to identify new resources mainly through the application of aeromagnetic techniques. No new resources were found. It became obvious that if iron mining were to continue, the focus would have to change from natural ore to taconite concentrate—requiring the investment of very large sums of money by the private sector to create the infrastructure necessary to manufacture taconite concentrate from raw iron-formation. The mining companies were unwilling to spend the necessary funds without a guarantee from the state that this investment would be protected from an unreasonable tax structure. That guarantee was provided with the passage of the Taconite Amendment to the Minnesota Constitution in 1964.

The aeromagnetic surveys and follow-up drilling of the late fifties and early sixties established that the geology of northern Minnesota was very much like that in adjoining parts of Ontario where a variety of mineral deposits are found. This idea was further developed by the Minnesota Geological Survey, which mapped much of the exposed bedrock in northeastern Minnesota in the 1960's. This mapping provided the basis for a major exploration effort for base-metal sulfides (copper and zinc) in the late sixties and early seventies.

Mineral exploration and development underwent a sharp decline with the oil embargo of 1973-1974 and the recession that followed. Demand for metals remained depressed even when the world economy recovered in 1978. That lack of demand was in part caused by an oversupply of metals, and by the combination of downsizing, conservation, and substitution of other materials. Exploration for base-metal sulfides in Minnesota was terminated as part of a cost-saving program. In contrast, prices for the precious metals remained strong. For example, the price of gold rose from about $200 per ounce at the beginning of 1979 to nearly $700 by the end of the year. The increased price of gold, coupled with new methods of extraction, allowed many old and abandoned deposits to be reopened. Exploration for new deposits became highly successful. The discovery of a world-class gold deposit near Hemlo, Ontario in 1982 led to intense exploration in northern Minnesota where the geologic setting is similar. Additional impetus for exploration has been the availability of the results of a state-wide high-resolution aeromagnetic survey, which began in 1979 in northeastern Minnesota and was completed in 1990 in southeastern Minnesota.

From the late sixties to the late eighties there was considerable exploration in Minnesota for several different kinds of what can be called unconventional mineral deposits. In 1968, the first example of a new class of uranium deposits, the so-called "unconformity-related deposits," was discovered in Northern Territory, Australia. Shortly thereafter, similar deposits were found in other places in Australia as well as in Saskatchewan, Canada. As the name implies, these deposits occur along unconformities, generally between Precambrian strata of Early and Middle Proterozoic age. Using this criterion, explorationists in the early eighties recognized that such deposits could exist in east-central Minnesota, especially in Carlton, Pine, and Kanabec Counties. The search ended five years later, not because it was established that the area lacked uranium, but because so many new deposits were found around the world that the price of uranium plummeted.

In the late eighties Minnesota also was the site of a search for diamonds. In South Africa and Australia, diamonds occur in an igneous rock called kimberlite, typically as swarms of very small (<.5 mile in diameter) plutons. These plutons, though of much younger age, are typically found in Precambrian terranes. Geologic mapping by the U.S. Geological Survey found several kimberlitic plutons in the southeastern part of the Upper Peninsula in Michigan. Aeromagnetic data established that parts of east-central and northern Minnesota were characterized by anomalies like those associated with kimberlite swarms, and the search broadened to Minnesota. One kimberlite-like body was discovered along the Minnesota River in northeastern Redwood County. The search continues.

Lastly, the idea of petroleum in Minnesota would have been unthought of in the early eighties. Today, because an estimated 10 percent of the world's discovered petroleum resources are contained in rift-related rocks of various ages, and because rocks at the world famous White Pine copper mine in Michigan contain liquid hydrocarbons, some members of the petroleum industry believe that the sedimentary parts of the Midcontinent rift system are a favorable exploration target. Exploration in the rift system has now reached the point where drilling has been done in Kansas, Iowa, Michigan, and Wisconsin. More than 87,000 acres of land over the rift system were leased in the late eighties in east-central and southeastern Minnesota. Although subsequent work has shown that the rift system has less potential than originally believed, there is no geologic reason why drilling should not also take place in southern Minnesota at some time in the future.

IMPORTANCE OF MINING IN MINNESOTA

It is the iron-mining industry that has made the minerals sector important to the state's economic growth. In all, Minnesota has produced nearly 3.5 billion tons of iron ore for the United States steel industry (Fig. 2). Today only the Mesabi Range continues to produce ore, but it remains one of the largest iron-mining districts in the world (Fig. 3). In 1994, seven mines accounted for more than 75 percent of U.S. iron production, valued at nearly $1.35 billion. Also in 1994, according to the Minnesota Iron Mining Association, Minnesota's taconite industry generated more than $1 billion in economic activity, and paid more than $95 million in state and local taxes.

In 1994, Minnesota ranked ninth among the states in total nonfuel mineral production having an annual production valued at $1.57 billion. Iron ore accounted for 86 percent of that total. It is clear that other commodities, including the low-value large-volume industrial materials, also are important. The principal industrial material mined and used in Minnesota is construction aggregate, either in the form of sand and gravel or crushed stone. In 1994 aggregate accounted for about 10 percent of the state's non-fuel mineral value. Consumption in the state exceeds the national per capita consumption and is at least 10 tons per person, based on estimates provided by the U.S. Geological Survey and on statistics derived from a voluntary aggregate tax collected in twenty-three counties in the state. Aggregate is a necessary component in roads, bridges, houses and commercial and industrial buildings. It also has a variety of other uses ranging from decorative stone to ballast for railroad tracks. Aggregate is produced in all eighty-seven counties in Minnesota and more than 5,500 sites have been mined at one time or another (Figs. 4 and 5). Even though a considerable amount of aggregate has been recycled and reused, new mining sites must be continuously identified. Unfortunately such sites are becoming scarcer to find and when found more expensive to develop.

Also in 1994 Minnesota ranked 9th among states reporting peat production, 6th in dimension stone, and 6th in clay. Most of the clay is produced along the valley of the Minnesota River from Courtland to near Redwood Falls.

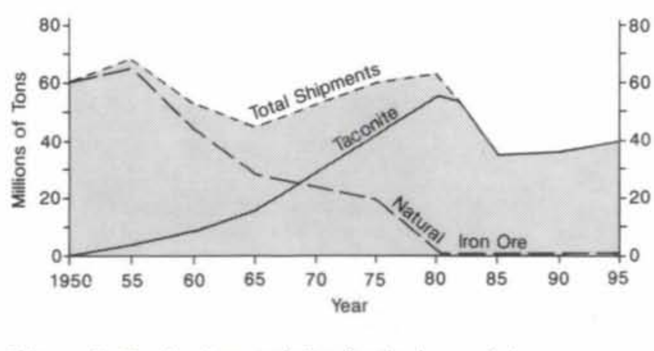


Figure 2. Production statistics for the iron-mining industry in Minnesota from 1950 to 1995.

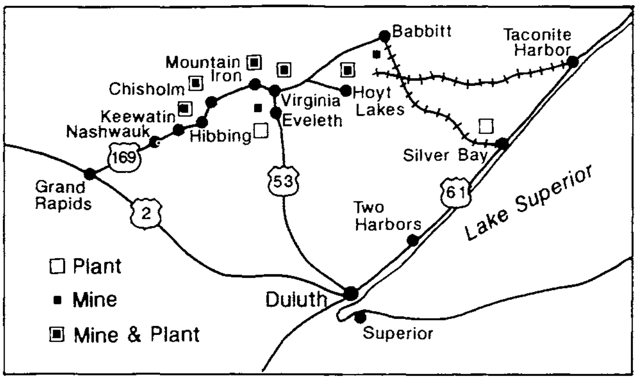


Figure 3. Operating iron mines on the Mesabi Iron Range, northern Minnesota.

Although an important aspect of the state's economy, the development of industrial minerals in Minnesota has been traditionally a local issue. Counties, townships, and municipalities generally have responsibility for zoning and issuance of conditional-use permits. Developing post-mining uses for borrow pits has been determined generally by local real-estate demands. Most pits are relatively small and are used only intermittently so there have been no overriding reasons, other than certain mandates that relate to environmental concerns, for state involvement in the development of industrial mineral resources. Consequently the remainder of this discussion will focus primarily on the role of the state in the search for metallic mineral deposits associated with Precambrian bedrock.

EXPANDING THE FUTURE MINERAL BASE

It is estimated that the Mesabi range contains more than 170 billion tons of crude ore or 36 billion tons of iron-ore concentrate that will be recoverable for more than 200 years using current open-pit mining methods. Geologic studies show that a vast, but low-grade, copper-nickel resource is located in the lowermost part of the Duluth Complex near Babbitt, in eastern St. Louis and western Lake Counties. The resource consists of 4.1 billion tons of material that has an average copper value of 0.7 percent and a copper to nickel ratio of 3.33 to 1. Even though the identified copper-nickel deposits are marginal in grade, they could become an important future source for copper as well as nickel and cobalt. The resources are well characterized, but their future economic viability depends on financial conditions driven by world-market conditions. There also is some interest in parts of the Duluth Complex for the platinum group elements.

Minnesota remains relatively unexplored for other mineral commodities compared to other areas of comparable size and geologic complexity in the United States. This historic lack of interest in exploration has at least two causes. First, many square miles of potentially mineral-bearing bedrock are covered by a mantle of Quaternary glacial debris, which makes exploration difficult (Fig. 6). The practical effect of the debris is well illustrated by the fact that much of the historical mining is where bedrock is at or near the land surface, and where exploration was relatively easy (Fig. 7). Unfortunately, glacial deposits are thicker than 100 feet almost everywhere in the northern half of the state except the northeastern quadrant. Thicknesses exceed 650 feet in the west- and north-central regions (Fig. 8). Much of the thickest sequences consists of water-saturated sand and gravel.

In addition to glacial materials, the overburden in much of the state includes several tens of feet (locally more than 300 feet) of residual clay or saprolite—developed in situ on solid bedrock during subaerial weathering in pre-Late Cretaceous time—and local erosional remnants of poorly lithified shale, siltstone, and sandstone of Late Cretaceous age. The total thickness of unconsolidated material above solid Precambrian basement, including clay, Cretaceous strata, and glacial debris, is routinely greater than 400 feet in large areas of western Minnesota, and in places is more than twice that. Successful exploration in the covered areas requires techniques for selecting and characterizing "blind" targets, which are likely to have small horizontal dimensions and thus be difficult to resolve.

A second deterrent to exploration was the lack of interest by the state in furthering knowledge of its geology during a period of approximately thirty years, from about 1930 to 1960. In 1960, knowledge of the state's geologic framework was still based on a map published in 1933 that was in large part slightly modified from a map first published in 1903. Those maps adequately portrayed the nature of the bedrock in the parts of the state where the glacial drift is thin and rock outcrops are numerous. It is in these same places where much of the early mineral exploration took place. Early exploration involved the direct study of rock outcrops. This technique was, and probably still is, the most effective means of exploration throughout the world. An exception to simple outcrop prospecting techniques in Minnesota was the discovery of iron ore on the Cuyuna Range in 1909, utalizing geophysical methods (the magnetic dip-needle) that could be used to locate buried mineral deposits.

Northeastern Minnesota has been the site of considerable exploration activity over the years. This has been taken by some to imply that the mineral endowment there is unique within the state. However, we know that northeastern Minnesota is unique only in that the glacial deposits that overlie prospective Precambrian rocks are relatively thin. Therefore, prospecting was and still is relatively easy. Today geologists have used a variety of analytic tools to establish that many of the drift-covered parts of the state are underlain by rocks and structures which are very much like those exposed in parts of northeastern Minnesota and elsewhere in the world where an extensive mineral industry exists. The analog suggests that Minnesota also has a similar but as yet undiscovered mineral wealth. However, any discussion of the potential for a new mineral resource in Minnesota must revolve around three questions: (1) What is the probability that various kinds of as-yet-undis-

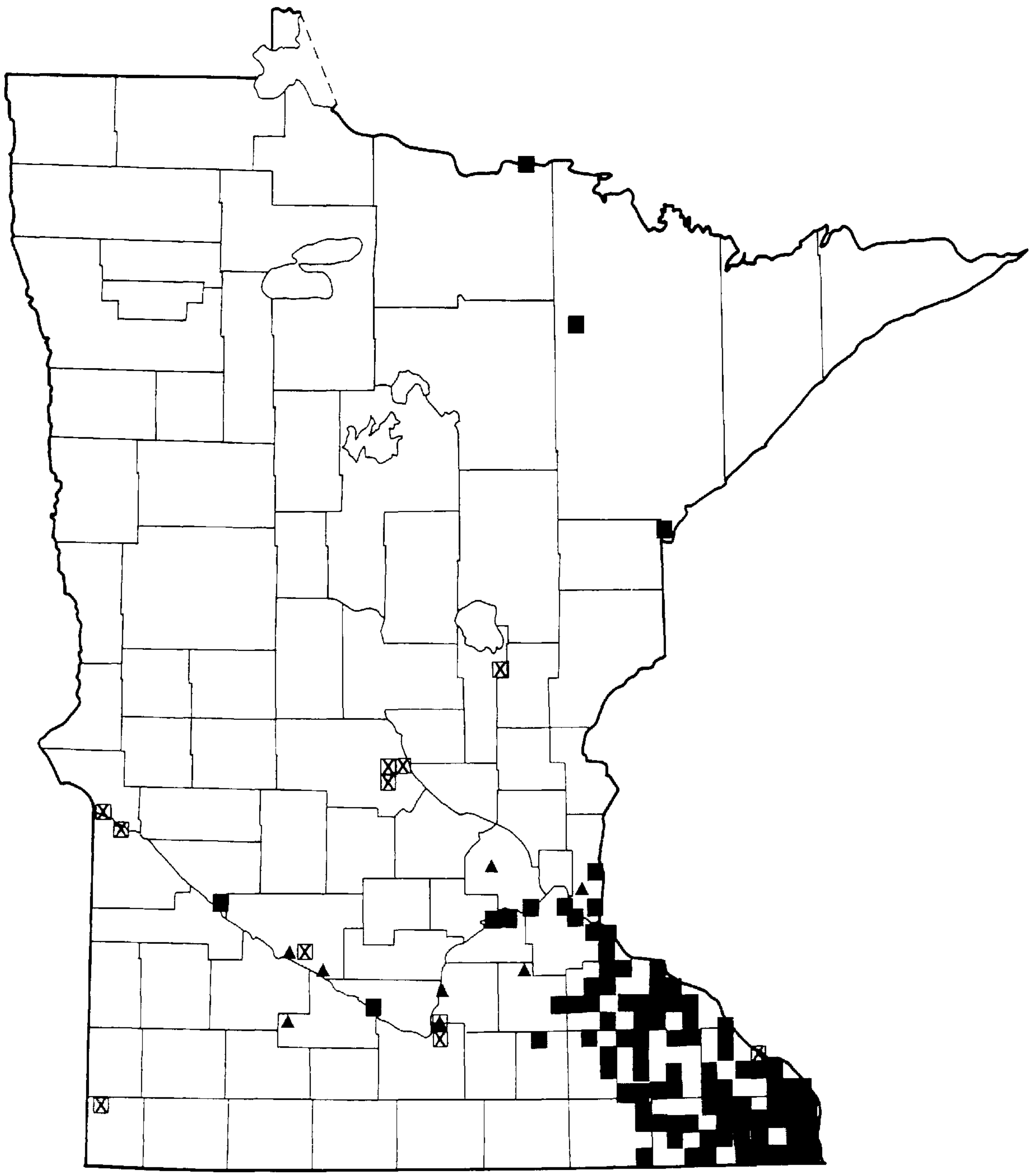


Figure 4. Locations of some industrial mineral operations active in Minnesota as of 1991. ⊠, Abrasive stone and dimension stone quarries; ■, crushed stone quarries; ▲, clay/shale and silica sand borrow pits.

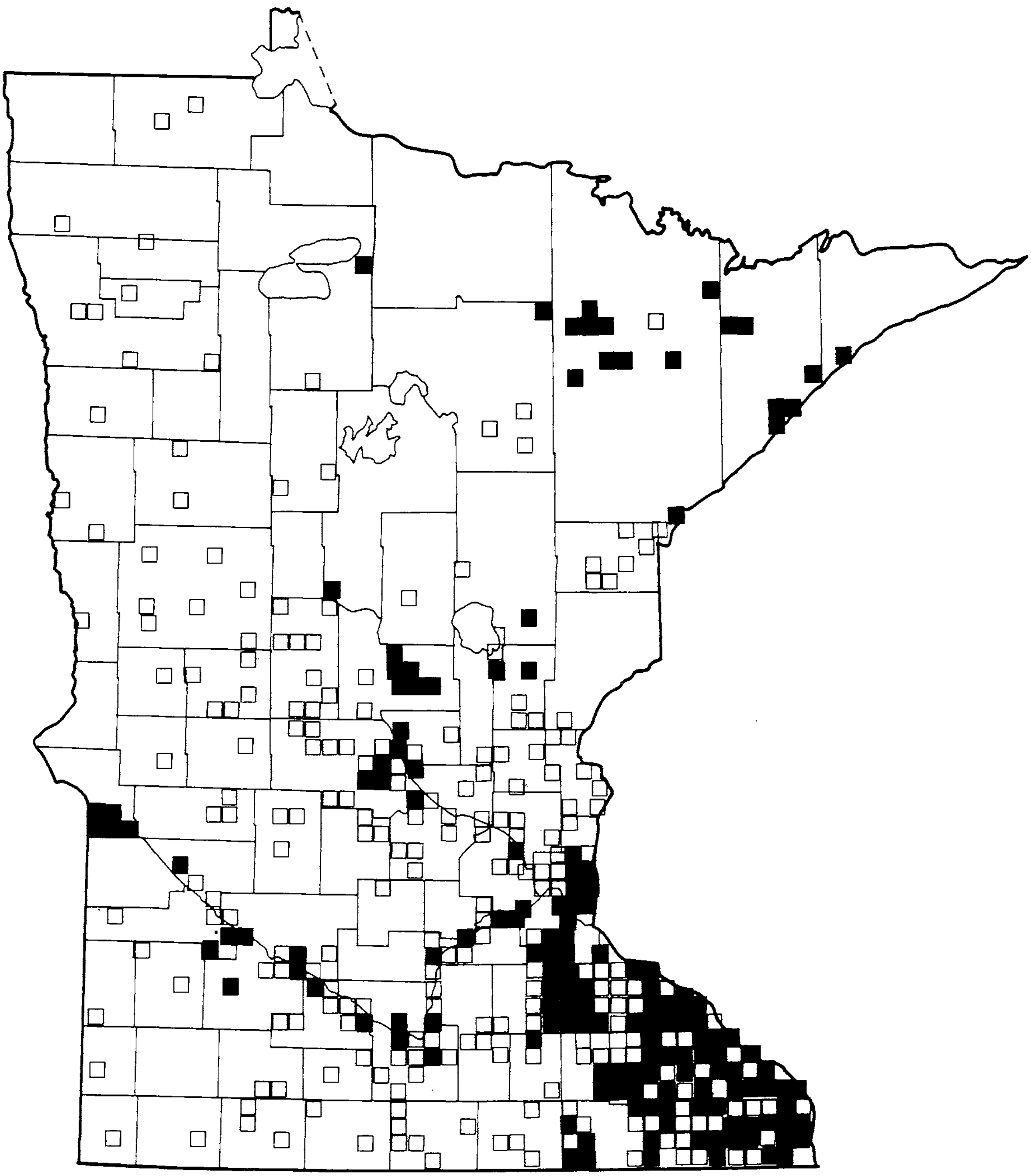


Figure 5. Location of some inactive industrial mineral operations in Minnesota as of 1991. ■, Crushed stone quarries; □, claystone/shale borrow pits or brickyards. Many of these localities may be operative in the future.

Figure 6. Sketch map showing the maximum extent of Pleistocene glaciation in North America about 14,000 years ago. Note that much of Minnesota lies within a zone of deposition (marked by a thick cover of glacial debris) whereas far northern Minnesota lies within a zone of maximum erosion (marked by a thin) cover of glacial debris. The thickness of a thick cover of glacial debris makes a mineral exploration more difficult in much of Minnesota.

covered mineral deposits actually exist in Minnesota? (2) What is the probability that one or more of these mineral deposits will actually be found? and (3) What is the probability that a deposit, once found, can and will be mined?

WHAT IS THE PROBABILITY OF UNDISCOVERED MINERAL DEPOSITS IN MINNESOTA?

During its 1987 session, the Minnesota Legislature considered programs to stimulate economic development in rural parts of the state. From that effort evolved the Minnesota Rural Development Act. Recognizing that the orderly development of the state's mineral resources could contribute to economic stability, the Legislature established a formal administrative framework—the Minnesota Minerals Coordinating Committee—charged with the development of a ten year plan that would emphasize economic expansion through long-term mineral diversification. The idea was to encourage as many exploration companies as possible to search for as many different commodities as possible, in as many different places as possible in the state.

Ten years have passed, without the discovery of an ore deposit. At this point, the skeptical reader might ask, "Why do geologists still believe that potentially important mining districts exist in Minnesota, particularly given the obscure nature of the bedrock?" The reasoning is very simple. Much of the bedrock here is very similar to that in other places in the world that have significant mineral wealth. In detail, mineral deposits should be found in Minnesota because it has rocks and structures similar to those in adjoining parts of Ontario, which is one of the world's ten-leading metallic minerals producers. The rocks that contain these mineral deposits do not stop at the International Boundary, and, according to the argument, similar deposits should be found in adjoining parts of Minnesota (Fig. 9).

Minnesota has the potential to play a prominent role in the minerals industry because its geologic setting is so highly varied. Much of the state is underlain by combinations of rock types and structures that are known from other places to be associated with important deposits of metallic minerals. Our understanding of the rocks and their structures has improved significantly within the past decade, particularly since the availability of the high-resolution aeromagnetic and gravity surveys. The data from these surveys have been integrated with the results of a follow-up scientific test-drilling program and outcrop-based geologic mapping to produce revised interpretive maps of Precambrian terranes in the debris-covered parts of Minnesota. These maps, which are more detailed and more sophisticated than their predecessors, provide new ideas about how the rocks formed

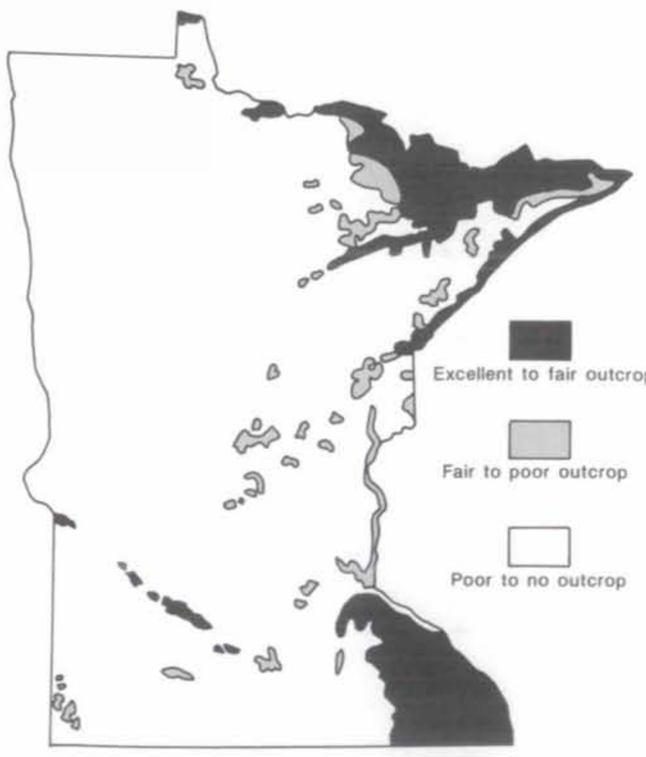


Figure 7. Sketch map showing the distribution of bedrock at or near the land surface.

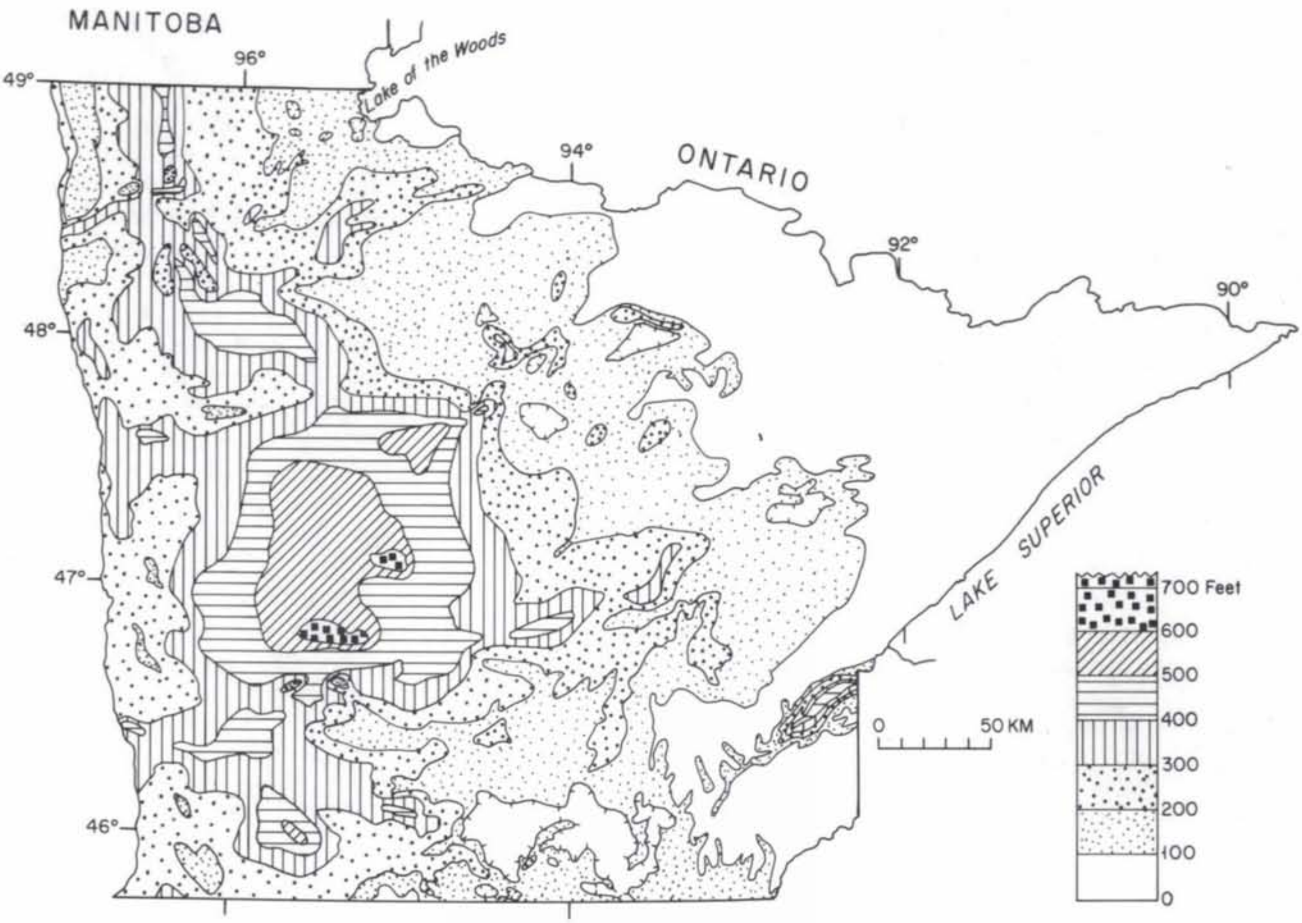


Figure 8. Contour map showing the thickness of glacial debris and poorly consolidated sedimentary rocks of Cretaceous age above solid bedrock in northern Minnesota. Compiled by D.L. Southwick.

and consequently new exploration targets. Equally important is new information being developed on the distribution, thickness, and stratigraphic complexity of the Cretaceous and Quaternary overburden in Minnesota, which provides realistic parameters on the technical difficulties and costs to be faced by explorationists working where the Precambrian bedrock is buried. Many of the new interpretations are based on data supplied by the exploration industry during 1970-1975 (base-metal sulfides) and 1983-1990 (gold).

The Precambrian bedrock of Minnesota can be conveniently subdivided in four major terranes. They are (Fig. 10): (1) the Superior Province of late Archean age (>2,500 Ma), which includes a dominantly greenstone-granite terrane to the north and a much older gneiss terrane in the south; (2) the Penokean orogen of Early Proterozoic age (ca 1,800 Ma); (3) the Sioux Quartzite of Early Proterozoic age(1,760-1,600 m.y.); and (4) the Midcontinent rift system, a continental-scale rift that developed in Middle Proterozoic time (ca. 1,100-1,000 Ma).

Archean Terranes

To date, belts of weakly to moderately metamorphosed Archean volcanic rock (so-called greenstone belts) within the Superior Province in northern Minnesota have attracted considerable interest in the search for gold and base-metal sulfides. This is because the metavolcanic rocks and the fault zones that traverse them are similar to the rock types and fault zones associated with gold-producing greenstone belts in Ontario and other parts of the world. Greenstone belts in Ontario also have been the site of considerable exploration and development of base-metal sulfides. Although both gold and base metals may be found in greenstone belts, they require different exploration strategies. Many of the gold deposits in Ontario occur along major linear structural breaks that can be recognized in the aeromagnetic data, even where the rocks are covered by glacial deposits. In contrast, base-metal sulfide deposits that contain copper and zinc, by analogy with those found in Canada and elsewhere, can be expected to occur at the tops of volcanic sequences where host rocks of felsic composition are abundant. Because of the sulfide constituents these deposits also are amenable to geophysical exploration by electrical methods.

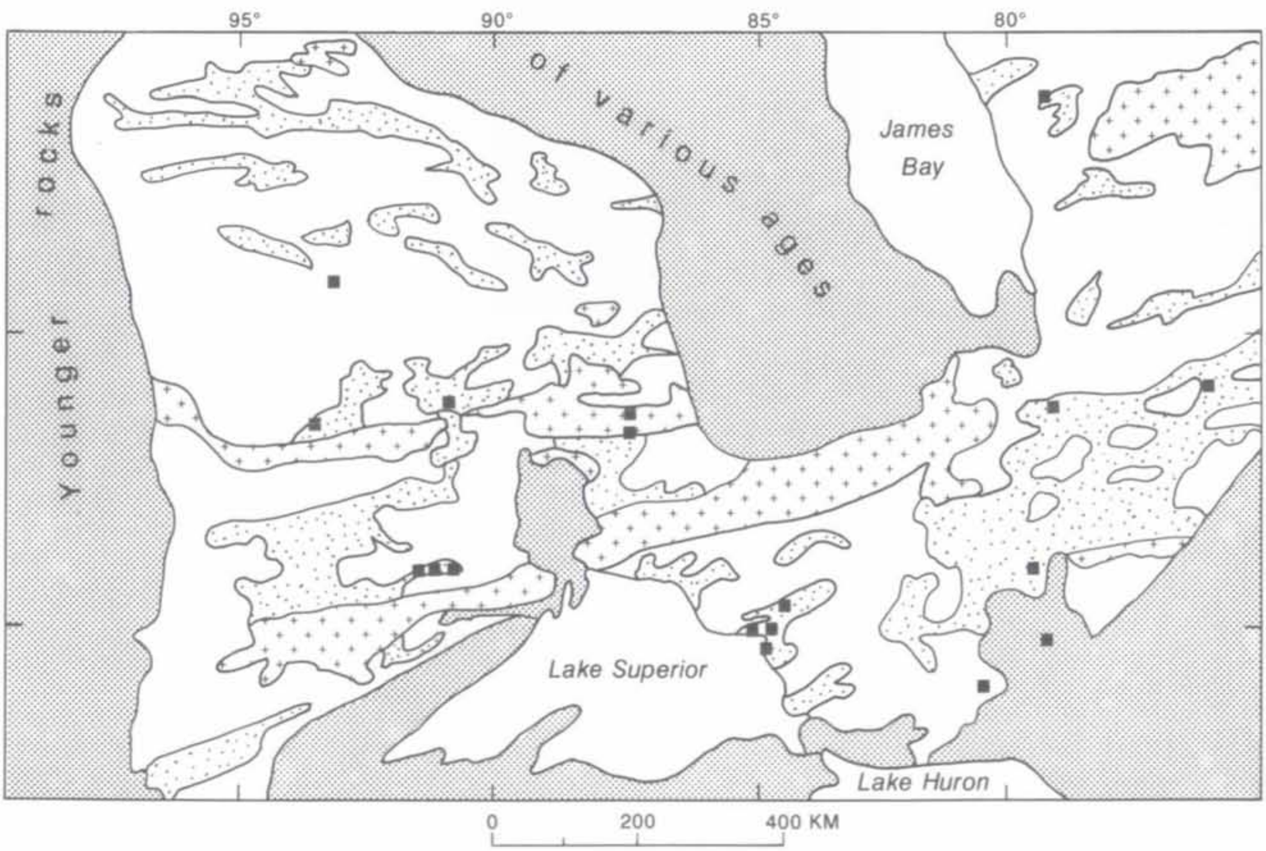
The Archean gneiss terrane of southwestern Minnesota consists predominantly of quartzofeldspathic gneisses and younger granitoid intrusions that have undergone a long and eventful Precambrian history. Some gneisses formed from volcanic and sedimentary rocks that may have been analogous to greenstone-belt associations; these too may have some gold and base-metal potential.

Penokean Orogen

The Early Proterozoic supracrustal rocks that comprise part of the Penokean orogen in east-central Minnesota may be divided into two entities, a belt of strongly folded and faulted strata to the southeast, overlain by one or more depositional basins to the northwest. The folded and faulted belt contains metamorphosed sedimentary and volcanic rocks of moderate- to low-grade. Some of volcanic rocks are similar to sequences in Wisconsin where at least eight base-metal sulfide deposits of economic significance have been discovered. The Wisconsin deposits are dominated by copper and zinc and, accordingly, are similar to volcanic-hosted base-metal deposits in Archean greenstone belts. The belt of folded and faulted rocks are fringed on the north by a sediment-filled basin that contains the major iron deposits of the Mesabi range on its outer fringes. Rocks in other parts of the basin contain appreciable manganese. The manganese resource is too small to be worked by conventional mining methods, but the manganese may be extracted someday by unconventional mining techniques that were being developed by the U.S. Bureau of Mines prior to its demise. Furthermore, recent research at the Minnesota Geological Survey has indicated that some of the manganese deposits may be guides to sedimentary-hosted base-metal and precious metal deposits—deposits not yet recognized elsewhere in Early Proterozoic rocks of the Lake Superior region.

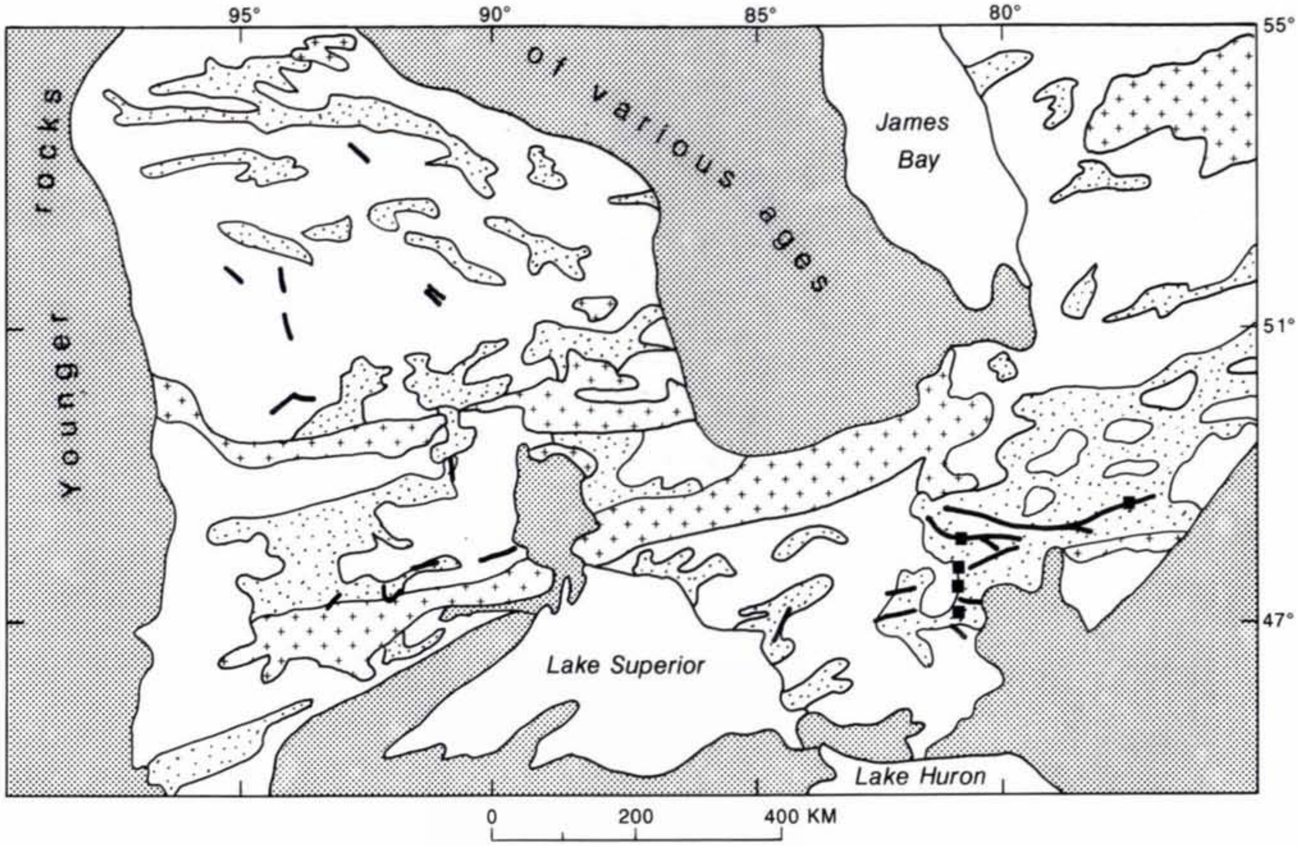
Masses of granite and related igneous rocks inplaced well after folding had ceased in the Penokean orogen may be found

Figure 9. Generalized geologic map of the Superior province of the Canadian Shield showing the distribution of some known metallic mineral deposits and occurrences.

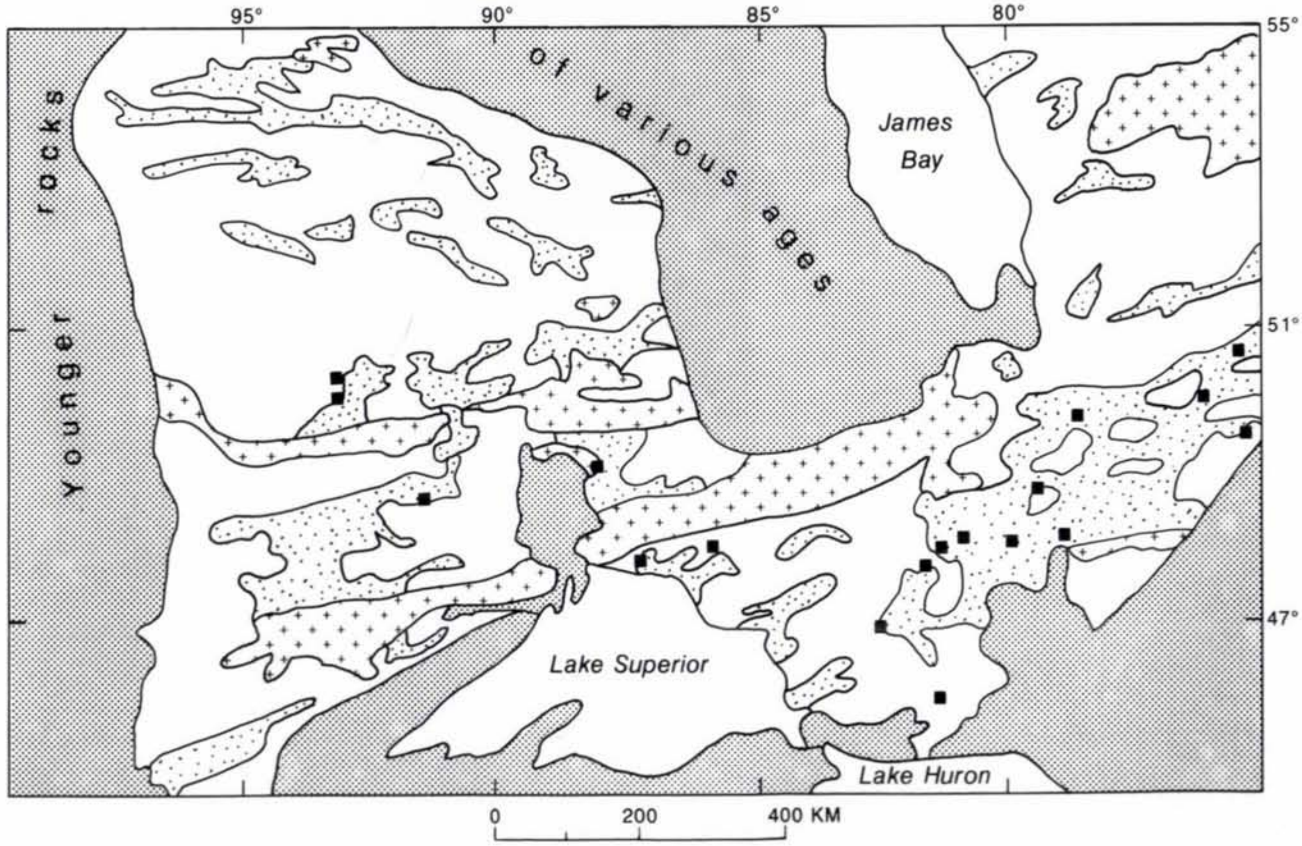


A. ■, major units of iron-formation.

Figure 9 Continued

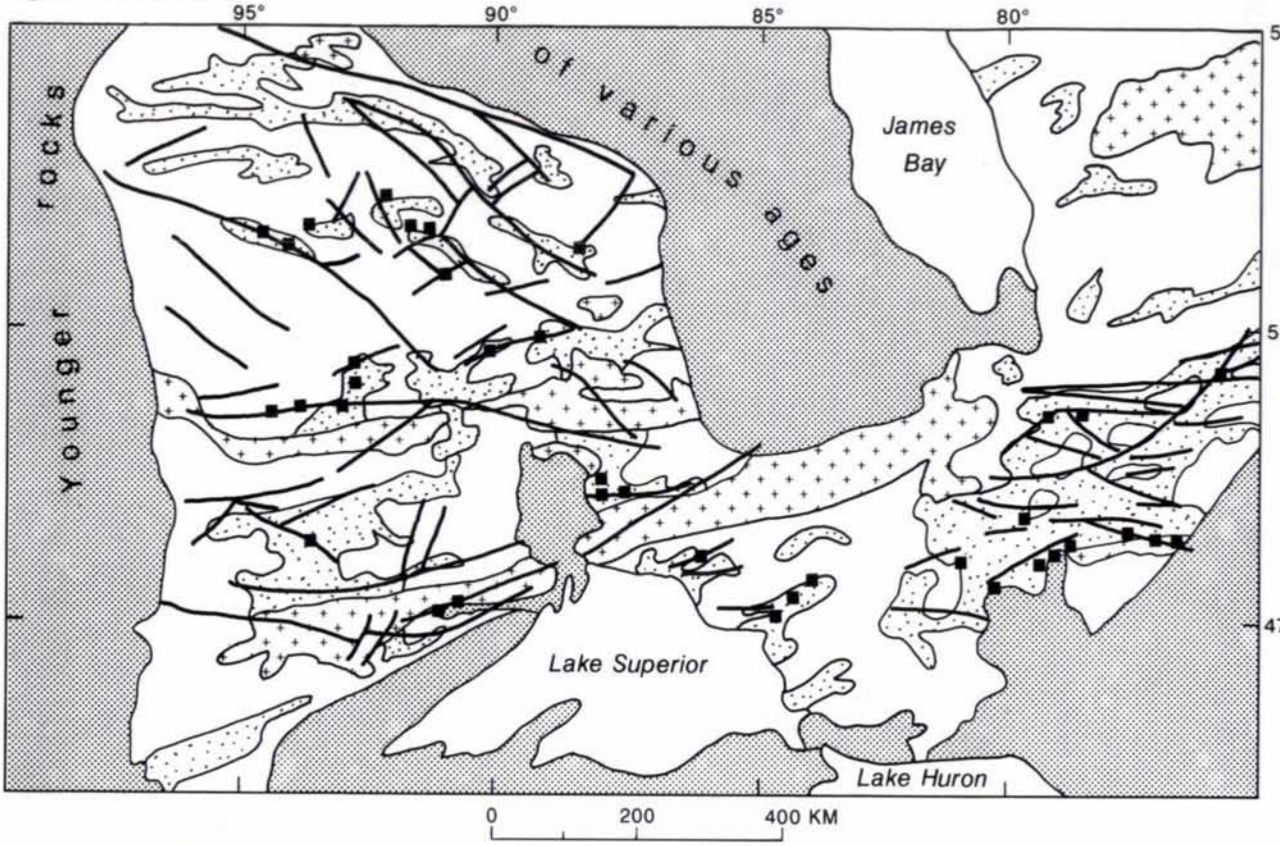


B. ▬, komatiite successions, and associated nickel-copper-platinum group element deposits, ■.

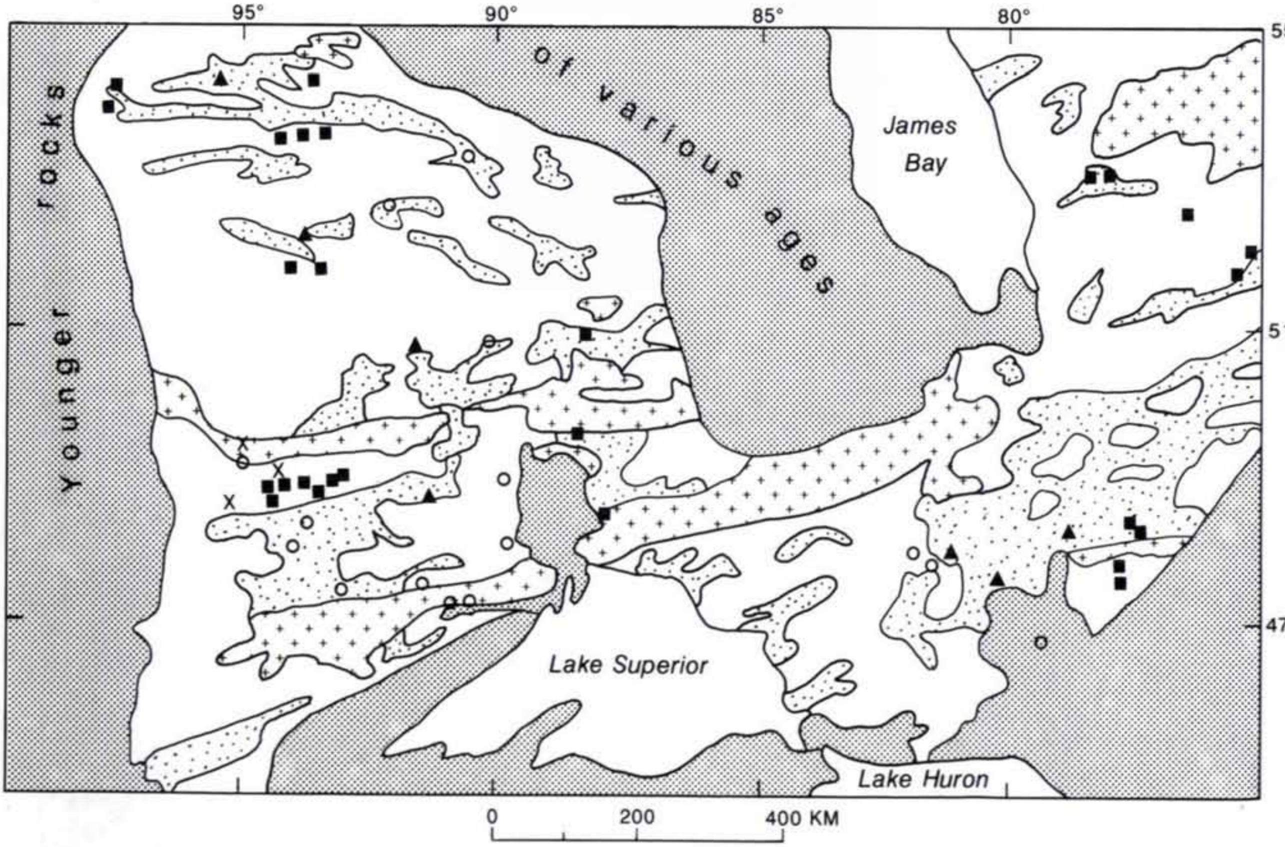


C. ■, volcanic-associated massive base-metal sulfide deposits.

Figure 9 Continued,



D. ▬, regional deformation zones, and spatially associated lode gold camps, ■.



E. ▲, porphyry-like copper-molybdenum-gold occurrences and deposits related to intermediate and felsic intrusions; ■, rare earth elements and other pegmatitic associated deposits; X, uranium, and/or thorium pegmatitic associated deposits; o, nickel-copper-platinum group elements and chromite associated.

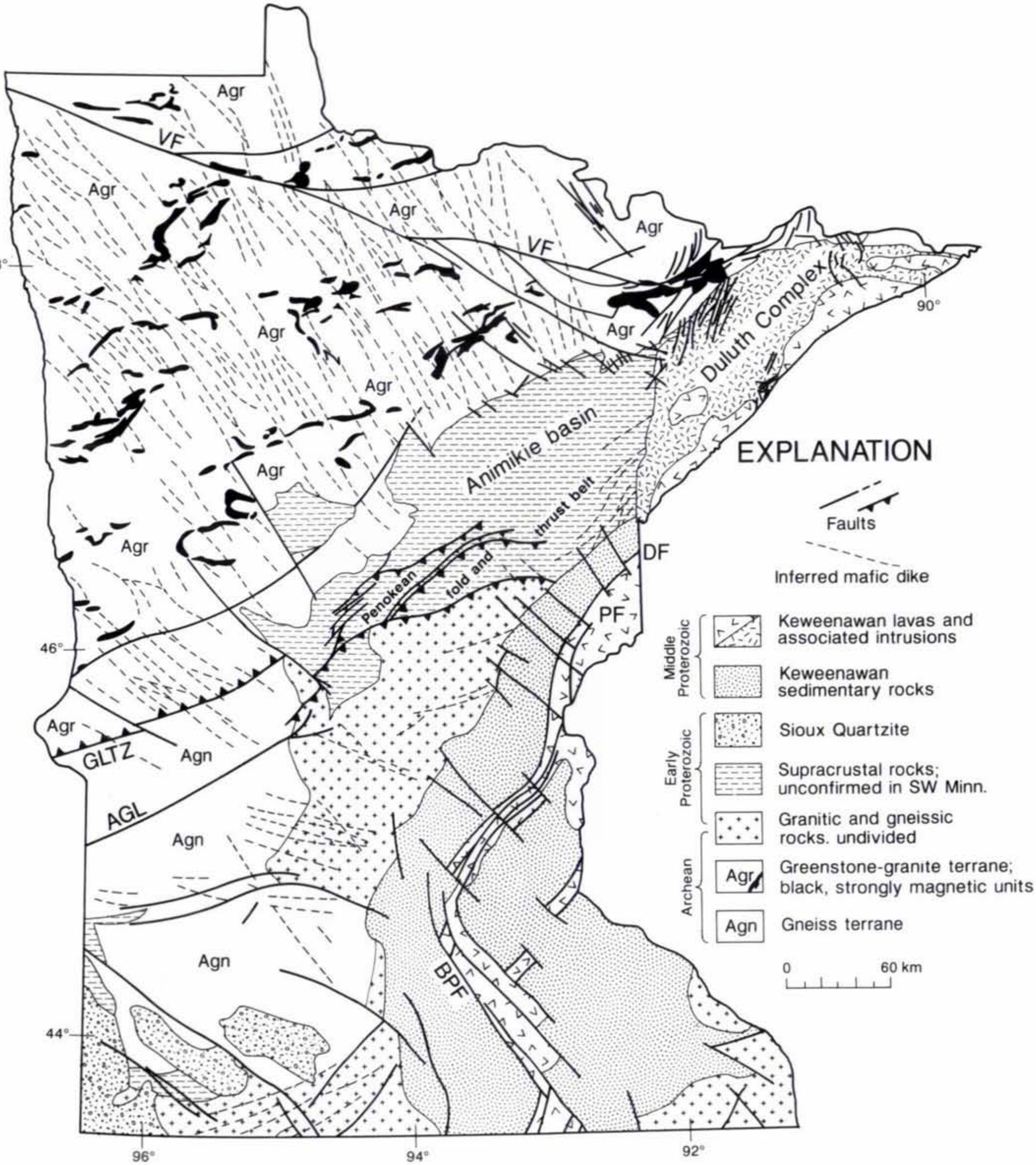


Figure 10. Generalized Precambrian geologic map of Minnesota compiled by D.L. Southwick. Strongly magnetic units within the greenstone-granite terrane shown in black. Mafic dikes largely inferred from aeromagnetic data. Named linear features include: AGL, Appleton geophysical lineament; BPF, Belle Plaine fault; DF, Douglas fault; GLTZ, Great Lakes tectonic zone, PF, Pine fault, and VF, Vermilion fault.

extending southward from central Minnesota to Iowa. These granitic rocks are an important source of dimension stone in east-central Minnesota and parts of the Minnesota River Valley, where glacial cover is thin or absent.

Sioux Quartzite

The Sioux Quartzite of Early Proterozoic age rests unconformably atop Archean and older Proterozoic rock in southwestern Minnesota. The Sioux is a dominantly red sandstone sequence that may contain placer gold deposits. Serious exploration of the Sioux is hampered, perhaps fatally, by poor exposure and a generally thick cover of Cretaceous rocks and Quaternary glacial deposits.

Midcontinent Rift System

The Midcontinent rift system, the last of the major Precambrian subdivisions in Minnesota, consists dominantly of rift-related basaltic flows and intrusions, and post-rifting sandstone and shale. The stratified rocks comprise part of the Keweenawan Supergroup. Prominent among the rift-related intrusive rocks is the Duluth Complex, a very large multiple intrusion of mafic rocks, which since 1949, has attracted considerable attention as a potential source of copper, nickel, vanadium, titanium, cobalt, and platinum-group elements, all in a variety of discrete geologic settings. Eventual mining for copper, nickel, and platinum-group elements will depend at least as much on the development of metallurgical and benefication techniques for low-grade sulfide ore as it will on further regional geologic research. Nonetheless, geology remains important because mining and benefication must be tailored to specific deposits, which requires detailed mineralogic, petrologic, and structural studies not yet undertaken.

There also is an excellent potential for copper and silver deposits in post-rift related sedimentary rocks that underlie parts of central and southeastern Minnesota. Both native copper and stratiform copper sulfides (+ silver) have been found in the same or broadly similar sedimentary rocks in Michigan (White Pine Mine) and Wisconsin. As has been documented many times, such units are pyrite-rich and act as very efficient chemical traps for copper and silver in oxidized, sulfate-rich ground water. However, the promising strata in Minnesota are covered by substantial thicknesses of Phanerozoic sedimentary materials in most places, which makes exploration difficult.

Significance of post-Precambrian weathering

Much of the Precambrian bedrock in western Minnesota is marked by a layer of residual clay or saprolith, which in places is more than 300 feet thick. The layer crops out in only a few places, in particular along the walls of the Minnesota River Valley, where it is mined for cement filler and brick. Much of the area where saprolite is developed in northwestern Minnesota is underlain by mafic volcanic rocks of Archean age. As noted, volcanic rocks in these so-called "greenstone belts" have potential for lode-gold and base-metal (zinc and copper) deposits. Although exploration has focused on finding a primary deposit, it is interesting to speculate about the size and grade of a world-class Archean deposit that was subsequently enriched by downward-flowing groundwater related to an episode of intense weathering.

In summary, the rocks and their structures in the state are complex and variable from place to place. Mineral potential also varies from place to place, and there is no reason at this time to exclude any part of the state from having at least some potential. Furthermore, we have learned from the aeromagnetic data that many of our previous ideas regarding the geology of the buried bedrock of the state were erroneous. Indeed, our knowledge is so vague that it is not even possible at this time to consider the full range of mineral deposits that could occur in these areas. Nonetheless, it is safe to conclude that the mineral potential of these unknown areas will increase as our geologic knowledge increases.

WHAT IS THE PROBABILITY OF FINDING AN ORE DEPOSIT IN MINNESOTA?

The probability that a variety of mineral deposits exist within the state may be fairly high, but the probability of actually finding a deposit is much lower. Given the fact that much of the most prospective bedrock is buried, it is highly unlikely that a mineral deposit will be found by chance. A deposit will be discovered only if someone is applying the best geological, geophysical, and geochemical know-how to look for it, and that search will succeed only if both the public and private sectors contribute. The line between public and private contributions to the exploration processes is commonly broad and imprecise. It is clear that decisions about where and when to explore belong to the private sector, which generally guards its decision-making power closely. Private explorationists protest strongly, and rightly so, if they think that government is embarking on a geologic program designed specifically to produce a discovery. The role the public sector plays in the exploration process is less well defined. To understand what that role should be involves an understanding of how a company goes about deciding where it will spend its exploration budget. From their perspective, the basic exploration problems are threefold: (1) Area selection, or deciding in which county, region, or district to initiate an exploration program; (2) area evaluation, or deciding how best to search the selected areas to identify specific targets; and (3) target evaluation, or determining within reasonable financial limits if in fact an economic ore body exists once the desired geological targets have been identified. In effect, the exploration processes is designed to reduce the size of the target area so as to maximize the financial and scientific resources of the exploration companies (Fig. 11).

Exploration requires a large, continuing financial investment, and it may be years before an economically viable discovery is made (Fig. 12). Most searches end in failure and involve considerable financial loss. Thus, an exploration

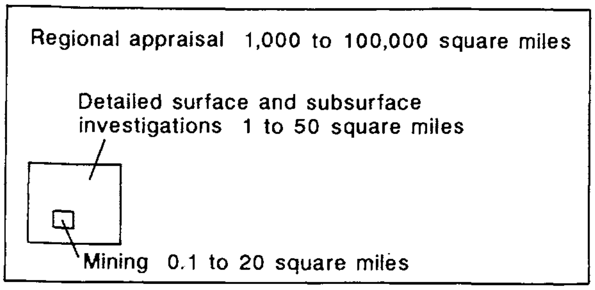


Figure 11. Comparison of areas needed for regional reconnaissance studies, detailed investigations, and (if an economic deposit is discovered) an actual mining operation.

company will decide to explore only if there is a reasonable probability that their investment can be recovered in the future. Exploration, especially in today's short-term market, tends toward financially "safe" places that have favorable political and economic environments. Exploration also tends toward places with a long history of mineral production and where exploration will be a relatively simple task. From a company's view, the best places to explore are in the immediate vicinity of producing mines, or where strongly anomalous concentrations of some commodity can be confirmed from outcrop sampling or inferred from geophysical and geochemical techniques. In virtually all places the decision to explore involves both political and geologic factors.

Geologic factors are most important in the area-evaluation phase. Exploration managers use geologic information to judge how much effort should be put into an area in Australia, for example, in contrast to an area in Canada, or for that matter, Minnesota. When all other factors are more or less equal, the critical question is "how quickly can the size of the target areas be reduced to manageable sizes so that their potential can be evaluated as quickly and inexpensively as possible?" It is clear that the more that is known about a region, the more quickly a company can move through the area-evaluation stage to the selection and evaluation of favorable geologic targets.

One way an exploration company can quickly evaluate a particular area involves the use of mineral-deposit models that summarize geologic attributes believed to be important in concentrating a particular mineral commodity into a mineral deposit. One might assume that mineral deposits occur more or less indiscriminately, like "raisins in a pudding." This is partly true; mineral deposits are distributed widely but unevenly throughout the earth, as are rock types. Different deposit types are formed in different places and at different times because the geologic processes responsible for them are unevenly distributed in space and time. It is the exploration geologist's job to identify those geologic processes and attributes that characterize a particular kind of deposit. Thus geologists study already identified deposits and then use that information to search similar geologic settings for undiscovered deposits, either in known mining districts or in entirely new areas.

As one example of the site-selection process at work, prospectors in northern Minnesota during the late 1800's recognized that most of the gold deposits they sought were commonly associated with veins of white quartz. Exploration for undiscovered gold deposits therefore focused almost exclusively on places where outcrops of white rock could been seen. This is outcrop prospecting at its simplest. Although now more scientifically based, outcrop-prospecting continues to serve well where considerable bedrock is exposed. However, in many parts of the world the possibility of finding ore at the outcrop face is gradually being exhausted. Consequently, explorationists must project their targets to sites deeper below the surface or into areas covered by glacial debris. As this kind of exploration goes forward, success will depend less on raw prospecting and more on geologic understanding. Modern mineral deposit models, and especially those that combine geologic, geochemical, and geophysical information, offer a potentially powerful method for organizing knowledge and identifying blind targets (Fig. 13).

The hypothesis that gold is associated with white quartz in northern Minnesota is a very simple mineral-deposit model. Today's models are much more sophisticated. They summarize concisely all of the geologic, geochemical, geophysical, and economic information available about a particular kind of mineral deposit. One such exploration approach using a variety of data as advocated by the U.S. Geological Survey is illustrated in Figure 14. Even this model, like all other mineral deposit models is in one way or another incomplete, depending on its maker's access to information. The models continue to change as new information is acquired and new discoveries are made. Furthermore the model approach to exploration has serious limitations because the models are based on known deposits; models cannot be used to find speculative types of deposits that have not yet been recognized and described. This class of deposit almost always will be discovered by chance, because explorationists "can see only those deposits they know to look for."

We can illustrate the use of mineral deposit models with an example from Minnesota. We already have concluded that there is a high probability of lode-gold deposits typically associated with greenstone belts of Archean age in northern Minnesota. Interest in the search for lode-gold deposits, first in Canada and later in Minnesota, was heightened by the 1982 discovery of the Hemlo gold deposits on the north shore of Lake Superior, approximately 100 miles east of Thunder Bay. The Hemlo deposits occupy the extensively deformed central part of a large Archean fault system and contains at least 80 million tons at an average grade of 7.7 grams/ton of gold. These deposits are of world-class size.

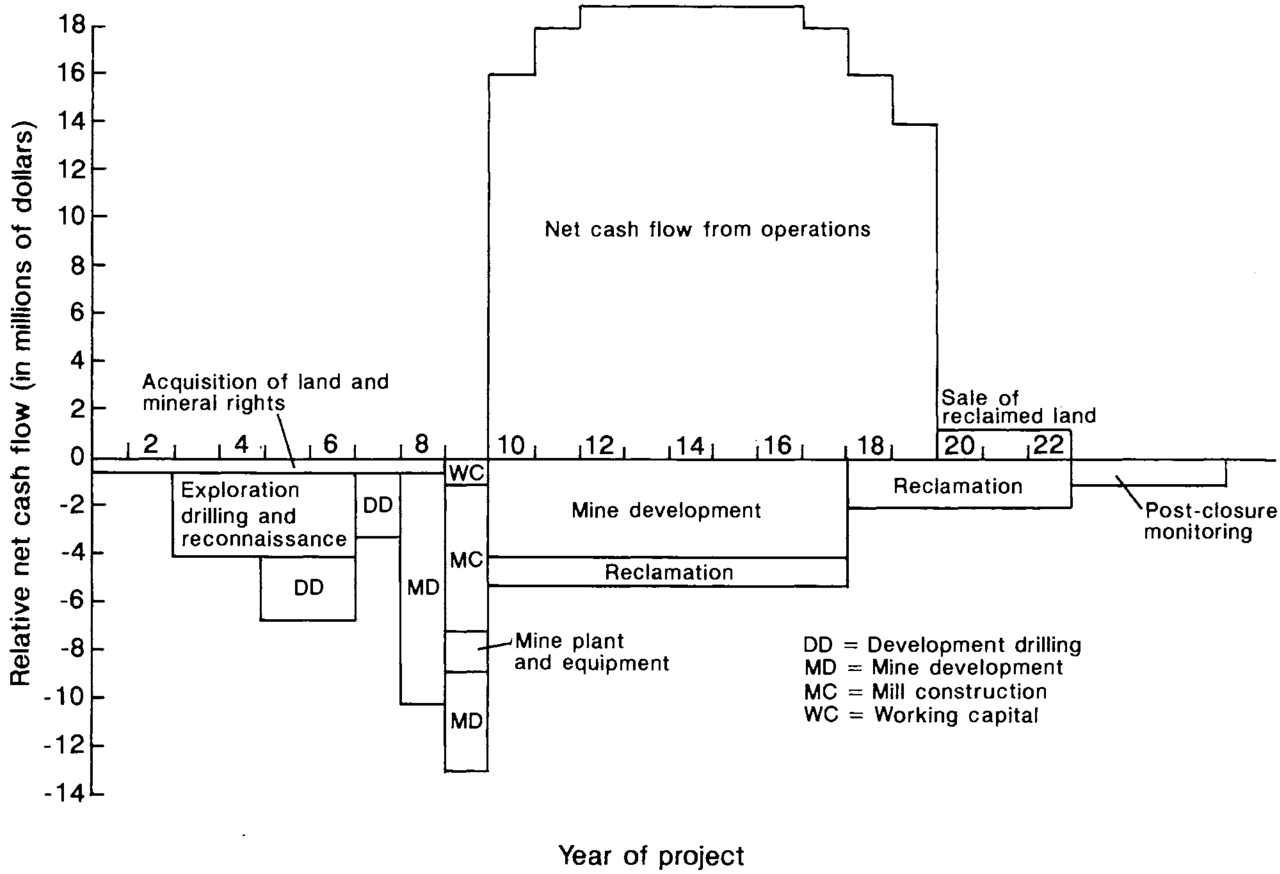


Figure 12. Pattern of cash flow over time for a hypothetical mining deposit.

Geologists working in and around the Hemlo deposits have identified a set of characteristic geologic attributes that can be used to construct several preliminary mineral deposit models. The immediate host rocks to the ore zone are mostly so badly fractured and altered that their original character is no longer discernible. Gold mineralization occurs within the fracture zones in lenses of quartz and carbonate and apparently was deposited there by hot fluids moving through the rocks along channelways formed by faulting on a regional scale.

One deposit model surmises that the gold was emplaced after metamorphism and fracturing had peaked, whereas a second model surmises that the gold was present before peak metamorphic conditions occurred and that it was subsequently remobilized and redeposited at its present locations by through-flowing solutions. The question of early-formed versus late-formed gold is an interesting geologic problem. However it is clear from both models that one will not find a Hemlo-type deposit in the absence of fault zones. Thus, in our example, areas within Archean greenstone belts in Minnesota that contain regional faults along which alteration has occurred would be selected as having two of the key criteria associated with Archean lode-gold camps in Canada, Australia, South Africa, and elsewhere. In Minnesota such regional fault systems are readily apparent on aeromagnetic maps such as the one shown in Figure 15.

All of this illustrates an important point: Companies need geologic maps and other kinds of information to complete their evaluation of an area. Thus the ability of an exploration company to select and constrain search areas is almost entirely governed by the amount of reliable geologic, geochemical, and geophysical data available in the public record. Thus in our gold example, without the information that Archean rocks, faults, and alteration zones collectively exist in northern Minnesota, the exploration companies would be unable to define reasonable search areas; they would then turn their focus to other places where such information is available. Therefore mineral exploration, and ultimately mineral development, depend above all on the availability of regional and intermediate-scale geologic maps and reports as well as existing exploration data.

A lack of regional and intermediate-scale geologic maps not only restricts where an exploration company will search, but also can cause some companies to decide not to come to

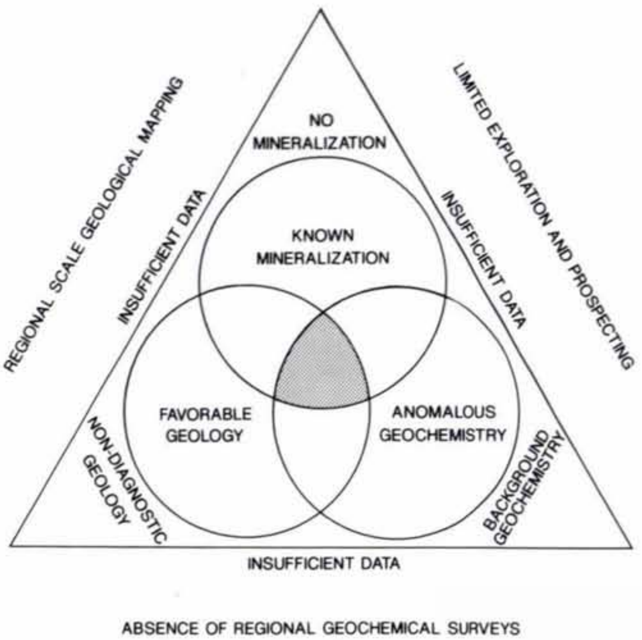


Figure 13. Diagram showing how a greater degree of confidence regarding the mineral appraisal of an area may be achieved when favorable elements from distinctly different kinds of data are considered simultaneously.

an area at all. Mineral exploration companies rarely will use their own resources to produce regional-scale geologic maps. Therefore it is the responsibility of the public sector to produce the necessary maps and reports if they wish to attract and sustain exploration activity.

Exploration for gold, base-metal sulfides, uranium, diamonds, or petroleum has taken place in Minnesota not by chance, but because there already existed documented geologic studies in the form of maps and reports that showed the presence of appropriate geologic conditions for these commodities. In many situations those geologic maps and reports were prepared for other reasons. However good maps and reports emphasize factual data that remain useful even though specific needs change. Thus mappers should not map with a specific commodity or exploration model in mind. History has shown that once a mining company begins to explore, some individuals will exert political pressure to have mappers focus on certain criteria that make up part of some mineral deposit model because that is what the explorationists "needs to know." If that mapping strategy were to be followed, each area would have to be mapped and remapped, depending on what commodities and deposit models were in vogue. Regional and intermediate-scale geologic maps prepared in the public sector should never be commodity- or model-driven. Though they must satisfy the needs of the present generation of explorationists, they also must be broad-based enough to satisfy a future generation searching for currently unthought-of or speculative commodities.

WHAT IS THE PROBABILITY OF AN ORE DEPOSIT BECOMING A MINE IN MINNESOTA?

The discovery of an ore deposit of sufficient size and grade is the first step toward developing a mine, but a discovery—no matter how large or rich—will not necessarily lead to mining. For an ore deposit to be mined requires that the commodity can be extracted profitably with existing technology and under current economic conditions. Thus, all the geologic knowledge in the world will not make a mine (Fig. 16). Given the economic constraint, it is obvious that many discoveries never become mines. It is less obvious, but equally true, that many mines are closed—not because the resource has been depleted, but because continued mining loses money.

Two examples, both from Minnesota, illustrate this point. Exploration showed that the basal part of the Duluth Complex contains a vast but low-grade copper-nickel resource. It was clear from the beginning that the disseminated nature of the potential ore would require the handling, processing, and disposing of large volumes of materials. Furthermore, the potential ores, by-products, and waste materials were thought to be potentially harmful to the environment. The state was prepared to require stringent procedures to protect the environment; costs associated with these procedures would have added substantially to the overall project costs.At about the time these economic questions were being considered, worldwide copper and nickel prices decreased dramatically. It became apparent that the deposits in the Duluth Complex could not be mined for a profit at that time. Interest in these deposits remained on "indefinite hold" for a number of years, but there is now renewed interest mainly because the economic outlook for copper has improved. It is also clear that new extractive technologies must be developed before these deposits will be mined. Mining engineers, metallurgists, and geologists in the public sector can and must help in that work, but in the last analysis the economic success of copper and nickel in the Duluth Complex will depend almost entirely on pricing structures driven by worldwide supply and demand.

The second example concerns iron-ore deposits on the Vermilion range, also in northeastern Minnesota. There, the iron ore crops out at the bedrock surface and tabular bodies of high-grade hematite that have steeply dipping to near-vertical configurations. Consequently, the ore was first mined by open-pit methods, but it was soon recognized that ore could be extracted efficiently only by expensive underground methods. Mining started in 1884 and by the time the last mine on the range had closed in 1963, 103 million tons of ore had been shipped to down-lake ports. However, according to estimates of the Minnesota Department of Revenue, more than 8 million tons of identified ore remained in the ground when the mines closed. Most of the remaining ore was located in the deeper parts of the mines, where it will stay until it again becomes economically feasible to extract and transport iron ore from underground mines. That may be a very long time!

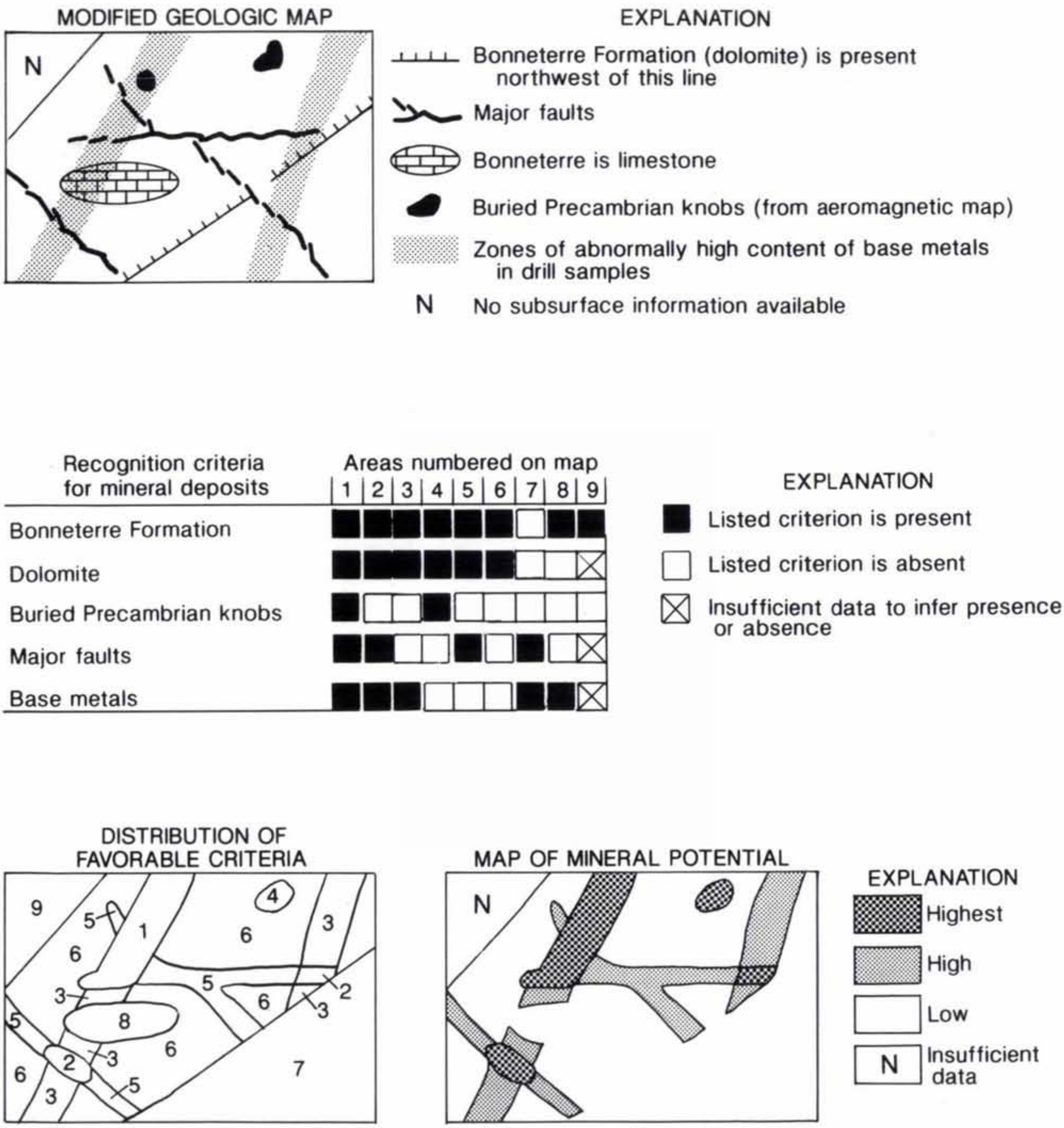


Figure 14. An example of a mineral appraisal scheme advocated by the U.S. Geological Survey. It begins with the preparation of a modified geologic map showing features related to potential mineral deposits, in this case Mississippi Valley type (MVT) lead-zinc deposits. As summarized in the column next to the map, the Bonneterre Formation is shown where it has been altered to dolomite, typically around older Precambrian rocks or along faults. Deposits also may be surrounded by traces of lead and zinc in surrounding rock. The middle map shows the distribution of rocks having these favorable characteristics, and the bottom map uses these zones to classify the map area in terms of the probability of containing MVT deposits.

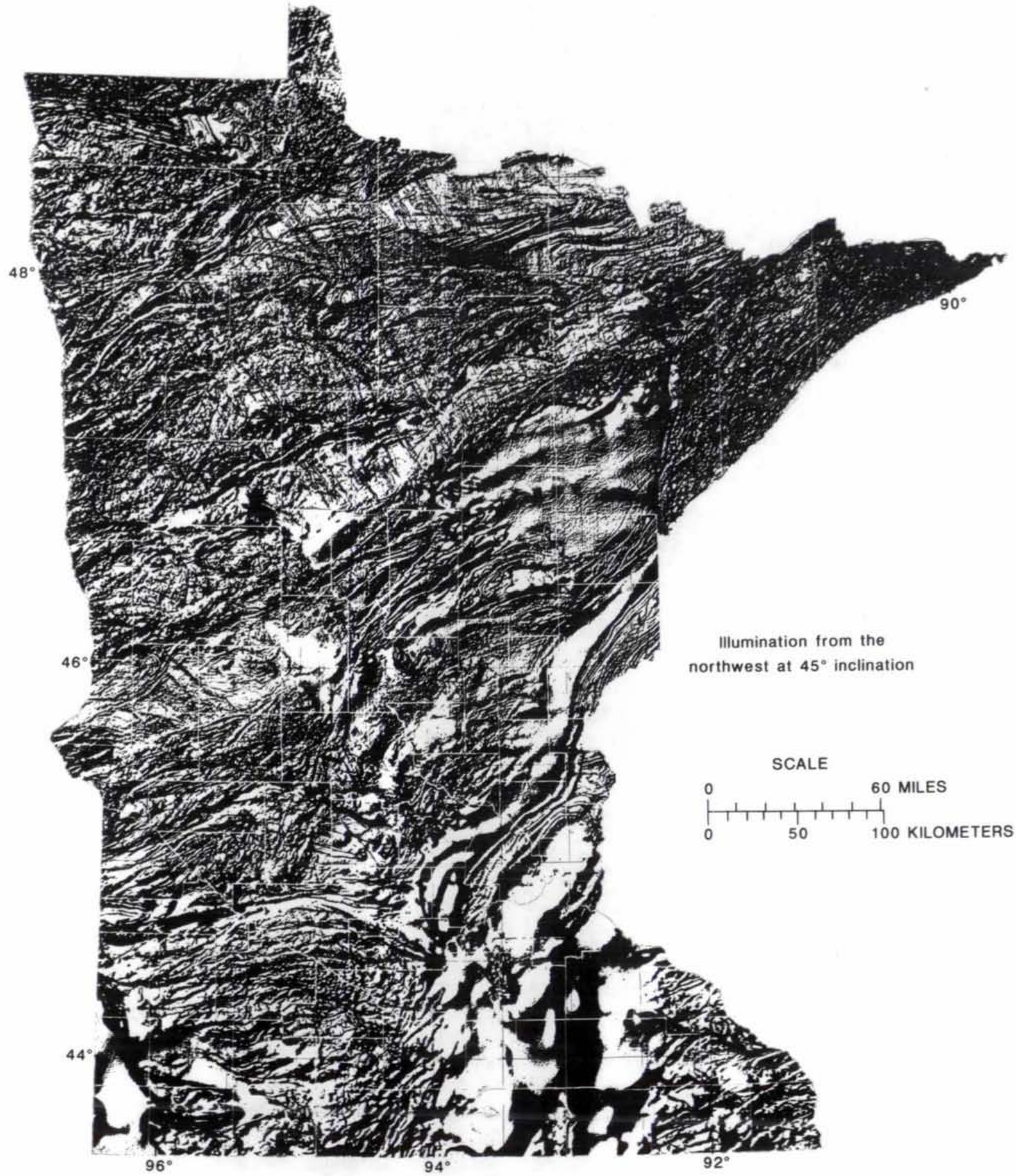


Figure 15. Aeromagnetic map of Minnesota. Note the numerous linear trends that can be seen on this map. Many, and especially those in northern Minnesota, correspond to major fault zones.

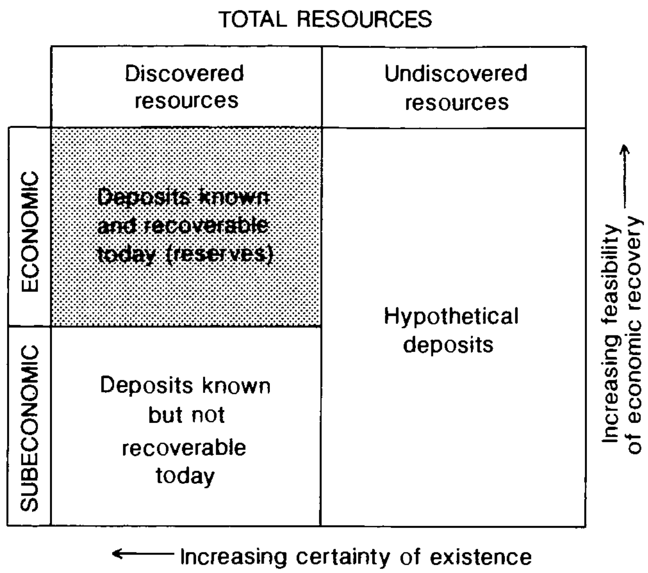


Figure 16. Resource classification scheme used by the U.S. Geological Survey. Note that on this diagram increasing amounts of geologic information move the resource to the discovery stage, but cannot produce a mine. Economic factors move a discovery from a resource to a reserve and to ultimate production.

In the end, the question to develop or not develop an ore body commonly turns on economic and public policy factors. The decision depends on specific factors such as taxes, royalties, environmental costs, and interest rates, as well as on less specific questions regarding potential impacts on the quality of life.

Today in Minnesota there are a number of commodities such as manganese, titanium, and cobalt that occur in fairly large quantities but that cannot be utilized at this time because they cannot be concentrated into economically viable products. Thus an important component of sustainable development is basic metallurgical research that will ultimately lead to the utilization of these geologic resources.

CONCLUSIONS

The rocks and their structures in those parts of Minnesota where they are close to the surface are complex and variable from place to place. These complexities work for us in that they create potential for a wide variety of mineral resources. However, the rocks of so much of the state is so poorly known that we cannot predict with any degree of certainty what commodities might be present or where they might be found.

Recognition and development of these resources depends on the close cooperation of the public and private sectors. The primary purpose of the private sector is to find ore and provide the marketplace with products that create a profit. The public sector should be more concerned with developing knowledge about the basic geological infrastructural of the state and evaluating its mineral potential. It also should investigate and promote ways to develop resources in anenvironmentally responsible manner and devise methods to distribute a fair and equitable income to the citizens. A further responsibility of public agencies is to collect, synthesize, and analyze basic data about mineral resources and to make the information available to those in both the public and private sectors who need it for decision-making. Within the framework of sustainable development it is important that mineral resources be managed so that the wealth they generate effectively substitutes for the depleting mineral asset and secures access to minerals by future generations.

It is likely that most of the obvious mineral deposits that occur on or near the land surface of Minnesota have already been discovered. Future exploration and mineral processing studies must focus more on finding high-grade deposits that are exposed poorly or not at all, and on developing low-grade deposits that would not have been profitable to mine in the past.

Geology is the principal scientific discipline used in mineral exploration. Exploration depends on a thorough understanding of the physical and chemical characteristics of mineral deposit types and their enclosing rocks and their overlying glacial cover. Regional geologic syntheses involving geological, geophysical, and geochemical data yield the information that can be used by the private sector to define exploration targets of manageable size. Very detailed studies in these areas by mining companies will confirm or deny the existence of a mineral deposit. That effort may require many years of frequently intermittent activity and large financial investment before a mineral deposit can be considered for development. Lead times of as long as 20 years are not uncommon from the beginning of an exploration project to the start of mining. The odds against making a significant discovery are high, and mining companies must be confident that they will be permitted a return on their money should they discover a deposit of mineable size. Government must recognize the long-term nature of mineral exploration and develop its policies accordingly.

As part of any mineral policy, the state must recognize its role in the exploration processes. The *sine aqu non* of exploration is a geologic map. In practice this means a series of thematic maps at appropriate scales, showing pertinentrocks, their structural distribution, geochemical, and geophysical attributes, and whatever else may be detected about the geology (Fig. 14). Most importantly that information must be available when a mining company first decides to embark on an exploration program. In Minnesota, we are fortunate to have a high-resolution aeromagnetic database. This database, which provides the means of seeing beneath the glacial drift, provides coverage in even very difficult terranes. Thus aeromagnetic, and to a lesser extent gravity, data that the state has collected are valuable tools in mineral exploration, particularly on regional and district scales. However, proper interpretation of geophysical or any kind of data depends on accurate geologic mapping, either on the outcrop or by use of the drill. Geophysical maps in no way replace the continued need for geologic maps, which depend on and integrate a wide variety of thematic data. Failure to produce geologic maps because the drift is too thick, or because of other reasons will mean that certain parts of the state will be "off-limits" for exploration.

Good intermediate-scale and regional geologic maps not only will encourage more industrial involvement in Minnesota, but also will get us out ahead in any competition with other localities. Several studies, including those of the U.S. Geological Survey, the National Academy of Sciences, and the Association of American State Geologists, have shown that on a national level, map production has lagged far behind need. This is true despite the near-unanimous opinion of geologists in industry that the single most useful product of government geological surveys is geologic mapping.

The same studies have shown at least two reasons for the decline in mapping. First, over the past 20 years or so the application of physical and chemical process-related research has carught the imagination of many academic geologists in leading research institutions. Many of today's academic leaders believe that geologic mapping is not an acceptable component of a graduate thesis. Thus many universities no longer train their student geologists to make geologic maps. Second, in many geological surveys, decisions regarding operational priorities have been taken from professional geologists and placed in the hands of administrators with no real knowledge of the role government is expected to play in mineral resources. Commonly the administrators opt for short-term flashy results rather than long-term results provided of good geologic maps.

Though the situation in Minnesota is not as bad as elsewhere in the country, we can and should do better. We must remember that good geologic maps are the products of good geologists who have been given the time and money to do the job properly. Good mappers are people who are equipped mentally, physically, and logistically to perform very difficult tasks.

The last ingredient of any successful exploration program is time. Successful exploration companies do not become discouraged after a year or so of effort. It took 17 years of active exploration by Western Mining to find the world-class Olympic Dam copper-uranium-gold deposit in Australia. The searches for other deposits in other parts of the world have taken equally long periods of time. Our political leadership must recognize the importance of time, particularly today when many are accustomed to think only in terms of short-term profits. The benefits of sustainable development will occur when we take the long-term view and recognize that today's profits provide the capital for tomorrow's mining ventures.

ACKNOWLEDGMENTS

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