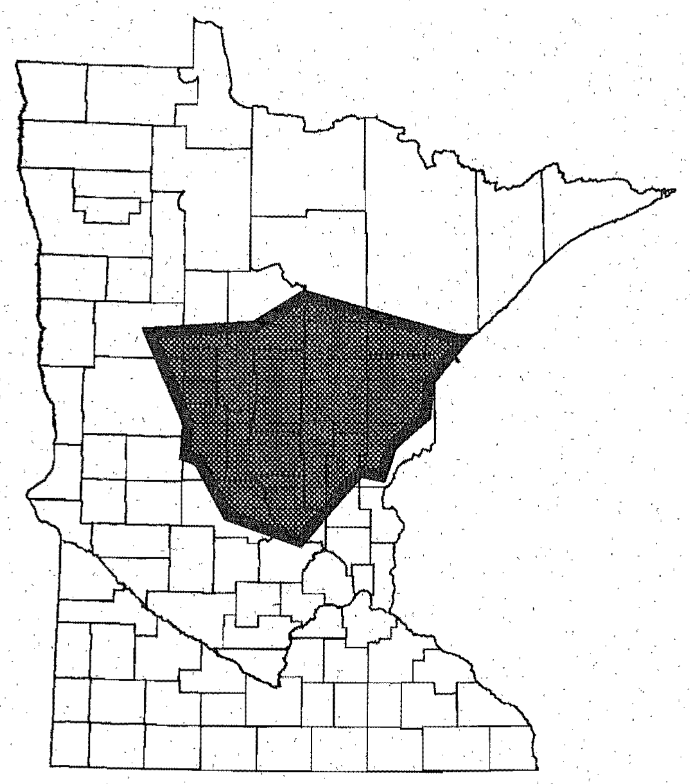
COMPILATION OF METALLIC MINERAL POTENTIAL DATABASES FOR ANALYSIS USING GEOGRAPHIC INFORMATION SYSTEMS

CENTRAL MINNESOTA



LOCATION STUDY AREA

REPORT 295

1997

Minnesota Department of Natural Resources
Division of Minerals

CENTRAL MINNESOTA:

COMPILATION OF METALLIC MINERAL POTENTIAL DATABASES

FOR ANALYSIS USING GEOGRAPHIC INFORMATION SYSTEMS

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REPORT 295
1997

MINNESOTA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF MINERALS
WILLIAM C. BRICE, DIRECTOR

Digital files for Report 295, Central Minnesota: Compilation of Metallic Mineral Potential Databases for Analysis Using Geographic Information Systems are provided with this report on floppy disks labeled P295.EXE and P295a.EXE; contents are listed in the Appendix. The report text and two other files are in WordPerfect format. Other files are in PARADOX, QUATTRO, and DATABASE format, and can also be provided in some other formats listed in the Appendix. Please contact DNR Minerals Information Systems to ascertain if a format can be provided to meet your needs.

This report is available at selected libraries in Minnesota. It may be purchased at the Hibbing Office, DNR Minerals Division. For further information contact Information Systems at (218) 262-6767, Fax (218) 262-7328, Internet: rick.ruhanen@dnr.state.mn.us.

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CENTRAL MINNESOTA: COMPILATION OF METALLIC MINERAL POTENTIAL DATABASES FOR ANALYSIS USING GEOGRAPHIC INFORMATION SYSTEMS

EXECUTIVE SUMMARY

Central Minnesota is an area of complex Archean and Proterozoic bedrock. The geologic units have undergone several periods of tectonic deformation, igneous activity, and alteration. Bedrock lithologies, structure, alteration, mineral occurrences, and geochemistry indicate that there should be undiscovered, valuable metallic mineral deposits. Because glacial cover is relatively deep, there are few bedrock outcrops, and exploration is hindered. There is a history of iron-manganese mining from the Cuyuna District. Farming, forestry, recreation, and urban sprawl compete for land use.

The objective is to provide a compilation of mineral potential data in a digital relational database where different kinds of digital data can be extracted and studied using geographic information systems (GIS) analysis for future mineral potential evaluations of a large part of central Minnesota. The purposes are: 1. to serve land-use planning within the Department of Natural Resources; 2. to encourage private exploration, and 3. to serve government planning of future programs. The objective is achieved by examination and analysis of existing data, acquisition of new data, and compilation of these data in a digital relational database format. Funding was provided from the general funds of the Minerals Division and by the Minerals Diversification Program of the Minnesota State Legislature.

Barry Frey logged 1,300 sample sets from 868 drill holes, or 107,667 feet of DNR Drill Core Library materials, with analysis of 1,399 new samples. James Welsh described 179 thin sections. Results indicate several areas of alteration and mineralization. Frey's descriptive logs, analytical data, and Welsh's thin section analyses provide digital contemporary lithologic descriptions. Drill hole location information was improved for many holes.

Under contract with the DNR, Allan Spector made four inferred geologic maps from geophysical interpretations at 1:62,500 scale, covering 62 contiguous townships, a portion of the study area. These maps were made using Minnesota Geological Survey airborne magnetic data, gravity data, and all available geologic information. Also some new data were provided by the DNR. The inferred maps display interpreted geology, a mineral potential analysis (which mapped 55 mineral potential areas), and depth to magnetic basement. These maps were tested with six new drill holes. Of the five holes into magnetic basement, four found the depth estimates to be reasonably accurate--within the expected error for the method used for the depth estimate. Most of the inferred lithologies were not defined in terms that could be tested by a few drill holes.

Under contract with the DNR, Don Shettel, Jr., and Patrick O'Hara interpreted four existing geochemical data sets, using contemporary statistical and geochemical modeling methods. From these models they constructed mineral potential anomaly maps for gold, base metals, iron, and uranium. These maps cover part of the study area. Some of their anomalies coincide with Spector's mineral potential areas.

Figure 1 is a graphic representation of how these data sets can be combined to provide mineral potential evaluations. Table 11 presents some of the more obvious evidence developed by

the study that undiscovered mineral deposits exist in central Minnesota. One example is drill cuttings in Section 12, Township 43 North, Range 32 West which contains 1,383 ppb of gold, 2,341 ppb of palladium and 1,339 ppb of platinum. These precious metals are hosted by an iron formation found in a metavolcanic belt. They are located in an area of steep magnetic gradient near the contact of mafic and felsic lithologic units, suggesting the possibility of structural deformation. They are plotted about a mile from Spector's mapped mineral potential area MPA-3 which suggests secondary alteration in the area. Another example is drill core from Section 32, Township 48 North, Range 18 West which contains 3,009 ppm zinc and 325 ppm lead. These analyses are from a phyllite breccia with quartz-sericite-carbonates and sulfides, showing favorable lithology and alteration. Faulting is indicated by the breccia and the geology and geophysics of the area. They are in or near a target area mapped by airborne electromagnetic surveys and near a geochemical anomaly (number 37) defined by Shettel and O'Hara.

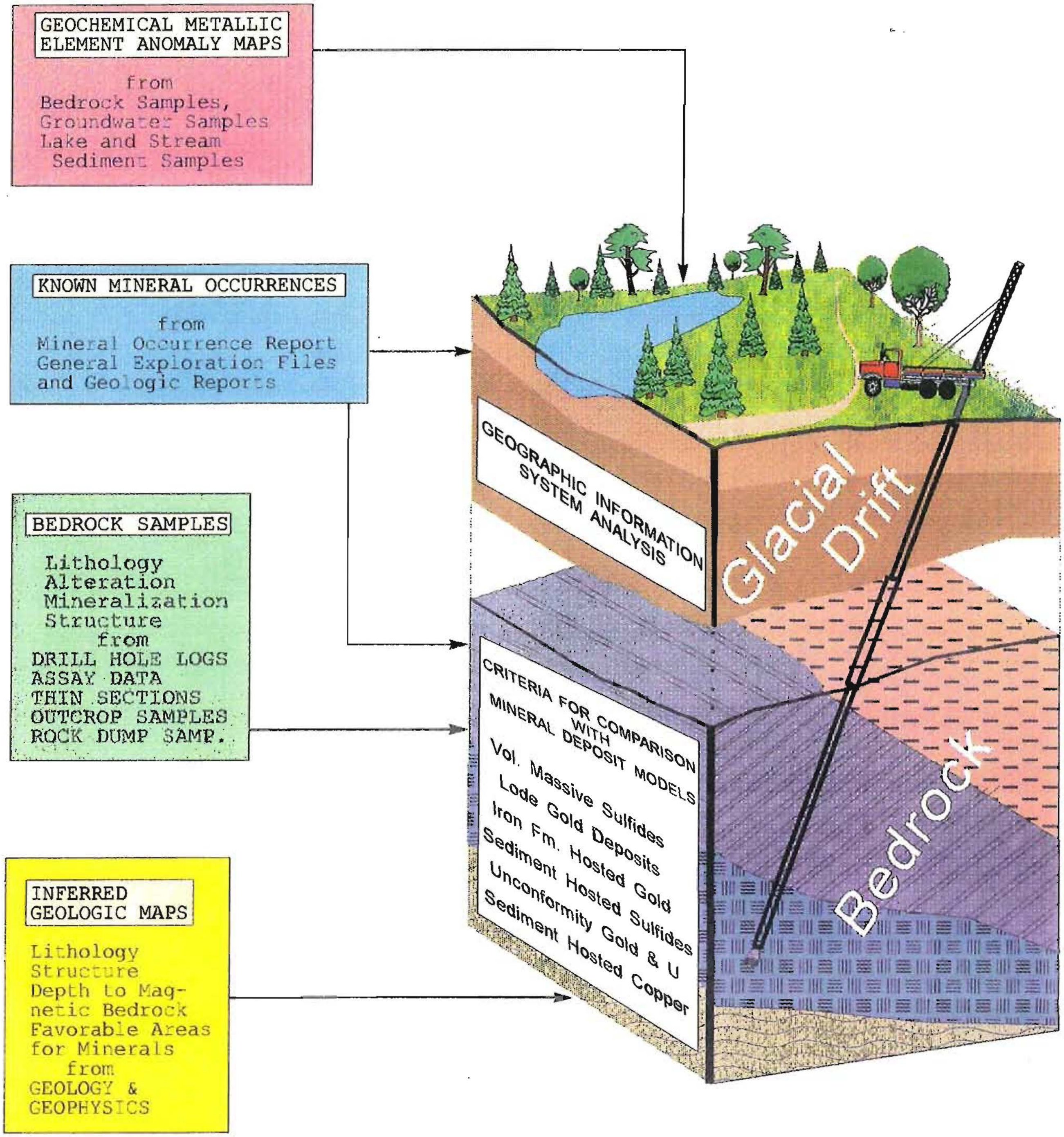


Figure 1. CENTRAL MINNESOTA COMPILATION OF MINERAL POTENTIAL DATABASES FOR GEOGRAPHIC INFORMATION SYSTEMS

INTRODUCTION

Purpose

Central Minnesota has a complex Archean and Proterozoic bedrock geology that holds the very real possibility of the existence of buried, undiscovered metallic mineral resources such as gold, copper, zinc, and manganese within the bedrock. The bedrock is buried beneath layers of glacial drift. Metallic mineral deposit potential is indicated by structure, observed alteration, mineral occurrences, and geochemistry which are similar to those found in areas where there are valuable metallic mineral deposits (Eckstrand, 1984; Cox and Singer, 1986). This evidence indicates there should be metallic mineral deposits valuable to the communities and economy of central Minnesota. Such undiscovered mineral resources are important to future generations. The Department of Natural Resources (DNR) administers State-owned mineral rights, and offers them for lease to private exploration companies. Farming, forestry, recreation, and urban sprawl compete with each other for land use. Development of mineral deposits would compete with all the other land uses. Making decisions that will sustain social and economic well-being while safeguarding the ecosystem requires knowledge of the mineral potential. Part of government responsibility, in partnership with private interests, is to plan for future land use. The purposes of this study are: (1) to serve land-use planning within the DNR; (2) to encourage exploration by private industry; and (3) to serve state and county governments, in partnerships with private interests, in planning of future programs.

The Problem

The problem is to perform reconnaissance scale mineral resource evaluation over a large area of central Minnesota using available samples, available information and limited funding for new data. One objective was to acquire new data that will supplement and increase the value of all the data. Another objective was to combine and reorganize existing data into a digital relational database format capable of being used in GIS software which will be more effective and efficient in the evaluation of the large datasets being accumulated.

Program Summary

Much of the bedrock underlying the area is prospective for gold, copper, zinc and other metallic minerals. Bedrock lithologies, mapped structural features, evidence of orogenic events, geophysics, and geochemical data compare with current models for such mineral deposits (Cox and Singer, 1986; Rogers et al., 1995). Thus, there may be buried mineral deposits in the bedrock that remain undiscovered at this time.

Because deep glacial deposits cover most of the area, bedrock drilling is very expensive. The cost would be excessive to obtain sufficient bedrock samples to accurately map mineral potential. There has been significant exploration drilling done, also some core drilling for reasons that were not economic. Reconnaissance drill core logging information has been created and stored as digital files. Several analyzed samples were anomalous for base and precious metals. Bedrock sample descriptions and thin section studies support and supplement these analytical indications.

For this study inferred geologic-mineral potential maps covering 62 townships were made from all available geophysical, geologic, and geochemical data. The inferred geologic maps and maps of mineral potential were done by Allan Spector under contract to the DNR.

Geochemical studies by contractors Shettel and O'Hara consisted of a review and statistical analysis of four sets of available data, and indicates a number of geochemical anomalies.

Study Area and Project Scope

The objectives of this study are: (1) to complete a reconnaissance nonferrous mineral potential compilation on a large part of central Minnesota, particularly where land-use competition is the greatest and existing data suggest the highest potential for nonferrous metallic mineral deposits, with focus on certain copper-zinc, gold, and silver models; (2) to integrate existing information with additional data, obtained at a reasonable cost, as a base for the mineral potential compilation, and (3) to develop methods of recording, interpreting, and presenting data that utilize contemporary computer relational databases and geographic information system methods. Figure 1 displays these objectives and the various databases created, the available information used to create these databases, and how they are compiled to allow geographic information system analysis of mineral deposit models. References for databases used in the compilation are marked with an asterisk in the bibliography. A geographic display of the areas covered by the various databases is presented as Figure 2. Table 1 lists the information or database used, the task, and the quantity of new data obtained for this study.

This study was a 4-year project, starting June 30, 1991, and ending with completion of this report. The original area considered for the study was an irregular polygon approximately 168 miles by 132 miles estimated to cover 16,000 square miles, containing all or parts of: Cass; Aitkin; Itasca; Carlton; Wadena; Crow Wing; Todd; Morrison; Mille Lacs; Kanabec; Pine; Stearns; Benton; Sherburne; Isanti; Wright; and Chisago counties. Based on the following considerations of the 16,000 square miles in central Minnesota, an area of roughly 10,000 square miles, as shown on Figure 2, was selected for this mineral potential compilation. This area was chosen for the following reasons: considerable exploration information was available; it is an area of competitive land use with considerable state and county ownership (a summary of this information taken from DNR PRIM maps is shown on Table 2 and described below); it is an area of excellent mineral potential. A good indication of an area's mineral potential is its history of exploration work, which is briefly reviewed later.

Public Land Ownership

The 1991 Public Recreation Information Maps (PRIM) show federal, state, and county surface-land ownership. Summarized on Table 2 is the government land in central Minnesota estimated from PRIM maps. PRIM map titles represent areas reading from west to east and north to south across central Minnesota. In the north, most government land is federal; in the central and southern parts, government land is mostly state and county. The table provides information on where state government will be involved in land transactions.

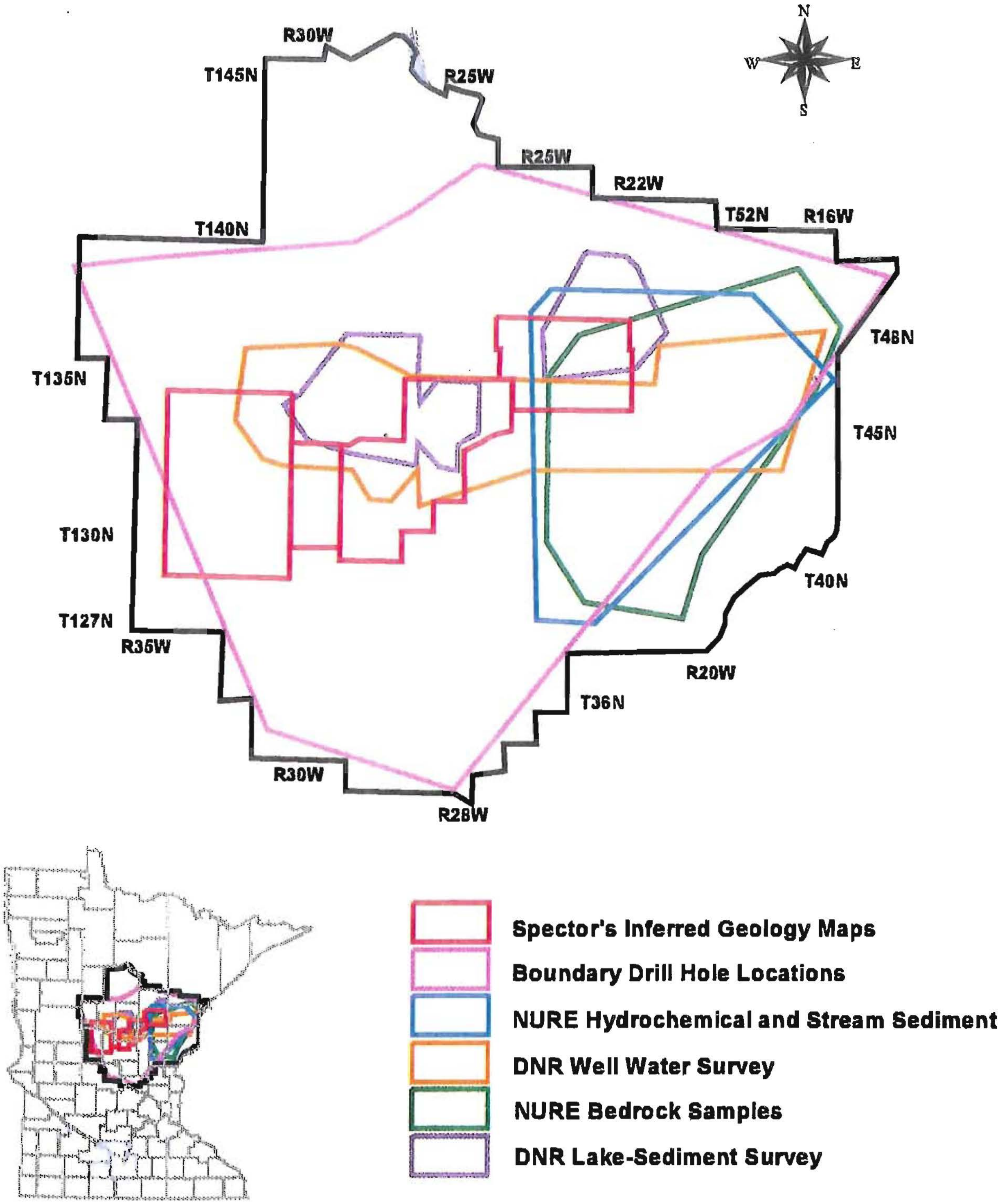


FIGURE 2. INDEX MAP OF CENTRAL MINNESOTA DATABASES USED IN COMPILATION OF MINERAL POTENTIAL

TABLE 1. PROJECT SCOPE AND PROGRESS	
TASK DESCRIPTION	**NUMBER**
Drill Core Library sample sets logged	1,300
Drill Core Library holes logged	868
Drill hole footage in database	107,667
Core Library samples analyzed	1,399
Thin sections described	179
Density measurements completed	1,937
Magnetic susceptibility measurements	3,183
Miles of ground magnetic traverse completed	246
Townships of inferred geologic maps completed	62
Anomalies identified by geochemical database reinterpretation	88
DNR east-central Minn. well samples	226
DNR east-central Minn. lake sediment samples	1,096
NURE lithochemical samples	200
NURE groundwater samples	883
Total number of samples reinterpreted	2,405

Regional Economy, Land Use, and Access

Land use, population density, and access are related to the local economy. In the northern part of central Minnesota, lower elevations are peat bogs or black-spruce swamps. Pine, aspen, and hardwood forests dominate higher land. There are some scattered farms. A large percentage of the land is government owned and access is limited. Logging, manufacture of forest products, and recreation maintain the local economy. This gradually changes and in the southern and far western parts of the area farmlands dominate, with hardwood (oak and maple) forest or wood lots. In the areas used for farming there is much less government land ownership and access is good. Larger population centers are cities surrounded by urban sprawl. Farming and small industry dominate the economy, together with some dimension-stone quarries along the southern edge of the area. All the lakes in the area are heavily used for recreation purposes. In all of central Minnesota most of the suitable lakeshore has been subdivided and developed for resorts, cabins, and summer homes. In the areas of intense farming, larger communities, and around lakes there is competition for land use.

Mining and Exploration History

TABLE 2. GOVERNMENT LAND-SURFACE OWNERSHIP				
PRIM MAP[1]	COUNTIES OR MAP WITHIN STUDY AREA	SMALL-PARCELS%	LARGE-PARCELS%	TOTAL GOV'T %
Bemidji	Cass	20	65	85
Grand Rapids	Cass and Aitkin	10	70	80
Detroit Lakes	Wadena	5	0	5
Pine River	Wadena, Cass, Crow Wing	10	30	40
Aitkin	Cass, Crow Wing, Aitkin, Carlton	10	50	60
Duluth	Carlton	5	20	25
Battle Lake	Wadena, Todd	1	0	1
Brainerd	Entire map	2	18	20
Mille Lacs Lake	Entire map	10	40	50
Sandstone	Map area in Minnesota	5	25	30
Alexandria	Todd and Stearns	3	0	3
St. Cloud	Entire map	3	0	3
Mora	Entire map	1	9	10
Willmar	Stearns	2	0	2
Litchfield	Stearns, Sherburne, Wright	3	0	3
North Metro	Wright, Sherburne, Isanti, Chisago	2	8	10
Glencoe	Wright	<1	0	1
South Metro	Wright	0	0	0

[1]Public Recreation Information Maps(PRIM) are published by the Minnesota Department of Natural Resources, funded by the Legislative Commission on Minnesota Resources (LCMR). These 1:100,000 scale maps are an overview of the recreational facilities and opportunities found in Minnesota. They can be obtained from the DNR Information Center, 500 Lafayette Road, St. Paul, MN 55155-4040, phone (612) 296-6157 or outstate 1-800-652-9747.

Deep glacial deposits cover most of central Minnesota, and there is very little bedrock outcrop. Obtaining bedrock samples for most of the study area requires deep, expensive drilling. The discovery of the Cuyuna Iron Range in 1904 was followed by a long history of mining these iron-manganese deposits. The total iron ore shipped from the Cuyuna Range was 106,437,863 tons (Lipp, 1988). Exploration for iron deposits and open-cut mining provided bedrock samples (drill core, rock bit cuttings, and rock pile samples) in this part of central Minnesota. However, exploration was mostly limited to the lithologic units containing economic deposits, and biased toward drilling geophysical expressions of magnetic iron.

There was considerable exploration for sulfides to obtain sulfur in the 1940s and early 1950s. A resurgence of interest in the iron-manganese deposits occurred in the late 1940s to early 1960s with acquisition of regional gravity surveys and magnetic ground surveys. There was interest in Blind River-type uranium deposits with a few drill holes into rock types that might support such mineralization reported in the DNR General Exploration files. In the 1970s there was significant interest in uranium exploration focused on an unconformity model between Early and Middle Proterozoic rocks (Ojakangas and Matsch, 1982 and DNR General Exploration Files). There has always been some sporadic interest in gold exploration depending on the market value for this precious metal. After the price of gold increased in the early 1980s there was significant interest in gold exploration from 1985 to 1990. In the 1980s and 1990s there have been 56 state exploration-mining leases in central Minnesota.

Bedrock drilling has provided a locally excellent but spatially irregular database for present and future searches for mineral deposits. Drill cores from these holes provide points of high-quality mineral-potential information. Using these points of information to help interpret geophysical and geochemical data expands the area of high-quality information. Without further expensive drilling, the compiled digital relational databases and GIS provide the best hypothetical presentation of the area's mineral potential.

Project Chronology

A number of people worked on this project over a time span of 4 years and enthusiastically contributed their talents. The work started on July 1, 1991, which was the beginning of state fiscal year 1992, and continued until the end of fiscal year 1995. Finishing this report extended the work into 1997. Table 3 displays program chronology with footnotes to describe results.

Acknowledgments

Eduard Dahlberg, as Manager of the Mineral Potential Evaluation Section, allowed as much individual initiative and freedom as possible. Dennis Martin supervised the project, performed much of the administrative work, helped to write contracts, arranged the sample analysis program, and reviewed this final report. Barry Frey worked full time on the project logging core, creating the digital files, recording data, directing the sampling, and writing a portion of this report. Pat Geiselman worked with Frey moving core, cutting samples, and collecting geophysical data. J.D. Lehr contributed the section on glacial geology, which we modified to integrate into the report. Phil Pippo expedited much of the contract and administrative work. Vicki Hubred effectively handled environmental problems. Tom Lawler, with help from Darold Riihiluoma, worked on the geophysics sections, helped write contracts, and also wrote most of the final report. Dorothy Cencich entered digital data into various databases or spreadsheets. Dave Dahl, Gregory Walsh, Darold Riihiluoma, and Renee Johnson created the

figures used in the report. Helen Koslucher, Coleen Keppel, Sue Saban, and Diane Melchert contributed word-processing and data-entry skills. Other staff members worked on the project as needed.

We particularly appreciate the help of D.L. Southwick, G.B. Morey, Val Chandler, and Mark Jirsa of the Minnesota Geological Survey, who took time to discuss various aspects of the project and critique the report.

TABLE 3. PROJECT CHRONOLOGY

TASK	PERIOD OF WORK
Area selection	July 1, 1991 - Sept. 30, 1991
Geophysical measurements	Aug. 8, 1991 - Apr. 15, 1995
Bedrock logging[1]	Aug. 8, 1991 - Mar. 31, 1995
Bedrock sampling[2]	Nov. 1, 1991 - Mar. 31, 1995
Ground magnetic survey	Mar. 1, 1992 - Sept. 9, 1992
Shephard inferred map	Mar. 1, 1992 - Sept. 30, 1992
Geochemical soil sampling[3]	Oct. 1, 1992 - Mar. 31, 1993
Shephard Extension inferred map	Oct. 5, 1992 - Feb. 28, 1993
295 Open-File Report	Nov. 1, 1992 - Sept. 1, 1993
GIS Geophysical Index Maps[4]	Nov. 1, 1992 - Dec. 31, 1993
Drilling program[5]	Apr. 1, 1993 - June 30, 1993
Long Prairie inferred map	Oct. 1, 1993 - Jun. 30, 1994
Camp Ripley inferred map	July 1, 1994 - Jan. 30, 1995
295 Final Report	June 1, 1994 - Sept. 1997

[1]Much of the available drill core had been logged only for ferrous minerals exploration. Logging it using contemporary methods for indications of other metallic minerals, including analytical analysis and thin section studies, was very effective.
[2]Analyzed samples were particularly effective for indicating mineral potential.
[3]Soil geochemical sample program dropped for lack of funding.
[4]Geophysical index maps were completed, but not digitized.
[5]Six holes were drilled at the end of the 92-93 biennium. These holes were vertical, drilled through the surface and far enough into bedrock to obtain an unweathered sample.

GEOLOGIC SETTING

Within the study area there is a paucity of outcrop, although McSwiggen (1987) maps a number of outcrops in the Denham-Mahtowa area and there are a few outcrops on the map of the Penokean orogen (Southwick et al., 1988). In the Cuyuna Iron Range, many of the outcrops are open cuts from mining operations. Between outcrops glacigenic sediments 100 to more than 400 feet thick conceal bedrock. There is information on depth to bedrock from about 3,000 exploratory borings and a few thousand water wells (Olsen and Mossler, 1982) and estimated depths to magnetic bedrock from Spector (1992, 1993, 1994, and 1995).

Central Minnesota is on the southern edge of the Canadian Shield and is part of an erosional onlap between Superior Province, Archean greenstone-granite terranes to the north (Fig. 3), and Paleozoic to Mesozoic sediments south of the study area (Morey, 1994). The Archean and Proterozoic rocks are structurally deformed and have complex metamorphic patterns. Progressively younger rocks are relatively less deformed.

To understand an area's mineral potential, an understanding of local geology including tectonic features and lithologic units is needed. Project proposals and early planning were based on the Minnesota Geological Survey Report of Investigations 37 geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text (Southwick et al., 1988), together with the Precambrian geologic framework in Minnesota (Southwick and Morey, 1991a). Figure 3 is modification of their simplified tectonic map of Minnesota. Shaded-relief aeromagnetic map interpretations by Chandler also provide insight into the tectonic framework (Chandler, 1991). Figure 4 is one of these images. Two sections of Minnesota Geological Survey Information Circular 34 were used extensively (Morey and Southwick, 1991); a modification of their Figure 3 is used in this report as Figure 5 to display structural features. Lithologic units as described and mapped by Morey (1994) were modified to form the digital geologic base map for this report (see Figs. 6A and 6B).

In their introduction Southwick et al. (1988) describe the Penokean orogen.

"We are concerned in this report with the tectonic evolution of the western end of the Penokean orogen. The orogen is known to extend along the southern margin of the Archean Superior craton from central Minnesota to the Grenville Front, and appears to have been the locus of tectonic activity from before 2200 Ma to about 1760 Ma . . . We restrict the term *Penokean orogeny* to the deformational and intrusive events of generally collisional nature that occurred toward the end of the evolutionary history of the Penokean orogen."

Continuing their introduction they write,

"It has been recognized for years that there are pronounced increases in stratigraphic and structural complexity, and also of metamorphic grade, from north-northwest to south-southeast across the regional trend of the Penokean orogen in Minnesota (see summary in Morey, 1983). . . . In Minnesota, a north-northwest to south-southeast transect of the Penokean orogen passes from essentially undeformed sedimentary rocks that lie directly on Archean basement along the northern margin of the Animikie basin, through zones of folded and thrust- faulted sedimentary and volcanic rocks in the southern part of the Animikie basin and the Cuyuna mining district to the complex metamorphic-plutonic terrane of the

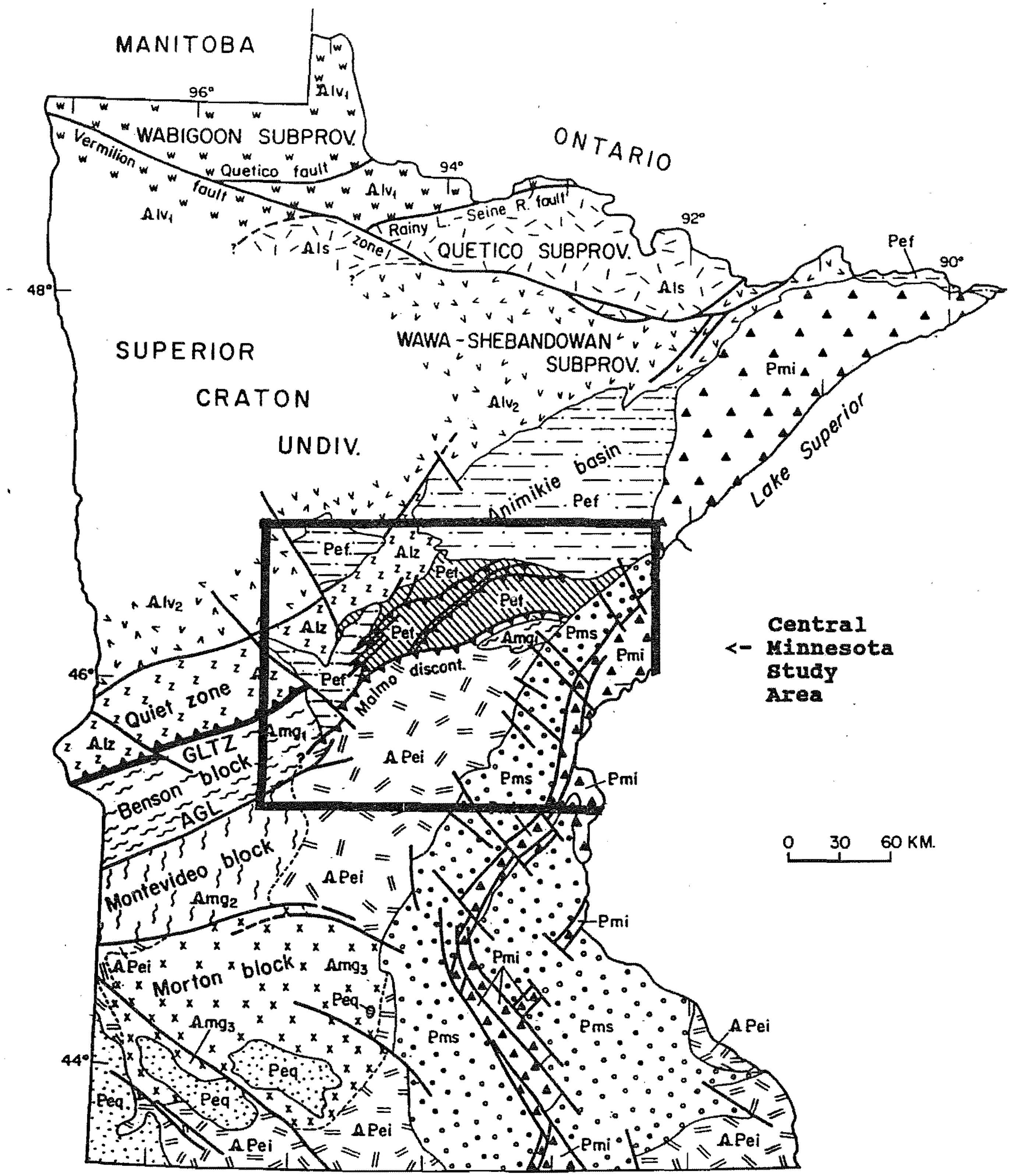


Figure 3. Simplified tectonic map of Minnesota (Modified from Southwick and Morey, 1990)

EXPLANATION

MAJOR PRECAMBRIAN TERRANES OF MINNESOTA

TECTONIC ELEMENT		PRINCIPAL ROCK TYPES	AGE
Midcontinent rift system			
late- and post-rift	Pms	Fluvial and lacustrine clastic sedimentary rocks	Middle Proterozoic; 1100–~1050 Ma
syn-rift	Pmi	Basalt, rhyolite, gabbroic intrusions; minor interflow sedimentary deposits	
Sioux Quartzite basins	Peq	Fluvial, sand-dominated redbed sequences in basins that may be fault-controlled	Early Proterozoic; probably between 1760 and 1630 Ma
Penokean orogen			
foredeeps	Pef	Turbiditic graywacke-shale sequences	Early Proterozoic; mainly between 2200 and 1760 Ma
fold-and-thrust belt	Pet	Passive-margin metavolcanic and meta-sedimentary rocks, tectonically imbricated	
intrusion-dominated magmatic terrane	APei	Syn- to post-kinematic intrusions of granitoid rocks into complex metamorphic terrane	
Superior craton			
Greenstone-granite terrane			
Wabigoon subprovince	Alv₁	Arc-like volcanoplutonic sequences; syn- to post-kinematic granitoid intrusions	Late Archean; volcano-plutonic belts mainly 2750-2695 Ma; Quetico belt 2690-2650 Ma
Quetico subprovince	Als	Turbidite-dominated metasedimentary rocks (accretionary complex?); granitoid intrusions	
Wawa-Shebandowan subprovince	Alv₂	Arc-like volcanoplutonic sequences; syn- to post-kinematic granitoic intrusions	
"quiet zone"	Alz	Poorly known belt of rocks comparable to Wawa-Shebandowan; regionally retrograded	Syntectonic plutonism, 2688 Ma (unpub. data, Z.E. Peterman)
Gneiss terrane			
Benson block	Amg₁	Poorly known terrane composed of gneiss and abundant granitoid intrusions	Middle and late Archean; complex history spans interval 3550 to 2550 Ma
Montevideo block	Amg₂	Amphibolite- to granulite-grade gneiss of plutonic and supracrustal derivation; granitoid intrusions	
Morton block	Amg₃	(same as Montevideo block)	

Inferred sequence of tectonic accretion (arrow from Wabigoon subprovince down to Morton block)

Major structural discontinuities

Malmo discontinuity (Early Proterozoic): Separates supracrustal panels of Penokean fold-and-thrust belt from deeper crustal zone to south

Vermilion fault zone (late Archean): Obliquely cuts and displaces subprovince boundaries within the Superior craton

Great Lakes tectonic zone (GLTZ; late Archean with probable Proterozoic reactivation): Separates high-grade gneissic terranes at southern margin of the Superior craton from classic greenstone-granite terrane of lower metamorphic grade on the north

Appleton geophysical lineament (AGL; late Archean with probable Proterozoic reactivation): Separates Benson and Montevideo blocks in gneiss terranes

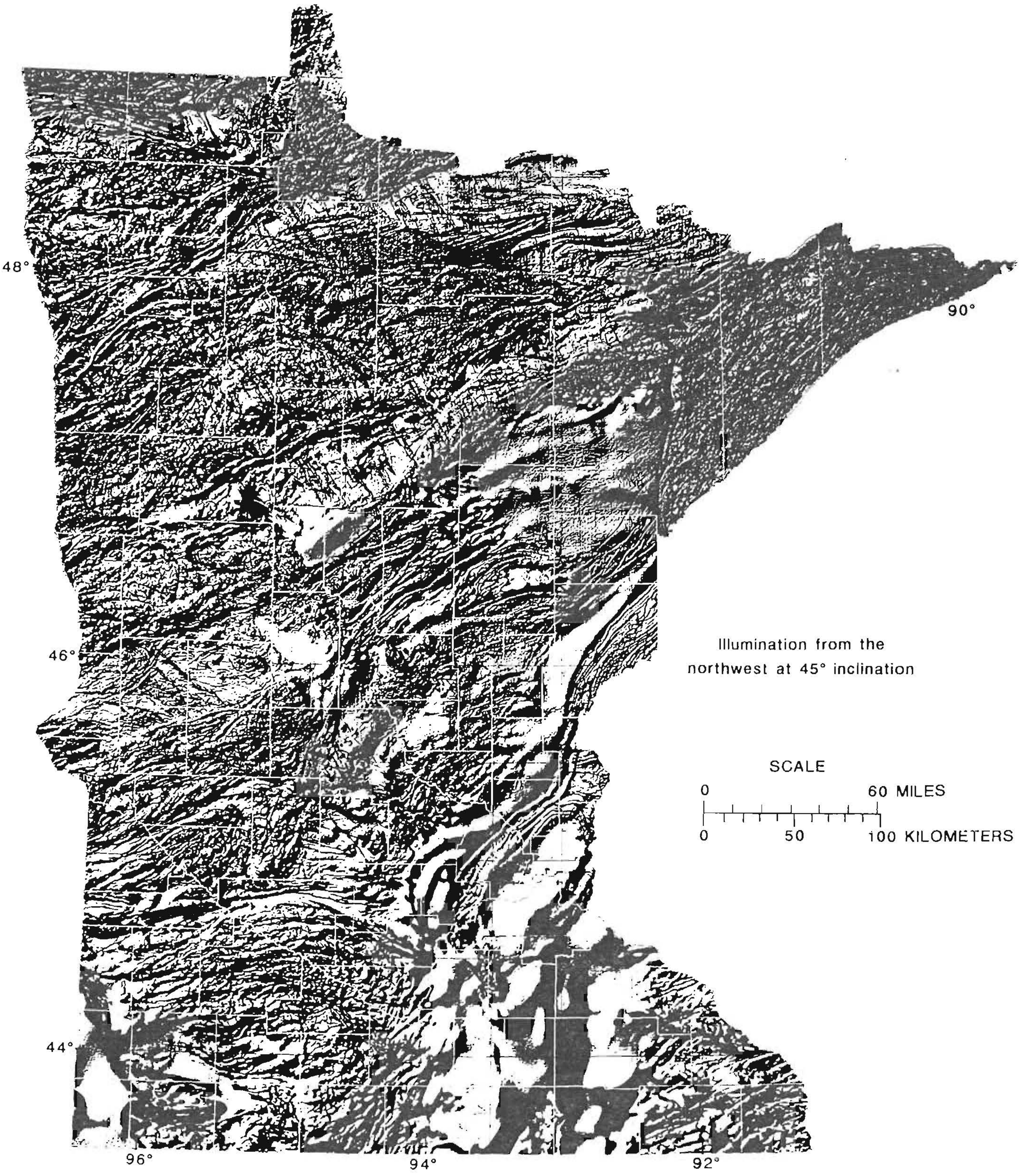


Figure 4. Shaded-relief aeromagnetic map of Minnesota. Modified from Chandler (1991).

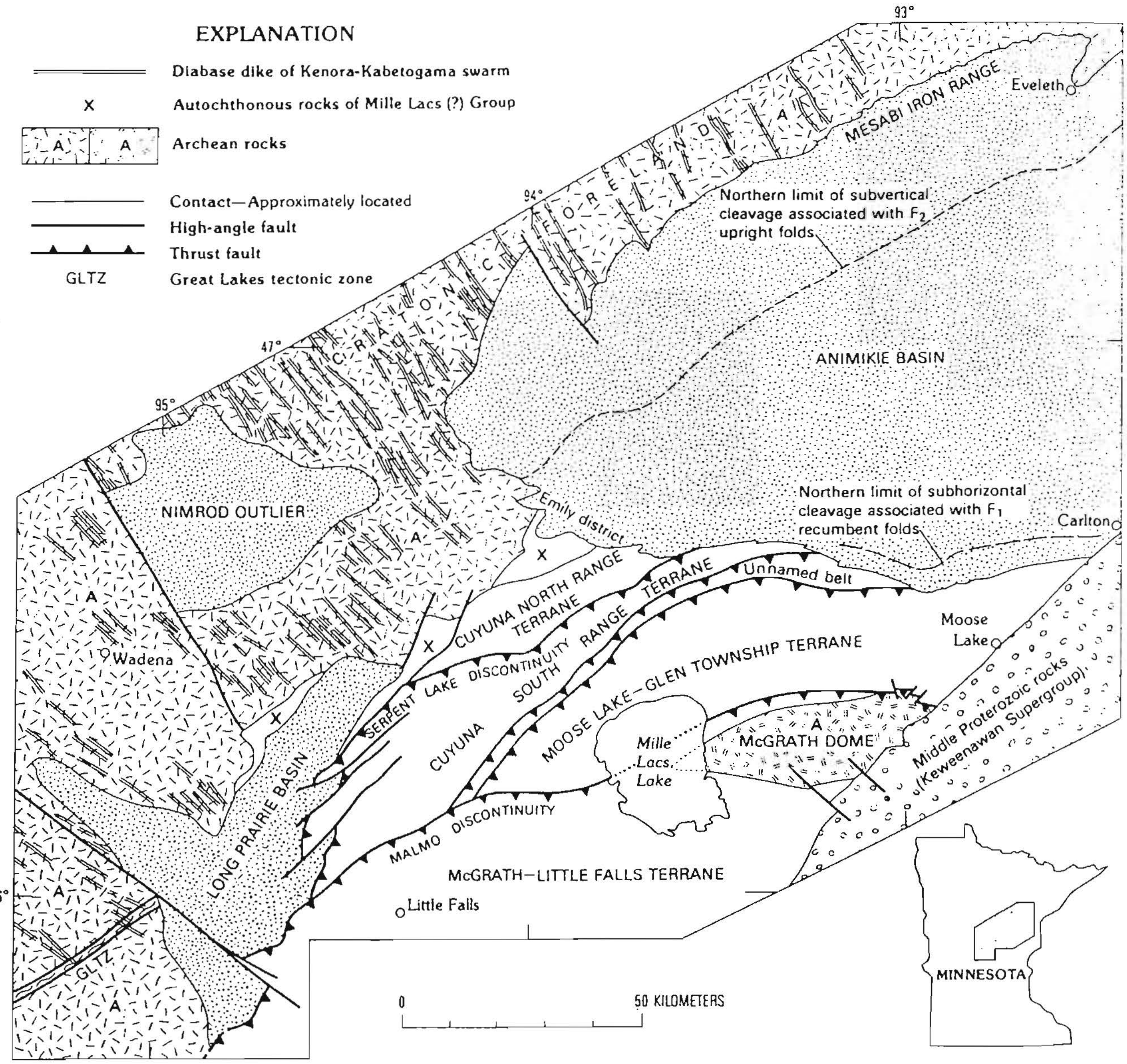


Figure 5. "Generalized tectonic map of the Penokean orogen of east-central Minnesota, showing major tectonic subdivisions as well as place names mentioned in text. Southern, more complexly deformed (internal) part of orogen consists of four named lithostratigraphic terranes, coupled with a fifth unnamed belt (mostly graphitic schist) between Cuyuna South range and Moose Lake-Glen Township terranes. Internal and medial terranes are bounded by structural discontinuites. Northern, external part of orogen consists of turbidite basins, including main bowl of Animikie basin, Nimrod outlier, and Long Prairie basin. The Animikie and Nimrod probably were once joined. Long-dashed line demarks northern limit of recumbent deformational style as mapped by Holst (1982, 1984) and extended in this study." (From Figure 3 of Morey and Southwick, 1991)

McGrath-Little Falls area and beyond (Fig. 1)."

Note that on their Figure 1, the regional tectonic interpretation is very similar to Figure 5 of this report, which was modified from a later publication. They describe their new data used in the geologic interpretations of Report of Investigations 37 as high-resolution aeromagnetic surveys, gravity data, 81 shallow test holes, and exploration records released by iron-mining companies. These data provided four major insights.

> "First, drilling has confirmed that the Virginia Formation of the Mesabi range is continuous with and passes directly into the Thomson Formation of northeastern Carlton County. The Virginia and Thomson together, therefore, comprise the main fill of the Animikie basin. Moreover, argillaceous sedimentary rocks probably correlative with these units extend about 40 km [25 miles] farther west and southwest than was previously realized, in what are now called the Long Prairie basin and the Nimrod outlier...[See Figures 5 and 6B of this report.]
>
> "Secondly, there is clear evidence that iron sedimentation occurred at several different times and under varying geological conditions. Major iron-formations are associated stratigraphically with volcanic rocks in the South range of the Cuyuna district and the Glen Township area; with black shale and argillite in the North range of the Cuyuna district; and with tidally deposited sandstone and siltstone along the northern margin of the Animikie basin, on the Mesabi range (Ojakangas, 1983). The largest of these, the Biwabik Iron Formation of the Mesabi range, is also one of the youngest. It and the other sedimentary rocks of the Animikie Group occur above a major deformed unconformity that cuts across previously deformed, somewhat older sedimentary and volcanic rocks in the Cuyuna district. The Trommald Formation and other iron-formation units in a locally twice-formed sequence beneath the unconformity cannot be correlative with the Biwabik; they are separate stratigraphic entities. The folded sedimentary rocks of the North range of the Cuyuna district comprise a distinct stratigraphic package that rests with slight unconformity on still older rocks provisionally assigned to the Mille Lacs Group. Iron-formations within the oldest sequence include those near Philbrook (Boerboom, 1987), those near Randall and at various other places along the South range of the Cuyuna district, and those in the Glen Township area of Aitkin County. Where the intervening North range sequence is missing, the unconformity between the Animikie Group and the Mille Lacs Group (Morey, 1978) is a major tectono-stratigraphic break.
>
> "Thirdly, there are several geophysically defined structural discontinuities in the southern part or the region, within and southeast of the South range of the Cuyuna district, across which demonstrable contrasts in metamorphic grade, stratigraphy, and structural style occur. The most pronounced of these are the Malmo structural discontinuity, which passes through Mille Lacs Lake, and the Serpent Lake structural discontinuity, which passes just south of Crosby . . . [Note these discontinuities are shown on Figure 5 of this report.] . . . The discontinuities

BEDROCK GEOLOGIC MAP OF CENTRAL MINNESOTA [1,2]

Scale 1:1,000,000

K Cretaceous; undivided---sedimentary rocks

C Upper Cambrian; undivided---sedimentary rocks

Pmh and Pmf Middle Proterozoic; Hinckley Sandstone and Fond du Lac Formation, sedimentary rocks

Pmc Middle Proterozoic; Chengwatana Volcanic Group, basalt and related volcanogenic rocks and interflow sediments

Peop Early Proterozoic; small mafic post-tectonic intrusions of the Penokean orogen

Pegr, Pegd, Agd, and Agr Felsic tectonic intrusions of the Early Proterozoic Penokean orogen and the Late Archean Algoman orogen

Peg Early Proterozoic; Animikie Group, sediments and associated volcaniclastic rocks

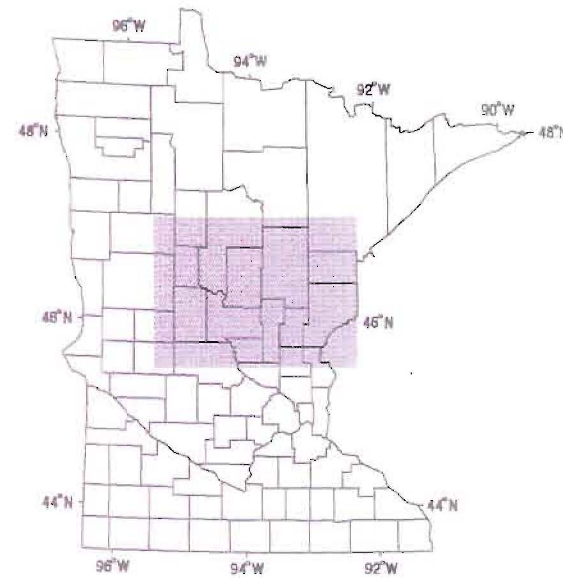
Pelf and Pelv Iron-formation---Includes the Biwabik Iron Formation, Iron Formations of the Cuyuna Range and those intercalated with rocks of the Mille Lacs Group where confirmed by drilling

Pemq, Pems, Pelf, Pen, Ams, and Aps Metasediments of the Early Proterozoic, North Range, Mille Lacs Group, and Little Falls Formation, also the Late Archean (Ams) metasediments, and the (Aps) paragneiss equivalent units

Pemb, Pemv, Amm, and Amv Mafic metavolcanics of the Early Proterozoic, Mille Lacs Group, and the Late Archean (Amm) mixed volcanics, also (Amv) mafic volcanics

Aqz Late Archean rocks of the magnetically "quiet zone"--includes felsic to intermediate volcanic and volcaniclastic rocks, mica schist, phyllite, and granitoid rocks

Amg Middle and Older Archean migmatitic gneiss, amphibolite, and granite



[1]Modified from Morey, G.B., 1994, Geologic Map of Minnesota Bedrock Geology scale 1:1,000,000, Minnesota Geological Survey

[2]Figure 6B and Plate 2, an overlay of drill hole locations, may not register exactly due to paper shrinkage.

Figure 6A. Bedrock Geologic Map of Central Minnesota - Legend and Map Location

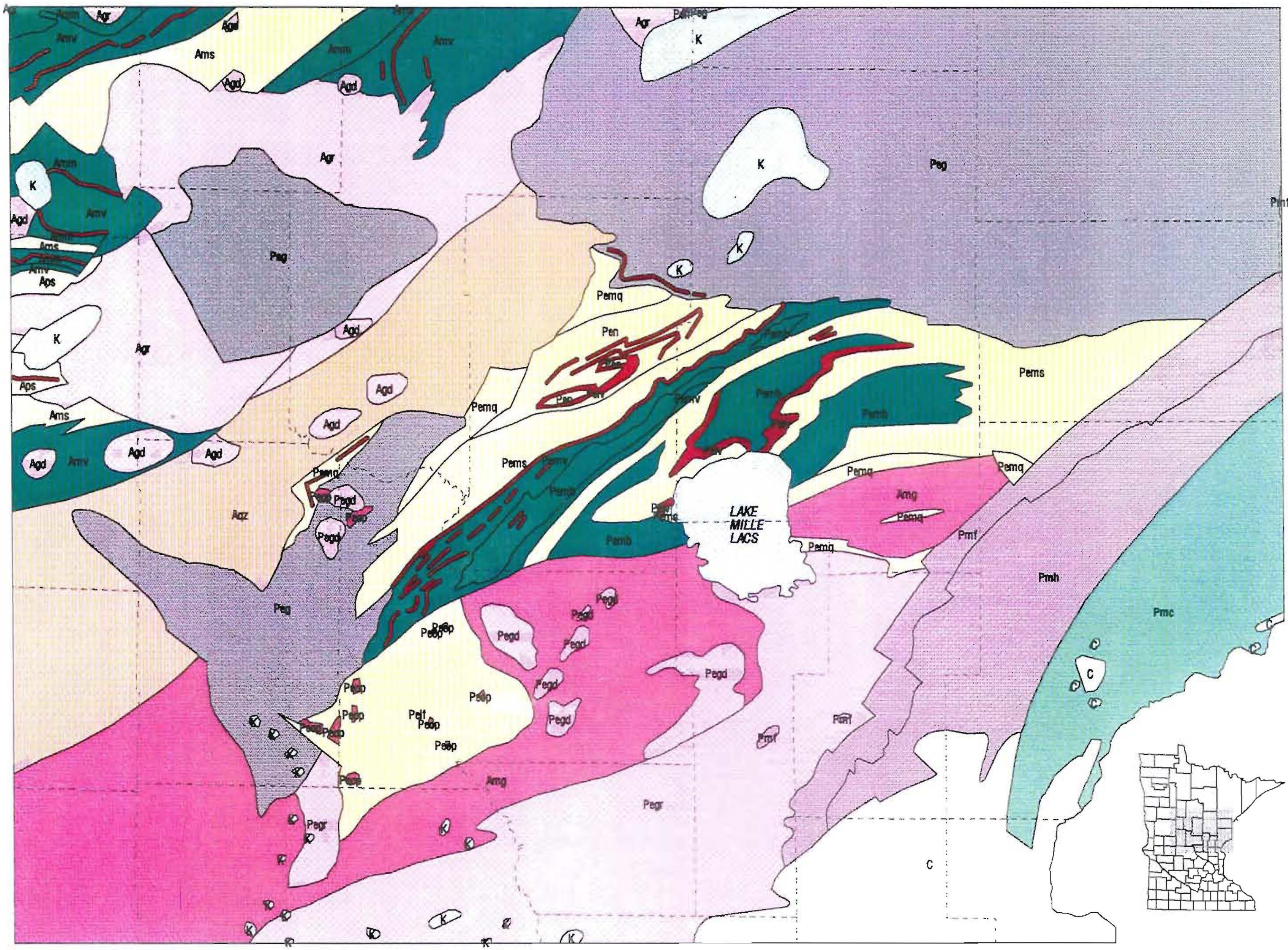


Figure 6B. Bedrock Geologic Map of Central Minnesota

mapped . . . are interpreted as tectonic boundaries, probably involving major thrust faults between slices of folded rocks.

"Finally, the region henceforth referred to as the fold-and-thrust belt (Fig. 1) [Figure 3 of this report] contains a much larger proportion of volcanic rocks than was heretofore realized. Sizable areas formerly thought to be underlain by metasedimentary rocks or granitoid gneiss, because of their subdued magnetic signature, are now known to be underlain mainly by mafic and intermediate metavolcanic rocks, which are weakly magnetic."

Details of study area geology starting with the McGrath-Little Falls panel (Fig. 5), are described by Morey and Southwick (1991),

"The McGrath-Little Falls panel contains relatively high-grade schist and gneiss, a mantled gneiss dome that is cored by multiply deformed Archean gneiss, and several late-tectonic to post-tectonic granitoid plutons. The McGrath-Little Falls panel has the attributes of a deep-seated crustal slice that has been elevated by tectonic imbrication. It is interpreted to occupy an internal position within the Penokean orogen. To the north of the McGrath-Little Falls panel, the Moose Lake-Glen Township and Cuyuna South range panels both contain folded volcanic and sedimentary rocks of variable but generally low metamorphic grade. These two panels are separated from each other by a long, arcuate zone of probable thrusting that is localized by a belt of structurally weak and highly deformed graphitic schist. Both panels contain considerable mafic to intermediate volcanic and hypabyssal rock, abundant metapelite, metasiltite, graphitic argillite, many thin, lensoidal units of iron-formation, and poorly known amounts of quartzite and related arenaceous rocks. All these rocks are closely folded and cleaved, and locally show evidence of multiple fold generations. The Moose Lake-Glen Township and Cuyuna South range panels, collectively, have the attributes of a medial tectonic zone dominated by fold-and-thrust deformation. Northwest of these terranes, the Cuyuna North range panel contains weakly metamorphosed, less strongly deformed sedimentary rocks. Volcanic rocks are volumetrically minor. The main stratigraphic units include a thick lower section of metapelite and metasiltite, a medial section dominated by iron-formation units that define a complex synclinorium near the center of the panel, and an upper unit that consists of dark-colored, graphitic argillite and siltite with local interbeds of ferruginous chert. Taken as a whole, the Cuyuna North range panel has the attributes of a small restricted basin that was incorporated tectonically in the more external part of a fold-and thrust belt.

"The east-northeast structural trends of the fold-and-thrust belt are overlapped unconformably on the north by lower strata of the Animikie Group along the south margin of the main bowl of the Animikie basin (Figure 5). Although the Animikie basin is well known for the huge iron ore deposits of the Biwabik Iron Formation of the Mesabi range, sparse outcrops, drilling data, and aeromagnetic signature indicate that most sedimentary rocks in the basin are dark-colored turbiditic graywacke and argillite in formations that stratigraphically overlie the Biwabik. The rocks near the southern flank of the basin were folded when the underlying rocks were refolded during the later stages of regional compression, whereas they were scarcely deformed at all on the cratonal, northern flank. Sedimentary fill in the basin decreased in total thickness and in degree of low-grade metamorphism from southeast to northwest. Primary sedimentary structures in rocks near the rim on the north side of the basin clearly indicate a northern (cratonal) source, whereas the sedimentalogical and geochemical attributes of at least some of the lithic graywacke near the southern margin of the basin are consistent with a southern provenance. Taken as a whole, the broad features of the Animikie basin and its smaller analog are consistent with those of a migrating foredeep produced by tectonic loading and down-bowing of continental crust during attempted subduction of an Archean continental margin. This conceptual model, developed by Southwick and Morey [1991b], for the formation of the basin accords well with the general foredeep model developed by Paul Hoffman of the Geological Survey of Canada in 1987.

"The unconformable southern contact of the Animikie basin against previously folded rocks of the Cuyuna district precludes correlation of the Biwabik Iron Formation in the Animikie basin with other iron-formations of the Cuyuna North range panel. Moreover, it is by no means certain that units of iron-formation in the Cuyuna North range panel correlate with other units of iron-formation in the Cuyuna South range. Besides being separated from each other by a major structural discontinuity, the iron-formations of the two panels differ substantially in facies, geochemistry, and stratigraphic associations. The iron-formation of the South range panel is mainly of sulfide, carbonate, and silicate facies and was deposited as lenticular masses and thin layers in close stratigraphic proximity to mafic volcanic rocks and euxinic black shale. It is akin to Algoma-type iron-formation as defined by Gordon Gross of the Geological Survey of Canada. In contrast, the iron-formations of the Cuyuna North range panel have a more blanket-like morphology, are interbedded with dark-colored argillite and siltite, and are predominantly of carbonate and oxide facies. Both they and the iron-formation units of the Animikie basin have sedimentological attributes typical of Lake Superior-type iron-formation as defined by Gordon Gross . . . ."

"In Minnesota, deformation, metamorphism, and plutonism culminated about 1870 m.y. when voluminous syntectonic plutons were emplaced (Morey and Southwick, in press). Crustal down flexure and foredeep development may have begun prior to the onset of extensive plutonism and persevered for a long period of time. Early foredeeps—such as the ancestor to the Cuyuna North range synclinorium—eventually were overridden and incorporated in the imbricate thrust stack. Later foredeeps, including the Animikie basin, followed in turn as subduction continued and then waned. A second regional episode of deformation and metamorphism accompanied the emplacement of late-tectonic to post-tectonic intrusions in the interval 1820(?) to 1770 Ma; structures primarily of this generation developed in rocks of the Animikie Group and are overprinted on earlier structures in older rocks. Isostatic uplift is inferred to have culminated by 1740 Ma."

Northwest of the Great Lakes tectonic zone (GLTZ) is an area mapped as the Quiet zone on Figure 3. Southwick and Morey (1991a) describe the quiet zone as:

"An intriguing and little-understood subunit of the greenstone-granite terrane is the so-called "quiet zone" . . . Geophysical expressions over this area are relatively flat and featureless, comparable to those found over metasedimentary belts elsewhere in the Superior Craton, and yet the drill reveals a varied geology that includes volcanic and plutonic as well as sedimentary protoliths. Many of the drill samples from the quiet zone show evidence of late-stage epidote-chlorite-albite alteration, and it may be that the featureless aeromagnetic expression is due in part to a regional episode of retrograde metamorphism in which magnetite was consumed."

They then continue with a description of the Archean gneiss terrane and the Great Lakes Tectonic Zone (Southwick and Morey, 1991a).

"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. Although relatively minor, there are gneissic protoliths of volcanic, pelitic, and iron-formation compositions that may be analogous to greenstone-belt assemblages. Current studies have established that the gneiss terrane consists of at least three distinct strata-tectonic blocks that are bounded by zones of faulting and ductile shear (Schapp, 1989). Geophysical modeling indicates that the bounding shear zones, as well as the internal structures of the Benson, Montevideo, and Morton blocks, consistently dip at low to moderate angles to the north. These regional shear zones are parallel to the Great Lakes tectonic zone, which is a probable paleosuture between the gneiss terrane on the south and the greenstone-granite terrane on the north. All of these structures reflect a major shear event in late Archean time. The Great Lakes tectonic zone also was active in Early Proterozoic time."

Tectonic features mapped by the Minnesota Geological Survey which are important indications of mineral potential are shown on Figures 3 and 5. These are described here by quotations from their publications. Figures 6A and 6B (modified from Morey, 1994) present lithologic descriptions and a geologic map of the bedrock geology shown at a scale of 1:1,000,000. For an example of use of relational data bases and GIS, see Plate 2 in the pocket of this report, which is a mylar overlay made from a digital file of drill hole locations, which is to be used with the Figure 6B map.

Jirsa et al. (1995) reported on geologic and geophysical work south of the Malmo structural discontinuity which correlates this area with Wisconsin magmatic terrranes south of the Niagara fault. A unit they label the *Milaca Terrane* is the "most lithologically diverse, and from an exploration perspective, perhaps the most promising. The eastern part of the terrane is composed of a variety of plutons separating screens of older supracrustal rocks. These older rocks include exposures of basalt and anorthositic gabbro, and several drill holes intersected amygdaloidal and porphyritic basalt and dacitic to andesitic crystal-lapilli tuff. All are metamorphosed to at least greenschist facies, and intense shearing is locally evident in both plutonic and supracrustal rocks." This work changes the southern part of Figure 6B somewhat from what is presented here.

GLACIAL GEOLOGY

Pre-glacial Setting

Little is known about the geologic history of the study area from the Middle Proterozoic to the Late Cretaceous—rocks of this age are buried by glacial drift and have not been identified from this part of Minnesota. During this time, the Precambrian rocks of the study area were probably subjected to weathering and erosion. Just south of the central part of the study area, weathering of Early Proterozoic rocks of the Penokean orogen, prior to deposition of the Upper Cambrian Mt. Simon Sandstone, is shown by the presence of a saprolite containing kaolinite and mixed-layer illite-montmorillonite (Morey, 1972). This weathering probably produced a similar saprolite over most of the Precambrian rocks of the study area.

Another episode of deep weathering occurred during the early part of the Late Cretaceous Period. This weathering resulted in a widespread saprolite in the western part of the state, composed predominately of kaolinite with lesser amounts of halloysite, gibbsite, and boehmite (Parham, 1972). This saprolite developed in a variety of Precambrian lithologies as well as older saprolite. Total thickness of saprolite in parts of the study area is commonly 50 to 150 feet, and locally more than 300 hundred feet in the southwestern part of the study area (Southwick, 1989). A similar saprolite probably covered Precambrian rocks in the northeastern part of the study area, but it has been eroded from these areas.

During Late Cretaceous time, the eastern margin of the Western Interior Seaway transgressed into Minnesota, depositing primarily shale and sandstone, with minor amounts of marl, at least as far east as the central Mesabi Range (Setterholm, 1990). To the east of the fluctuating strandline of the Western Interior Seaway, a variety of fluvial and deltaic sediments were deposited by westward-flowing streams draining the Precambrian uplands of northeastern Minnesota and central and northern Wisconsin (Witzke et al., 1983).

Throughout most of the Tertiary Period, erosion must have been the dominant geologic process in the study area, because rocks of Paleocene to Miocene age have not been identified in Minnesota. Post-Cretaceous erosion has removed most of the Cretaceous sedimentary rocks, including the underlying saprolite, in the central and northeastern parts of the study area.

Pre-late Wisconsinan glaciations

Minnesota was glaciated repeatedly during the late Cenozoic ice age, but little is known about these early glaciations; many of their deposits have been eroded either during interglacial stages or by subsequent glaciations, and most remaining old deposits are deeply buried.

Till of probable Pliocene age (approximately 2.14 Ma) is exposed at the surface in southeastern Minnesota (Matsch and Schneider, 1987) and tills of similar age are undoubtedly present in the subsurface in portions of the study area (Meyer, 1986). A series of interbedded tills of both northeastern and northwestern provenance, speculated to be of pre-late Wisconsinan age, are present in the subsurface of the western part that is Todd County (Meyer, 1986). Work done in other areas (Winter et al., 1973; Gilbertson, 1990; Martin et al., 1988, 1989, 1991) can be used to speculate on the older till stratigraphy and glacial history. Generally, thick sequences of older glacial sediments are present in areas where the depth to bedrock is greatest (Olsen and Mossler, 1982).

Late Wisconsinan substage

The late Wisconsinan glaciation of Minnesota is the best understood because these deposits occur at the surface throughout most of the state. Also, these deposits are young enough not to have been appreciably eroded. Consequently, the interpretation of genesis, including vertical and lateral facies variability, can be accomplished through study of these depositional landforms and their constituent sediments (Eyles, 1983).

The late Wisconsinan Laurentide Ice Sheet spread out from several accumulation centers in Canada, three of which influenced glaciation in Minnesota: One from land west of Hudson Bay (Keewatin ice); one from the southern part of Hudson Bay (Hudson ice); and another from northern Quebec (Labrador ice) (Dyke and others, 1989). In Minnesota, Keewatin ice advanced from the northwest, while Hudson and Labrador ice advanced from the northeast. As the Laurentide Ice Sheet expanded southward, its margin became lobate, following major preexisting lowlands such as the Great Lakes. Late Wisconsinan glacial deposits can be differentiated on the basis of provenance, and are mapped according to the glacial lobe from which they were deposited. The lobe of Keewatin ice that advanced south-southeastward through the Red River Valley is referred to as the Des Moines lobe. Two distinct lobes of Hudson ice advanced into Minnesota at different times during the late Wisconsinan, the Wadena and Rainy lobes. A fourth major lobe, the Superior lobe, advanced into Minnesota from Labrador ice to the northeast, following the axis of the Lake Superior basin. The chronology of these glacial lobes is presented in the following paragraphs and shown on Figure 7 (Lehr and Hobbs, 1992). Figure 7 summarizes the probable and successive ice movements associated with the late Wisconsinan glaciation and illustrates the complexity of the ice movements and the resulting glacial features and sediments.

The first few glacial advances of the late Wisconsinan are not as well understood as the last few, but the first advances were probably of the confluent Superior and Wadena lobes into western and southwestern Minnesota and adjacent parts of the Dakotas (Fig. 7A). As seen on Figure 7B, these northeastern advances were immediately followed by multiple advances of the Des Moines lobe into southwestern Minnesota and northern Iowa (Lehr and Hobbs, 1992).

As the confluent Wadena and Superior lobes retreated into central Minnesota, the margin of the Wadena lobe stabilized at the Alexandria moraine complex and the Superior lobe at the

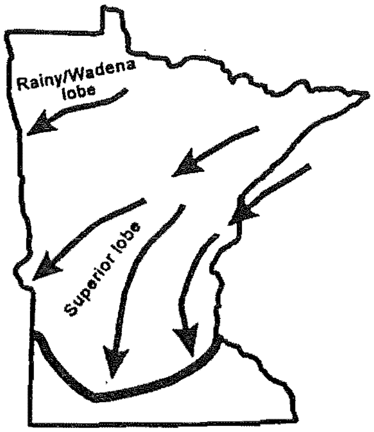


Figure 7A. Early late-Wisconsinan advance from the northeast

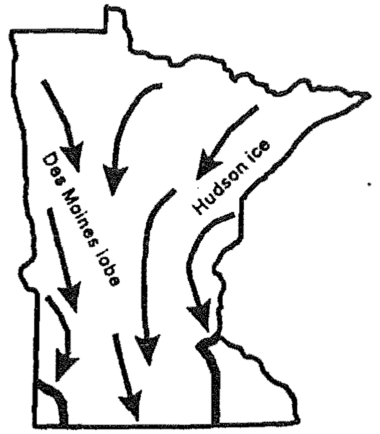


Figure 7B. Early late-Wisconsinan advance from the northwest

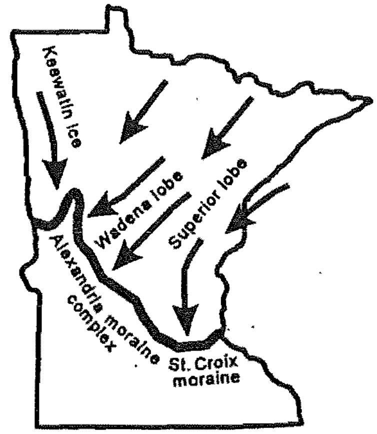


Figure 7C. Alexandria phase

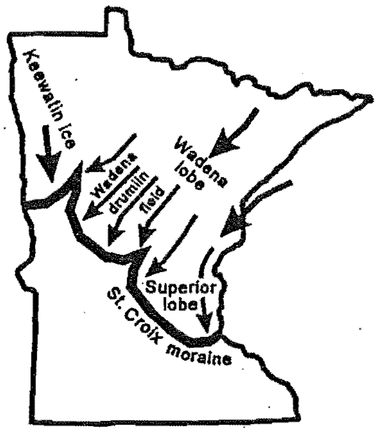


Figure 7D. Recession from the Alexandria moraine complex

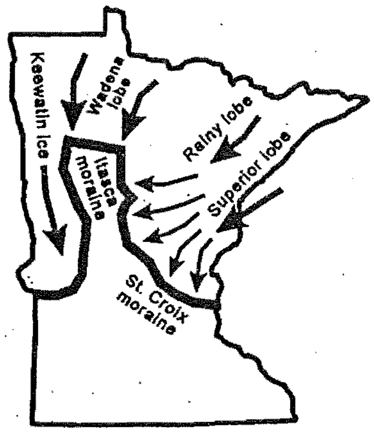


Figure 7E. St. Croix phase

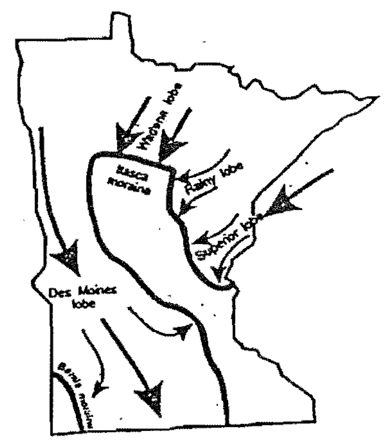


Figure 7F. St. Croix phase recession

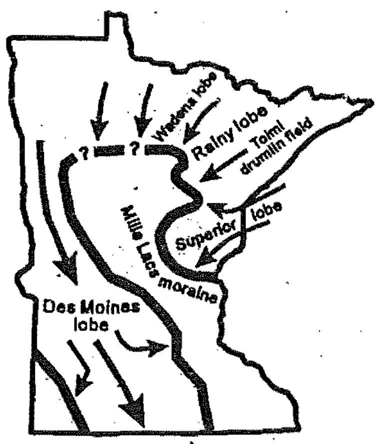


Figure 7G. Superior lobe readvance to Mille Lacs moraine, Rainy lobe recession and readvance of Des Moines lobe

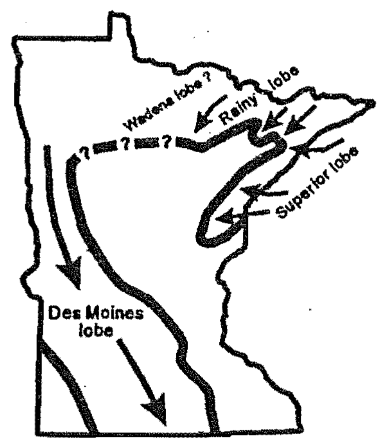


Figure 7H. Recession of Rainy and Superior lobes and readvance of the Des Moines lobe

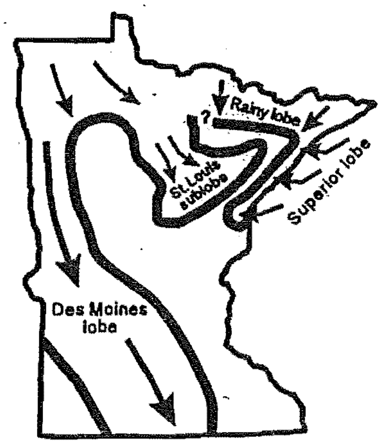


Figure 7I. Recession of Rainy and Superior lobes and advance of St. Louis sublobe

Figure 7. Ice Movements Associated With Late Wisconsinan Glaciation in Minnesota. Modified from Lehr and Hobbs (1992).

southern part of the St. Croix moraine (Fig. 7C). The Wadena and Superior lobes stood at this position for some time, because both the Alexandria and St. Croix moraines are massive end moraines composed of several individual end moraine ridges and a variety of thick ice-contact stratified deposits.

As the Wadena lobe retreated from the Alexandria moraine complex, it formed the Wadena drumlin field, stabilizing at times, long enough to deposit narrow belts of stagnation moraine, small outwash plains, and valley train (Fig. 7D). Concurrent with the retreat of the Wadena lobe, the Superior lobe withdrew from the western part of the St. Croix moraine, also periodically stabilizing long enough to deposit belts of stagnation moraine.

Continued ice recession resulted in a reorientation of ice flow in the Wadena lobe from southwestward to a more southward direction and a stabilization of the ice margin at the Itasca moraine (Fig. 7E). The Wadena lobe stood at the Itasca moraine for quite some time, as shown by the size of the moraine and the extent of outwash deposited south of the moraine. Upon retreat of the Wadena lobe to the Itasca moraine, the area formerly occupied by the southeastern part of the Wadena lobe was filled by the Rainy lobe flowing west-southwest. At this time, the Superior lobe was confluent on the south flank of the Rainy lobe, forming a lobate ice margin marked by the St. Croix moraine (Fig. 7E; Mooers, 1988). The Wadena lobe remained at the Itasca moraine while the Rainy and Superior lobes retreated from the St. Croix moraine, depositing a series of end moraines and other ice-marginal deposits (Fig. 7F).

Following retreat of the Rainy and Superior lobes from the St. Croix moraine, the Des Moines lobe began a series of rapid advances south down the axis of the lowlands now occupied by the Red and Minnesota rivers (Fig. 7F). Some of this northwestern ice spilled into low areas to the east, formerly occupied by either the Wadena, Rainy, or Superior lobes. One of these offshoots, the St. Louis sublobe, advanced through the gap between the Itasca moraine and the Mesabi Range into the lowlands of the Animikie basin. The Des Moines lobe was active in the western and southern areas of the state. The Rainy and Superior lobes continued to retreat to the northeast. The Superior lobe, being thicker and more dynamic than the Rainy lobe, flowed into an area formerly occupied by the Rainy lobe in the Mille Lacs Lake area and built the Mille Lacs moraine along the west shore of the lake (Wright, 1972). The margin of the Rainy lobe at this time was just north of Mille Lacs Lake (Mooers, 1988), and was probably drained by meltwater streams (Fig. 7G). As it retreated (Fig. 7H) into the Animikie basin, the Rainy lobe became bordered by a lake (Lehr and Hobbs, 1992), but interpretation of these Rainy lobe sediments is difficult because they are now covered by deposits of the St. Louis sublobe.

The Superior lobe was thicker, and it remained active in Minnesota longer than the Rainy lobe. As the Superior lobe retreated from the Mille Lacs moraine toward the Lake Superior basin, proglacial lakes developed. The last few advances of the Superior lobe were into these proglacial lakes, resulting in clayey tills. The outwash plains and valley trains in Carlton County were deposited from these last Superior lobe advances (Hobbs and Goebel, 1982). It was while the Superior lobe was at these positions near the west end of Lake Superior that the St. Louis sublobe advanced into the Animikie basin (Fig. 7I).

METHODOLOGY

Synopsis

A compilation of reconnaissance mineral potential requires organization and analysis of available data and acquisition of new data. Pertinent features can then be compared with models of known mineral deposits. For this study all new data and some older information were stored in a digital format on DOS-compatible disks (included in the back of this report). File 295MAST.DB provides information and links to other files including inventory numbers, sample numbers, project file numbers, drill hole numbers, and locations. The database information is preserved in relational database computer files, but is also available in digital form for less sophisticated computer systems. Digital data can be queried to quickly provide answers to questions from large volumes of data. Reports, open-file information, and the relational database-geographic information system maps make it very easy for anyone to obtain and use the compilation.

For exploration geologists, the most significant data come from bedrock samples. The data are categorized by lithologic description, observed evidence of alteration, structure, and mineralization. Some bedrock samples from outcrops and rock dumps were examined, but most of the bedrock sample data came from drill core or cuttings stored in the DNR Drill Core Library. Thin section studies support and expand the bedrock sample logging. Analytical data further define economic mineral potential and determine geology. Four inferred geologic map areas were interpreted from geophysical data which cover 62 townships. These maps are combined and displayed as Plate 1 in this report. Within this area, geology was interpreted at a scale of 1:62,500. The mineral potential of 55 areas was interpreted, and depth to magnetic basement (usually bedrock) was estimated. Inferred geologic map accuracy was improved with acquisition of 246 miles of ground magnetic traverses. Computer modeling of geology was also enhanced with acquisition of density and magnetic susceptibility measurements on drill core. All exploration data, in DNR General Exploration Files, from Inferred Map areas were provided as background for Spector's work. A statistical reinterpretation of four geochemical data sets further enhanced study results.

Economic Geology and Models of Ore Deposits

Information from the General Exploration Files and a compilation of ore mineral occurrences suggest that several ore deposit models might provide a useful characterization of mineral potential. The models are included in this section with the following qualifications: At the reconnaissance exploration level, indications of mineralization can be compared only tentatively to ore deposit models. Subsequently, after an ore deposit has been well defined by drilling or mining, many features will fit into the selected ore deposit model, but other features will appear to be related to a different model or models. Most exploration personnel use mineral deposit models with considerable skepticism. However, these models can be a useful tool for describing mineral potential and encouraging further exploration. It must be recognized that many of the models indicated at the reconnaissance stage will be discarded or replaced as more data become available, or geologists with different backgrounds study the data.

Cox and Singer (1986) have edited a publication describing most of the features of many mineral deposits including those that might occur in the study area. Sangster (1972) describes Precambrian volcanogenic massive sulphide deposits in Canada. Eckstrand (1984) edited a publication describing Canadian mineral deposit types, some of which pertain to Minnesota geology. Beus and Grigorian (1977) describe the geochemistry related to a number of mineral deposit models. Kissin (1992) describes the five-element ore type of deposit (Ag-Ni-Co-As-Bi) which he relates to rifting. Hodgson et al. (1981) describe structure, lithology, alteration, and indicator mineral elements (Au, Sb, W, and Hg) which comprise a model for lode gold deposits. Thorman et al. (1991) edited a U.S. Geological Survey Bulletin describing gold and platinum-group minerals related to iron formations hosted by greenstone belts in Brazil. Models described by these authors can be compared with study area results that suggest mineral potential. The following models and qualifications were considered in planning and describing results of project programs:

Berger, B.R., *in* Cox and Singer (1986, p. 239). Descriptive model of low-sulfide gold-quartz veins. Qualifications: The model geologic environment includes greenstone belts which might not be applicable in the study area although mafic volcanics would be appropriate.

Berger, B.R., *in* Cox and Singer (1986, p. 244). Descriptive model of Homestake Au: APPROXIMATE SYNONYMS: Volcanogenic gold, iron-formation-hosted Au, Archean lode gold. This model includes the Thorman and Ladeira model of iron-formation-hosted Au and platinum- group elements. Qualifications: In the study area the lithologic units related to this model of deposit are Proterozoic not Archean.

Briskey, J.A., *in* Cox and Singer (1986, p. 211). Descriptive model of sedimentary exhalative Zn-Pb: APPROXIMATE SYNONYMS: Shale-hosted Zn-Pb; sediment-hosted massive sulfide Zn-Pb. No recognized qualifications.

Singer, D.A., *in* Cox and Singer (1986, p. 189); Sangster (1972). Descriptive model of Kuroko massive sulfide: APPROXIMATE SYNONYMS: Noranda type, volcanogenic massive sulfide, felsic to intermediate volcanic type. Qualifications: Sangster's model may be partially obsolete and a workable contemporary model should relate Minnesota mineral potential to Wisconsin mineralization. At present the Wisconsin mineralized terrane is correlated with a terrane south of the study area.

Cox, D.P., *in* Cox and Singer (1986, p. 205). Descriptive model of sediment-hosted copper: APPROXIMATE SYNONYM: Sandstone Cu, includes Cu-shale. No qualifications.

Grauch, R.I., and Mosier, D.L., *in* Cox and Singer (1986, p. 248). Descriptive model of unconformity U-Au: APPROXIMATE SYNONYM: Veinlike type U. No qualifications.

Data from Bedrock Samples and DNR Drill Core Library

Drill hole materials were logged in two digital files. The first set of digital files is called PARADOX database file MASTLOG.DB. The fields for this file are shown on Table 4. The purpose of this file is to ensure that all core intervals having the same lithology, alteration, and mineralogy would be located by a computer search of the file, and therefore, unique digital descriptions were written for each observed lithology, alteration, and mineralization. For each core interval logged, the unique descriptive digital files were copied and inserted in the log, thus ensuring uniform wording. Thin-section studies and element analyses were supplemented by visual logs. The second digital file, PARADOX database file MASTCOM.DB, was directed toward unique geologic features specific for individual holes, and the primary parameter was the drill hole.

TABLE 4. DRILL LOGS DATABASE FIELDS[1]

FIELD NAME	MAXIMUM CODE ENTRIES IN FIELD	DESCRIPTION OF FIELDS
INV	ONE	DNR's INVENTORY (INV) DDH number
DDH	ONE	DDH number (as usually written on boxes)
TOP INT	ONE	Top footage of record interval
BOT INT	ONE	Bottom footage of record interval
LITHOLOGY	ONE	Code for lithology type
LITHOLOGY DESCRIPTOR	EIGHT	Codes that further describe lithology
ALTERATION TYPE	ONE	Code for alteration type (mineralogies)
MINERALIZATION DESCRIPT	FIVE	Codes that describe mineralization mineralogy
MINERALIZATION TYPE	NINE	Codes that describe the mineralization type

[1]As new lithologies have been logged a different set of unique codes was developed to represent lithology and alteration types in a more useful format. The new code numbering system uses four digits instead of three, and will be used in future work. The old three digit system will no longer work to search the database.

Table 5 shows the drill-log comment fields. This file includes short lithology summaries, information on the sample materials available, and crushed core colors—sometimes the only discernible information available. These methods produced a digital database of study area drill cores that will yield consistent answers to queries.

Most data are recorded in relational database files to facilitate extraction and reproduction using GIS software which can produce multiple map layers of related data. These digital files allow search patterns that will locate all drill intervals with similar attributes, such as banded iron formation or sheared greenstone. The coded attribute numbers allow for easy searching, management, and manipulation of the database. Because of constraints (particularly computer memory), the database was kept rather simple, and a certain amount of "lumping" was used. For non-relational database use, the digital data are also available in other formats.

TABLE 5. DRILL-LOG COMMENT FIELDS		
FIELD NAME	**CODE ENTRIES IN FIELD**	**DESCRIPTION OF FIELDS**
INV	**ONE**	**DNR's INVENTORY (INV) DDH number**
DDH	**ONE**	**DDH number (usually written on boxes)**
COMMENTS	**TEXT: NO CODES**	**Can contain anything— miscellaneous information**

The DNR Core Library maintains for public use samples from over 6,000 drill holes for a total footage of over 1,700,000 feet. Significant improvements (Figure 8) were made to the drill core information system:

(1) In the study area multiple splits of core from the same drill hole had been given the DNR at different times, and many holes had more than one DNR unique INVENTORY (INV) number assigned to them. Drill hole numbering and location were clarified by examination of available maps and files at the DNR and additional data acquired from Hanna Mining Company. There was further clarification as available data were compiled in digital relational databases allowing comparison of hole locations and related data, such as drill hole number, depth of overburden, and sample intervals. For the project comparison work a sequential project file number was assigned to each bedrock sample whether outcrop, rock dump, boulder, or drill hole. Until the databases were fully digitized the project file numbers proved to be useful.

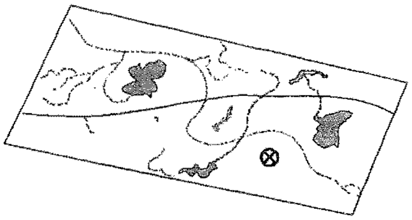
(2) There must be more than a quarter of the core to allow sampling, and therefore a number of holes could not be further sampled for analysis. Comparisons of drill-core-related data allowed recognition that multiple splits of the same core existed in the core library. This problem was largely eliminated for those drill hole materials logged. All resulting data improvement from this project have been incorporated into the current Drill Core Library Index.

(3) Consistent reconnaissance digital descriptions of bedrock lithology, alteration, mineralization, and structure were created. The descriptions created for the study area will be applicable to much of the Precambrian bedrock in Minnesota.

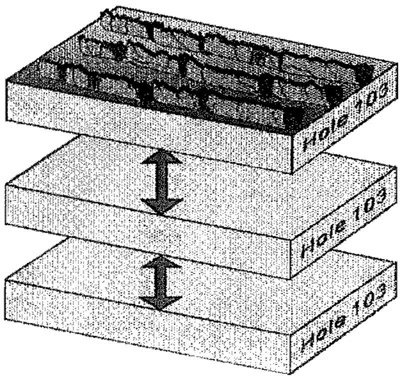
(4) The digital relational databases created for the study area for use with GIS software might provide a useful model for further geologic studies.

Studies of Thin Sections

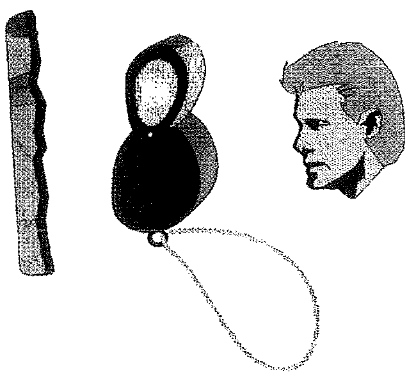
The purpose of the petrographic work was to supplement the core logging program. Specific



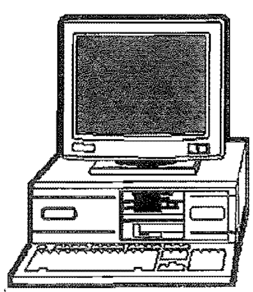
Improved location information for 1500 drill holes by compiling data, and from recently aquired data.



Recognized that multiple sample splits from one core were filed under different unique hole numbers in different core storage locations; improved current storage information.



Created consistent reconnaissance descriptions of bedrock, alteration, mineralization, and structure.



Created digital relational databases of drill core to be used with GIS software.

Figure 8. IMPROVEMENTS MADE TO THE DRILL CORE INFORMATION SYSTEM.

goals were to verify (and increase confidence in) macroscopic identification of primary rock textures, lithologies, and protoliths of the metamorphic rocks and characterization of alteration. Thin section samples were selected from a variety of rock types. Petrographic work on a total of 179 thin and polished thin sections collected by B. Frey was done by James Welsh of Gustavus Adolphus College. Samples collected during core logging, and also existing thin sections from the DNR thin section collection were examined. The rocks described in the petrographic work can be divided into the following groupings:

(1) Iron formation, oxidized and unoxidized.
(2) Clastic and calcareous metasedimentary rocks.
(3) Mafic metavolcanic rocks (including amphibolites).
(4) Mafic intrusive rocks.
(5) Fragmental and felsic metavolcanic rocks.
(6) Felsic to intermediate intrusive rocks.

A list of the thin sections and their locations is included in the PARADOX database file P295SAM.DB. Petrographic sample study results are described in the digital files which include the Thin Section Petrographic Summary digital file JWPET93.WP and the thin section descriptions digital file JWPET95.WP. JWDES93.WP is a digital file of 1,993 thin section descriptions by James Welsh. JWDES951.WQ2 is a QUATTRO (DOS) spreadsheet file of the thin section descriptions table. The second table DIGITAL FILE JWDES952.WQ2 is a QUATTRO table of thin section mineralogy.

Sampling and Analyses

The primary project objective, identification of indications of nonferrous metallic mineralization, was achieved through drill core logging and analyses. Sample selection, sawing, and compositing, supervised by Barry Frey from November 1, 1991, to March 31, 1995, produced 1,399 samples. Analyses focused on economic minerals and associated alteration in the core. This work was done to complement previous work, mostly done by private industry, and is available in DNR General Exploration Files. With limited funding, altered and mineralized rock were preferentially sampled over unmineralized and unaltered rocks. Where possible, cuttings were sampled over core to preserve the core, although we tried to keep a representative sample of the cuttings. Analyses were done under contract by Bondar-Clegg & Company, Ltd. of Ottawa, Ontario. Quality control was maintained with blind reference samples submitted by the DNR on a 20-sample interval, and by replicate analysis.

Users of the data should keep in mind that this is a "RECONNAISSANCE" study, and "the primary objective was to look for mineralization and gather mineralization-related data." The analytical contract with Bondar-Clegg was the result of a 6-month process, and a panel of DNR and industry scientists evaluated the submitted bids according to quality and price. The DNR requested two basic packages. A less expensive package (essentially an "exploration" package) analyzed for precious metals, base metals, some trace elements, and incompatibles. The more expensive package was used to analyze for whole rock oxides and expanded trace elements. The smaller package was chosen to obtain the most (mineral potential) analysis data possible for the greatest number of samples possible. Further, the objective was to log a large number of drill holes with the definition of mineral potential having top priority. There was neither the time nor the objective to do stratigraphic studies and tailor analysis to fit stratigraphy. The reconnaissance nature of the logging and sampling cannot answer every geologic question about the materials logged, but can serve as a guide for the end user as to whether additional time, effort, and resources should be spent on these materials.

Most of the drill samples came from holes drilled for iron and manganese exploration. There were also samples from holes drilled for uranium, gold, and base metal exploration. Core logging and sampling were complicated by the condition of the core. Much of the iron ore drilling exists as combinations of solid core and crushed rock produced using churn drills, a popular drilling method utilized in the early iron exploration. In some cases, where distinctive lithology or alteration changes fell within a crushed rock sample, the core was preferentially sampled for analysis. Sample intervals also depended on the amount of materials remaining, because by law one-quarter of the core must be retained, but with churn drill cuttings only a representative sample is retained. Sample intervals ranged from 2 to 20 feet, and some samples were composites. Sample intervals were defined primarily by alteration, lithology, and availability of materials. Sample selection required considerable judgment because of the variable quality of available materials. Samples requiring crushing and pulverizing were first prepared at Bondar-Clegg's facility in Hibbing, Minnesota (Lerch Brothers Inc.).

The "storage" histories of these samples varied—containers, especially for the crushed rock, included cardboard boxes, tinned steel boxes, aluminum boxes, glass vials (corked), and glass bottles (metal caps). Contamination was apparently minimal in most cases. Some sulfide-bearing samples (especially if they were initially stored wet?) had caused corrosion in cardboard and metallic boxes. One corroded tinned steel box was sampled and mixed with silica sand in order to "fingerprint" those elements that may "contribute" or contaminate analytical results. Some samples contained small fragments of cloth, notched wooden tags, and occasional lengths of black to dark-red (from cuprite?) copper wire. We assume that these samples were originally stored in cloth bags, marked with the wooden tags, and tied shut with the copper wire before placement in boxes. If sampled and discovered, wire fragments were removed. As a test of what results would be with wire contamination, some of this wire was mixed with silica sand and analyzed. Results of this chemistry are in QUATTRO spreadsheet file MISCCHEM.WQ1 (not included with this report). However, analysis indicated contamination, and single-element anomalies should be used with caution.

Two different sets of analyses were performed on samples. Most samples were analyzed for 19 elements including gold, common base metals, and platinum and palladium. These elements, analytical method, report units, and detection limits (which provide a range of claimed accurate analytical results for the methods used) are listed in Table 6. A limited number of samples were analyzed with a 52-element package. These elements, analytical method, report units, and detection limits are listed in Table 7. The samples that were analyzed are listed in PARADOX database file P295SAM.DB. The analytical results are listed in PARADOX database files P295CHEM.DB (all analyses without standards), P295CHSM.DB (smaller analytical package), and P295CHLA.DB (larger analytical package). Every batch of 20 samples included a reference standard sample. Reference samples and comparisons are listed in Quattro For Windows spreadsheet file P295STD.WB1 (not included in this report) and in the RESULTS section of this report.

Maps of Inferred Geology and Mineral Potential

Conventional bedrock geologic maps are a reflection of the quantity and quality of available bedrock geologic information. A paucity of geologic data results in simple maps showing only major lithologic units and structural features. Obtaining more geologic data with traditional drilling methods is expensive, particularly in areas of deep overburden. Geophysical interpretations using high-quality

TABLE 6. NINETEEN-ELEMENT ANALYTICAL PACKAGE PLUS PLATINUM AND PALLADIUM				
ELEMENT NAME	METHOD[1]	UNITS	LOWER DETECTION LIMIT	UPPER DETECTION LIMIT
Au	FA-30	ppb	5	10,000
Ag	ICP	ppm	0.2	50
Pb	ICP	ppm	2	10,000
Zn	ICP	ppm	1	20,000
Fe	ICP	%	0.01	10
Ba	ICP	ppm	1	2,000
Al	ICP	%	0.01	10
Ti	ICP	%	0.001	100
Mn	ICP	ppm	1	20,000
V	ICP	ppm	1	20,000
Cr	ICP	ppm	1	20,000
Ni	ICP	ppm	1	20,000
Cd	ICP	ppm	0.2	1,000
Cu	ICP	ppm	1	20,000
Co	ICP	ppm	1	20,000
As	ICP	ppm	5	2,000
Zr	XRF	ppm	1	20,000
Y	XRF	ppm	1	20,000
Nb	XRF	ppm	5	10,000
Pd	FADCP	ppb	1	10,000
Pt	FADCP	ppb	5	10,000

[1]FA-30 = Fire Assay 30-gram sample, ICP = Inductively Coupled Plasma Emmision, XRF = X-ray Fluorescence (Fusion), FADCP = Fire Assay Direct-Current Plasma Emission

TABLE 7. FIFTY-TWO ELEMENT AND OXIDES ANALYTICAL PACKAGE				
ELEMENTS AND OXIDES	METHOD[1]	UNITS	LOWER DETECTION LIMIT	UPPER DETECTION LIMIT
Cl	TITRA	%	0.01	100
SiO2, TiO2, Al2O3, Fe2O3, MnO, MgO, CaO, Na2O, K2O, P2O5	ICP	%	0.01	100
LOI Loss on Ignition	GRAV	%	0.05	100
Total		%	0.01	100
Li, V, Cr, Co, Ni, Cu, Zn,	ICP	ppm	1	20,000
C Total, S Total	LECO	%	0.02	100
Be	ICP	ppm	0.5	1,000
Sc, As	ICP	ppm	5	2,000
Ga, Pb	ICP	ppm	2	10,000
Rb	INAA	ppm	5	10,000
Sr, Y, Ba, La	ICP	ppm	1	2,000
Zr	ICP	ppm	1	20,000
Nb, Mo	ICP	ppm	1	10,000
Ag	ICP	ppm	0.2	50
Cd	ICP	ppm	0	1,000
Sn, W	ICP	ppm	20	2,000
Sb	ICP	ppm	5	1,000
Te	ICP	ppm	10	2,000
Ce	INAA	ppm	1	9,000
Ta	ICP	ppm	10	1,000
Bi	ICP	ppm	5	2,000
B	DCP	ppm	1	20,000
F	SPION	ppm	20	20,000
As	AAHY	ppm	1	1,000
Sb	AAHY	ppm	0.1	2,000
Hg	CVAA	ppm	5	5,000
Cr	ICP	ppm	10	10,000
Se	XRF	ppm	1	1,000
Ta	XRF	ppm	3	20,000
Pd, Au	FADCP	ppb	1	10,000
Pt	FADCP	ppb	5	10,000

[1]TITRA = Titration, ICP = Inductively Coupled Plasma Emission, GRAV = Gravity, LECO = Analysis using a LECO Furnace, INNA = Instrumental Neutron Activation Analysis, DCP = Sodium Hydroxide Fusion - Direct Current Plasma Emission, SPION = Potassium Nitrate Fusion - Specific Ion Measurement, AAHY = Hydride Generation Atomic Absorption, CVAA = Cold Vapor - Atomic Absorption, XRF = X-Ray Fluorescence, FADCP = Lead Collection - Fire Assay - Direct Current Plasma Emission

geophysical surveys and sophisticated computer enhancement techniques, combined with known geology can result in more accurately interpreted geologic maps. Maps made with these methods, which infer geology from geophysical data, are called here inferred geologic maps.

Under contract with the Department of Natural Resources: the Shephard Area (20 townships); the Shephard Area Extension (12 townships); the Long Prairie Area (24 townships); and the Camp Ripley Area (6 townships) were mapped by Allan Spector (1992, 1993, 1994, and 1995), Allan Spector and Associates Ltd., Toronto, Canada. Spector has a broad background in Precambrian terranes having gold or base-metal mineral potential and is experienced in geophysicalinterpretation. The mineral potential areas of these maps were selected by Spector on the basis of studies of available geophysical data; apparent high mineral potential from known bedrock geology; reported mineral occurrences; past exploration as described in DNR General Exploration Files; and reports of geochemical surveys. Published models of known mineral deposits were compared with characteristics indicating mineral potential.

For these maps Spector was provided with published information and all available bedrock and geophysical information from DNR files. V.W. Chandler et al. of the Minnesota Geological Survey have published several aeromagnetic maps pertinent to the study area, and the aeromagnetic data for the state are available from the National Geophysical Data Center on two CD-ROM disks. These aeromagnetic data were the primary database used to make the inferred maps. Gravity data—obtained from the Minnesota Geological Survey on a computer diskette—were the secondary database used.. The geophysical information included detailed total field magnetic ground profiles run by the DNR in the Shephard and Long Prairie areas. For much of the Shephard Area Extension, airborne electromagnetic data donated by United States Steel Corporation (DNR General Exploration Files) were very helpful.

In his reports (Spector, 1992, 1993, 1994, and 1995; Spector and Lawler, 1995), Spector provides a detailed description of how his interpretations are made. The interpretation starts with profiles of aeromagnetic flight-line data which are used for estimating: (1) depths to the causative feature from the shape of the magnetic profile; (2) bedrock lithologic units from the amplitude of profile anomalies; (3) contacts of lithologic units from the shape of the anomaly; and (4) indications of structure. Profile studies are supplemented with reduced-to-pole and second-derivative maps of the aeromagnetic data to better locate geologic features, resolve contacts, and estimate structural orientation. The resultant inferred map was correlated with gravity and any other available data to help define and resolve bedrock geology.

The inferred geologic maps are a 1:62,500-scale geologic interpretation. This information is based on: (1) Geologic information which includes some lithologic units and volcanic belts referred to as greenstones; structural features; and depths to magnetic source. (2) Area responses from magnetic and other data which are typical of reconnaissance mineral potential prospects.

DNR Ground Magnetic Traverses

After the Shephard Area was chosen, the geologic map of the Penokean orogen, east-central Minnesota, was studied to determine if ground traverses would be helpful (Southwick et al., 1988). The strike of most geologic features in the Shephard Area is northeast-southwest. Where some features strike to the north, east-west ground traverses following roads provided detailed profiles to supplement airborne profile interpretations.

Available equipment for magnetic ground surveys was a Scintrex IGS-2 system with an MP-4 magnetometer, and a second MP-3 magnetometer used as a base station programmed to measure the magnetic field at 2-minute intervals. If the surveys were to be on foot, time and budget allocations would have severely limited coverage. Trials were therefore made using an all-terrane vehicle (atv) with the magnetometer sensor mounted at the top of a 12-foot plastic (pvc) pipe. Profiles run with this method showed good repeatability compared with those done by walking. Using the atv with continuous manual (hand triggered) magnetic observations, we found that recorded observations were 20 to 30 feet apart, and averaged 25 feet. Stationing was tied to recognizable map features on 1:24,000- scale topographic maps at quarter-mile intervals. As a survey method, prorating station spacing worked well where recognized map features could be found at intervals of a quarter mile or less; where this could not be done, a Magellan NAV 1000 PRO ground position system was used to supplement location by map features. Passing motor vehicles would sometimes influence the magnetic field, but these created easily recognized spurious anomalies lasting one or, at the most, two stations. We were required to change to a rented golf cart for safety and legal reasons. A slow-moving vehicle sign was attached to the rear of the cart, and a truck followed with another slow-moving vehicle sign on its rear door.

Data dumps and profiles were made using a Compaq computer, Scintrex IGSDUMP software, and an Okidata printer. Printer profiles and digital data files were named for the date the profile was run. On some profiles, location data were written on the hard copy, but for most they were entered on the computer file using MSDOS edit software. Photocopies of 1;24,000 topographic maps were used to plot traverse locations and stationing. Profile locations were drawn on photocopies of 1:250,000-scale maps. All profiles are available on disks from the DNR Open-File.

In the Shephard Map Area, 70 miles of road traverses were completed. This is where most of the survey method design work was done. The profiles were submitted to Spector for use in making his inferred geologic map. In the Shephard Area Extension, the geologic strike of lithologic units and structural features is east-west, perpendicular to flight-line direction with little to be gained from running ground traverses; however, 176 miles of road traverse were completed in the Long Prairie Area to the west. We were not permitted to enter the Camp Ripley Military Reservation, but a few traverses were completed along public roads in the Camp Ripley Map Area.

Geophysical Measurements

Geophysical measurements of natural fields such as gravity or magnetic susceptibility are the most cost-effective data for interpretations of bedrock geology where bedrock drill samples are scarce. Interpretation of the geophysical data can be enhanced by density and magnetic-susceptibility measurements of available bedrock samples in the study area.

The instruments used, methods, and inherent errors for each of the different sample types are as follows. For all sampled intervals several measurements were made for each interval and recorded to make sure that a high or low reading representing a very small part of the sample was not used in a way which would bias results. The high, low, and average measurements for magnetic susceptibilities and densities are calculated for each sample interval. These, along with the number of readings, were entered in PARADOX database files MAGSUS.DB and DENSITY.DB. The location information for these sample readings can be found in PARADOX database file P295SAM.DB.

Bulk density measurements were made with a Mettler 33360 210260 density determination kit, used with a Mettler H43 balance. Distilled water was used for the sample weight in water, and the water temperature measured for determination of a water temperature constant. The sample was weighed in air and then in water and the calculation made using the formula: Density of a solid body equals (weight in air), divided by (weight in air minus weight in water), times the (water temperature constant). The density or volume of pore fluids in the in-situ natural environment is unknown, and thus there is an error in measurements of samples which have dried. A few porous samples kept taking on water during weighing and you could see small bubbles rising from the sample. In 3 or 4 minutes of soaking, sample weight changes would be several hundredths of a gram which would translate into an error of 1 to 2 percent. We tried to soak these samples until the weight stopped varying, but the results are questionable. These less accurate results are shown with a question mark in the tables and files. Measured samples taken from pieces of drill core typically were 1 to 3 cm in diameter.

Magnetic susceptibility measurements were made with an Exploranium KT-5 meter. Individual readings can be taken with a maximum sensitivity of 1×10^{-5} SI units. The manufacturer recommends the instrument should be held against a flat surface and should not be used to measure samples less than 50 mm thick with a surface smaller than the KT-5 face, 60 mm diameter. For outcrop, rock dump, and boulder samples this recommendation was followed all the time. On core samples the flat or split face of the core was placed against the instrument face, with as much of the face as possible being covered. An estimate of the percentage of meter face covered by core is also recorded. About 70 percent of the core readings had the meter face entirely covered, and 95 percent of the readings had more than 90 percent of the meter face covered. Some observations on rock samples with the face totally covered, compared with the face only 80 to 90 percent covered, were inconclusive. For rocks with low magnetic susceptibility (iron-poor rocks), there was a higher percentage of change in readings than there was for rocks with high susceptibility (iron-rich rock), but the change could be positive or negative with less of the meter face covered. Rocks with high iron content typically had readings of 400 to 900 SI units, in contrast to readings for iron-poor rocks which were typically .02 to 5.3. This will give the reader an idea of how accurate these observations are and how they can be used. With more comparison testing on core samples, we believe it can be determined whether a correction factor is necessary and what the factor should be. This would increase confidence in the method.

Reevaluation of Geochemical Data from Shettel and O'Hara

As shown on the Index Map (Fig. 2), four sets of geochemical data are available in the central Minnesota area. These are: (1) The National Uranium Resource Evaluation[1] (NURE) program's bedrock data, 200 samples (Morey and Lively, 1980). (2) NURE hydrogeochemical ground-water data, 883 samples (Morey and Lively, 1980). (3) DNR Report 236, lake-sediment data, 618 samples (Sellner, 1985). (4) DNR Report 236-2, well water, 226 samples (Beckwith and Clark, 1985). The DNR requested proposals for a contract to statistically evaluate these data using contemporary methods. D.L. Shettel Jr., GeoData Systems, and P.F. O'Hara, Kaaterskill Exploration, were awarded

[1] NURE was a U.S. Department of Energy program during the 1970s and early 1980s.

the contract. The following description of the methodology used in the reevaluation of these data sets is quoted from their report which is available on an open-file basis from the DNR (Shettel and O'Hara, 1992, Executive Summary, p. 1).

> "The data sets were reevaluated for mineral potential according to several genetic deposit models. Sample location maps and single element geochemical maps (using a Canadian symbol scheme) were produced at a scale of 1:250,000 for the National Uranium Resource Evaluation (NURE) program's Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) groundwater and bedrock samples, Minnesota Department of Natural Resources (DNR) groundwater samples, and DNR lake sediment samples in Brainerd, Duluth, and Stillwater 1°x2° NTMS quadrangles. For evaluation purposes, only groundwater data from producing wells was used.
>
> "Univariate (including robust) and multivariate statistical (including factor, discriminant, and cluster) analyses were performed on each data set as a whole and geological subsets (subdivided according to the 1988 geologic map of Southwick et al.). Data were transformed by both logarithm (base 10) and a Box-Cox power function to achieve (or attempt to approach as close as possible) a normal distribution for multivariate statistics. Factor analysis proved to be the most useful multivariate statistical technique and there was apparently little difference between the two data transformations. Relevant factor score maps were produced. Geochemical modeling (calculation of aqueous speciation and saturation of samples with respect to minerals) of the NURE HSSR detailed geochemical data produced saturation indices for several phases; saturation indices for coffinite and uraninite proved to be the most useful for delimiting the reduced groundwater samples. Bedrock data were not utilized further due to the lack of any anomalous elemental data.
>
> "Schematic target maps (sum of the number of elements above a threshold value) for each of four ore deposit models (base + precious metals, Algoma Fe, Superior Fe, and uranium) are reproduced by Shettel, D.L. Jr. and O'Hara P.F., that indicate those areas with mineral potential. Other ore deposit models (e.g., gold, tin-tungsten, beryllium-tantalum-niobium) were not utilized [because of] geology and the lack of relevant chemical analyses. Summary target maps are combinations of target maps of all sample media plus factor score maps and saturation index maps; six maps were produced at a scale of 1:250,000 for the Brainerd and Duluth + Stillwater quadrangles for uranium, base + precious metals, and Algoma & Superior iron models."

Drilling

At the end of the 1991-1992 biennium some money became available that was allocated to testing the inferred geologic maps with diamond drill holes. Longyear Company completed the drilling under contract with the DNR from April 1, to June 30, 1993. At that time Spector had completed the Shephard Area and Shephard Area Extension, and Shettel and O'Hara had completed their reevaluation of geochemical data from east-central Minnesota. The Shephard and Shephard Extension

Areas were selected as general locations for the drilling. Several criteria were used for drill site selection: (1) The sites would not test the possibility of an economic mineral deposit because such sites would likely be explored by industry. (2) The sites should test areas of inferred geologic units that would be favorable for economic mineral deposits, which had not been confirmed by outcrop or drill hole samples of lithology. (3) The sites would be on state or county land, located to avoid any ecological disturbance. (4) The sites should acquire drilling data from places that would contribute to a better overall understanding of the regional geology. Site selection was discussed with David L. Southwick, Minnesota Geological Survey, who kindly provided a list of sites that would meet the fourth criterion.

After field checks, ownership approval, and ecological impact assessment, eight sites were selected, for which allocated money allowed drilling of six holes. All the holes were vertical, drilled through the surface and a short distance into bedrock with a 4.5-inch rock bit. The hole was then cased and drilling continued with an NQ (2.75-inch) diamond core bit. Recovery of 90 percent was required by the contract. Enough core was recovered to provide a good bedrock sample, about 30 to 40 feet, the bottom being unweathered rock.

All six holes were permanently abandoned in accordance with applicable state laws. Casings were pulled and the holes were pumped full of cement. After abandonment drill sites were cleaned and seeded with a mixture of timothy and clover. Drill sites and mud sumps were carefully surveyed with a Mount Sopris SC-132 scintillometer for radiation and all were found to have normal background radiation counts. In October the drill sites were inspected; seeding had produced good ground cover, no slumping was observed, and there was no water flow at the sites.

RESULTS

Compilation of bedrock data

For exploration geologists the most significant data come from bedrock samples and the chemical analysis of these samples. The following bedrock samples were studied and logged: 19 outcrops, 12 rock dumps, 3 boulder samples from glacial deposits, and 868 Drill Core Library holes, (1,300 Drill Core Library sample sets containing 107,667 feet of core). The data are categorized by lithologic description, observed evidence of alteration, structure, and mineralization. Information on the data is presented in Tables 4, 5, and 11; also digital files LOCATE.DB, P295SAM.DB, DRILLCRI.DB, MASTLOG.DB, and MASTCOM.DB. The bedrock digital databases provide indications of favorable lithologies, alteration, and structure that can be related to economic mineral deposit models. For example, visible sphalerite was observed in core from hole DDH K-1.

Thin-section studies help determine geology, and 179 thin sections were described. This work supports and expands the bedrock sample logging. As an example, for sample 2950100239 (P295SAM.DB) the rock type is indicated as a fractured quartz vein, with limonite alteration and quartz grains sheared into thin ribbons. This is further described in file JWDESC93.WP. Digital files related to thin section studies are JWPET93.WP, JWPET95.WP, JWDESC93.WP, JWDES951.WQ2, JWDES952.WQ2, and P295TS.DB.

Economic mineral potential and geologic parameters are further defined by analytical data and 1,399 Drill Core Library samples were analyzed. A number of the analyses indicate the possibility of mineralization; for example, analysis of a 5-foot interval of core from DDH K-1 indicated 2.25 percent zinc. Table 11 displays some of the more obvious analytical evidence of mineralization processes combined with observed lithology, alteration, structure, geophysics, and geochemistry. Anomalous analytical data are found in this section of the report and in digital files P295SAM.DB, CHEM.DB, P295CHEM.DB, P295CHSM.DB, and P295CHLA.DB.

Gold, zinc, and copper content define most of the anomalies listed. The approximate accuracy and precision of the analytical work done by contractor Bondar-Clegg for these elements (as determined from reference sample analysis) is graphically presented on Figures 9, 10, and 11.

In the analytical data, high manganese-oxide contents are observed with high precious and base metal contents. For example, sample 2950100130 contains 5.77 percent MnO and 1,622 ppm copper; sample 2950100218 contains 2.73 percent MnO and 1,333 ppb gold. There is some concern that there might be "scavenging" by manganese-iron oxides of these metals during surficial weathering. Levinson (1980) describes element scavenging of certain elements by manganese-iron oxides, based on a multi-element correlation study of stream sediments and oxide coatings done by G. A. Nowlan in 1976 whereby:

"c. elements scavenged weakly by Mn-Fe oxides: Cu, Mo, Pb and Sr;
d. elements strongly scavenged by Mn oxides: Ba, Cd, Co, Ni, Tl and Zn;
e. elements scavenged strongly by Fe oxides: As and In."

A correlation matrix done for all project analyses (Table 8) shows the correlation coefficients with manganese.

TABLE 8. CORRELATION COEFFICIENTS WITH MANGANESE[1]				
V = - 0.11	**Cr = - 0.08**	**Co = 0.14**	**Ni = - 0.08**	**Cu = - 0.01**
Zn = - 0.06	**As = 0.15**	**Y = - 0.07**	**Zr = - 0.23**	**Nb = - 0.12**
Ag = 0.13	**Cd = 0.10**	**Ba = 0.41**	**Pb = - 0.01**	**Pd = - 0.02**
Pt = - 0.01	**Au = - 0.03**			

[1]The fact that correlation coefficients for elements of interest are low or negative precludes scavenging the metals from ground water.

Maps of Inferred Geology and Mineral Potential

Four inferred geologic maps of mineral potential interpretation areas were completed which covered 62 townships. Within this area geology was interpreted at a scale of 1:62,500, 55 mineral potential areas were mapped, and depth to magnetic basement was estimated. The maps of the Shephard Area and Shephard Area Extension were combined, revised to reflect drill data, and

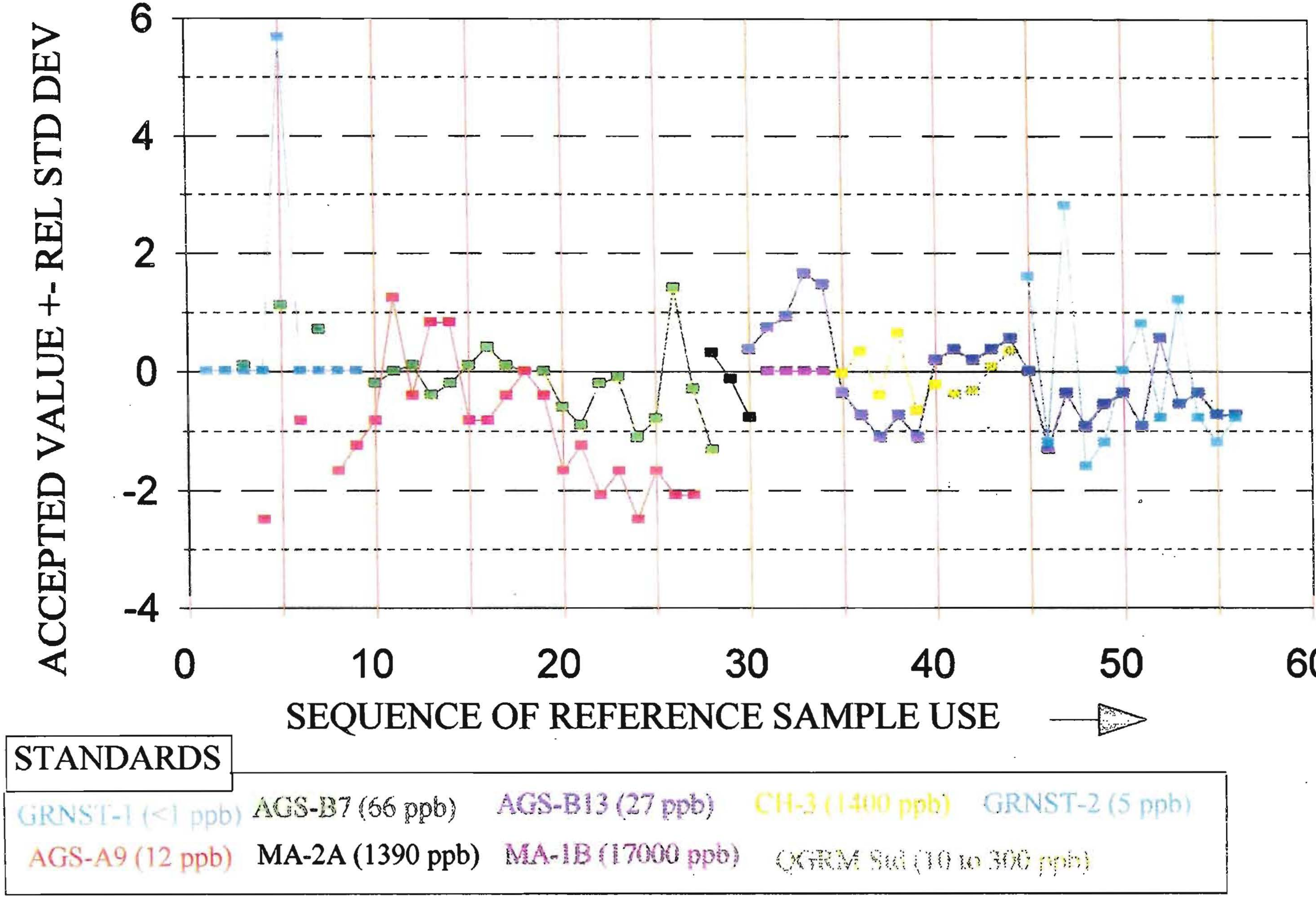


Figure 9. ALL Au STANDARDS FOR SMALL PACKAGE **(Analyses compared to accepted values.)**

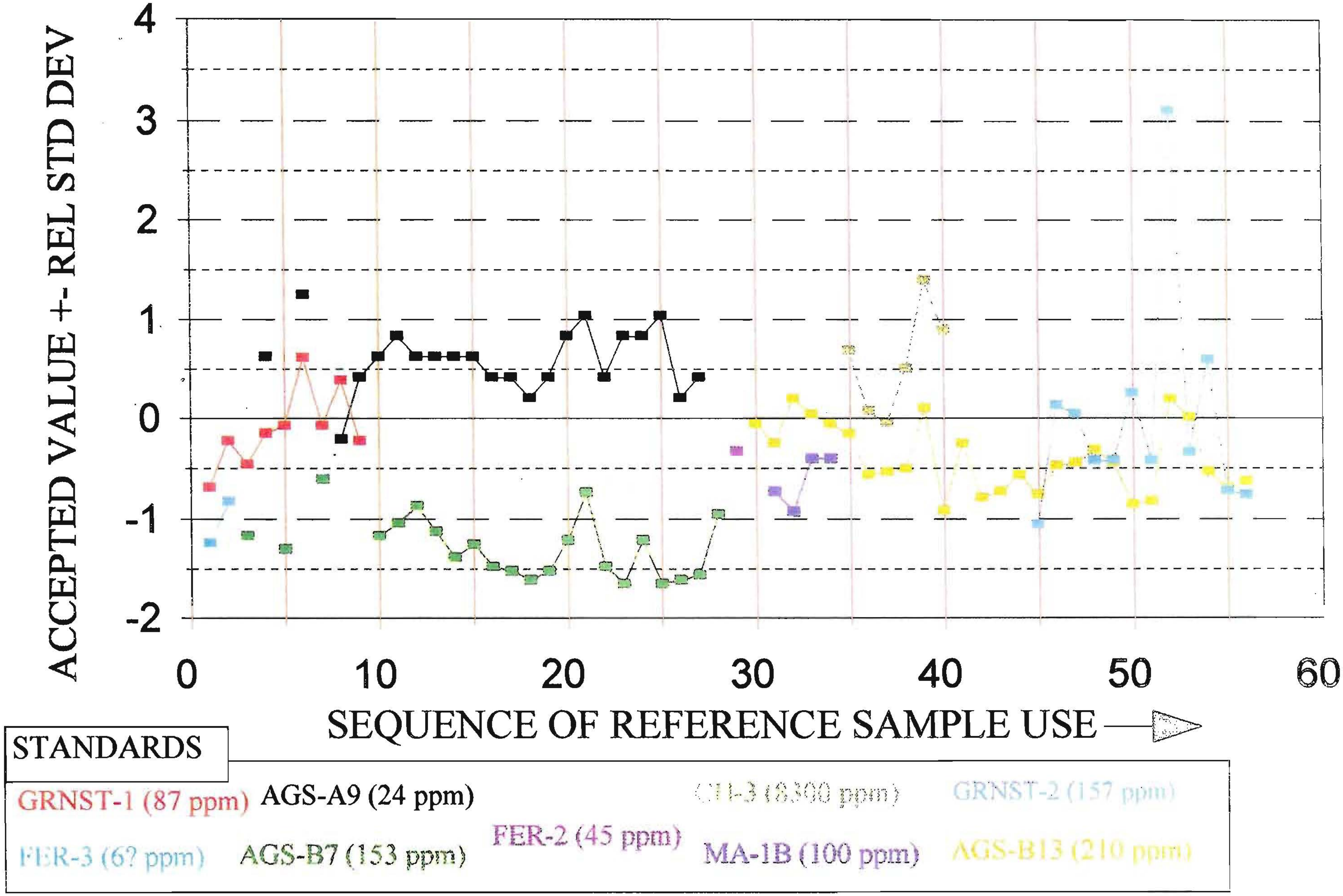


Figure 10. ALL Cu STANDARDS FOR SMALL PACKAGE **(Analyses compared to accepted values.)**

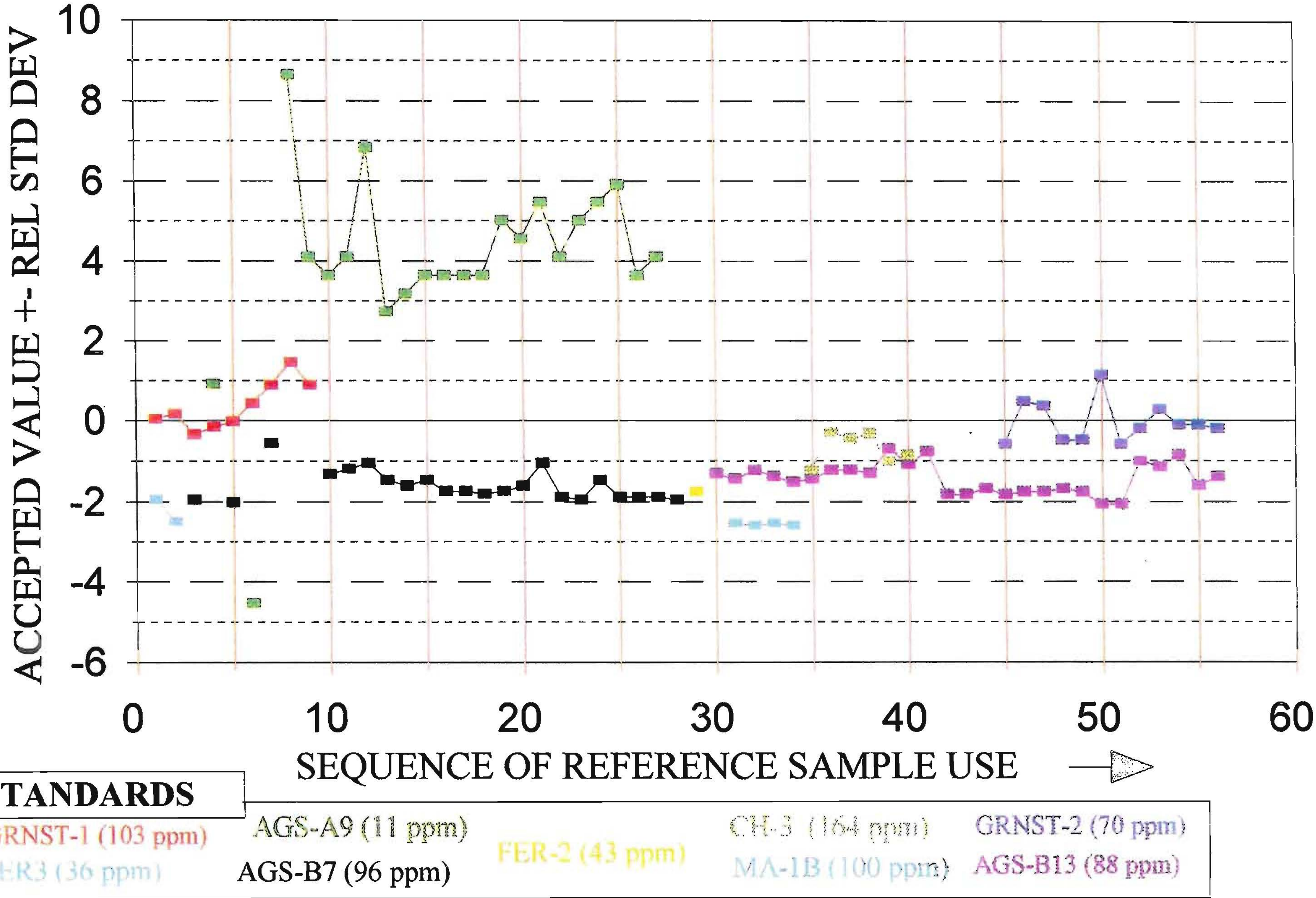


Figure 11. ALL Zn STANDARDS FOR SMALL PACKAGE **(Analyses compared to accepted values.)**

published in Geophysics (Spector and Lawler, 1995). This revised map, the Camp Ripley Area and the Long Prairie Area are combined and presented here as Plate 1 at a scale of 1:500,000. The location of section C-D (Fig. 12) from the revised Shephard Area Extension and section 3-3' (Fig. 13) from the Camp Ripley Area are also shown on Plate 1. Spector's reports are in open file and available on request from the DNR (Spector, 1992, 1993, 1994, and 1995; Spector and Lawler, 1995). The inferred geologic map accuracy was enhanced with 246 miles of ground magnetic traverses along roads. These are also found in the open-file data. Magnetic susceptibility, 3,183 measurements, and density, 1,937 measurements, from local lithologic units were used in Spector's computer models. These are found in digital files MAGSUS.DB and DENSITY.DB. All exploration data in DNR General Exploration Files for inferred map areas were provided as background for Spector's work.

The comments in the following paragraphs refer to Spector's original interpretations prior to obtaining the new drill hole data. The inferred geologic maps show a structurally complicated Archean-Proterozoic granite-greenstone terrane with volcanic and metasedimentary rocks wrapping around a mixture of Archean migmatitic gneiss and amphibolite intruded by units of younger Archean granite, as well as units of Early Proterozoic gneiss and granite. Lithologic units are dominated by a mixture of mafic metavolcanics that are strongly magnetic and metavolcanics with a moderate magnetic susceptibility. These are intercalated with metasediments including Algoma-type iron formations.

There are several places where Spector's interpretation is different from previous geologic interpretations of the area:

(1) Spector's interpreted geologic map of the Shephard Area Extension (Fig. 12, Plate 1) places the Malmo Discontinuity 6 to 10 miles north of where it was previously mapped..

(2) At the northwest end of Mille Lacs Lake (Shephard Area), Spector maps an intrusive feature which he calls the Mille Lacs Feature. Drill hole P295-6, which was drilled to test this feature, intersected conglomerate that could overlie an intrusion, and the feature was not further tested.

(3) West of Mille Lacs Lake, Spector interprets an area characterized by very deep non-magnetic rocks which he calls the Central Basin. This could be part of unit Pgs of the Penokean orogen map, (Southwick et al., 1988), an Early Proterozoic unnamed graphitic schist and slate. However, on Spector's map it has a shape and character more like the Animikie, Nimrod, or Long Prairie basins. In a personal communication, V.W. Chandler suggested that intrabasement anomalies or regolith might provide the same results. Drill hole P295-4, which was located on the feature, intersected siltstone at 311 feet. Spector's original depth estimate of >500 feet probably reflects depth to magnetic basement below the siltstone.

(4) On the Camp Ripley Area map, the southwest end of greenstone unit V1 has a depression which has been folded so that the top now faces north. Fault F1 crosses this feature. The lithology and structure of this site are favorable for massive sulfide deposits (Singer and Mosier *in* Cox and Singer, 1986).

(5) In addition to the inferred geology, Spector's maps have contours showing estimates to magnetic basement, which are typically depth to unweathered bedrock, although they can indicate depth to the base of a nonmagnetic lithologic unit. V.W. Chandler (personal communication) suggests that they also could represent depth to a lithologic unit which does not extend to bedrock surface.

(6) Finally, Spector has interpreted the inferred geology and discrete geophysical responses in terms of models of economic ore deposits. There are a total of 55 mineral potential areas described in his

Figure 12. Shephard Area Extension. Gravity profile is observed data, magnetic profile is a modeled qualitative correlation modified from Spector and Lawler (1995).

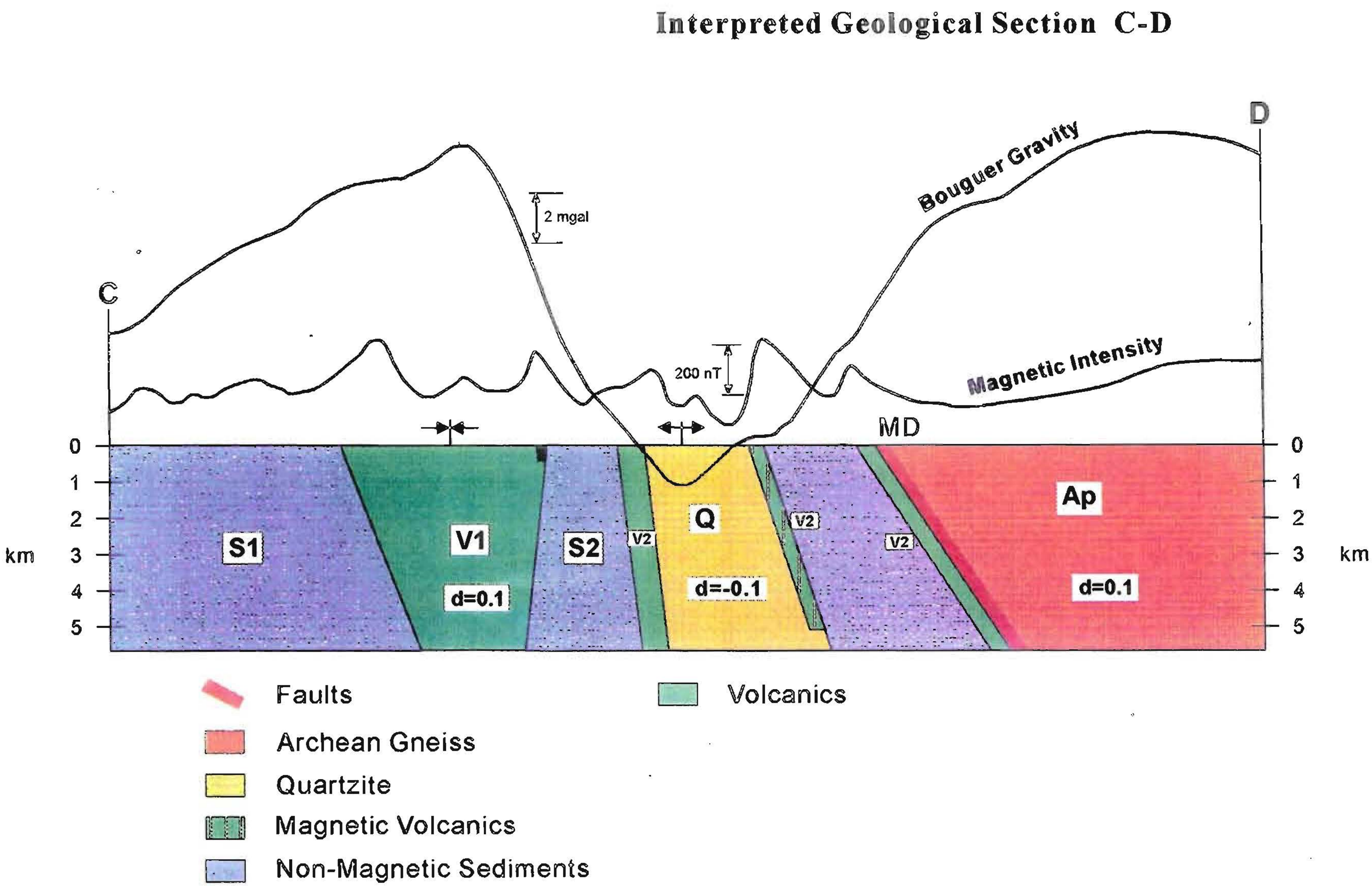
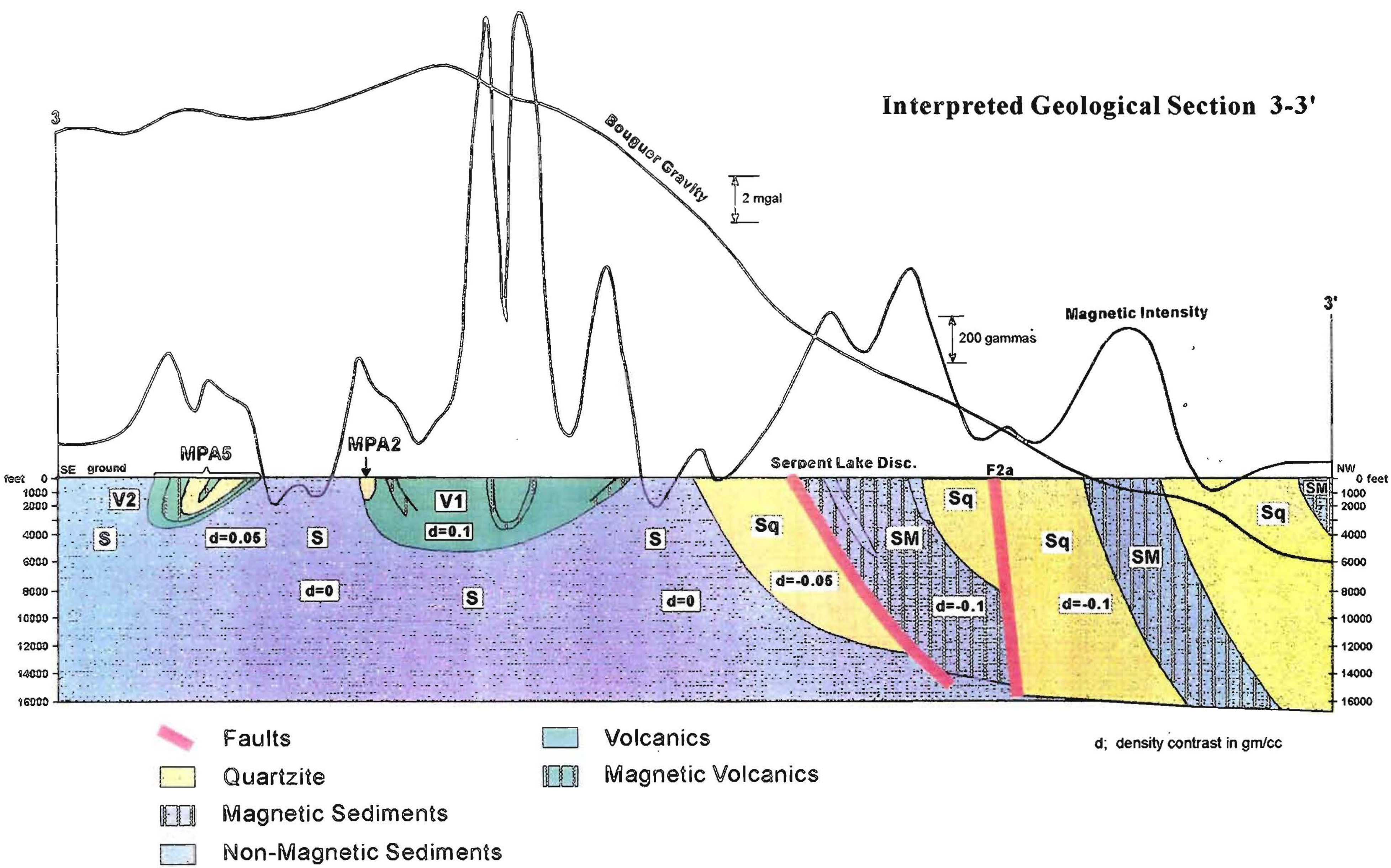


Figure 13. Camp Ripley Area. Gravity profile is observed data, magnetic profile is a modeled qualitative correlation modified from Spector (1995).



reports—16 in the Shephard Area, 16 in the Shephard Area Extension, 18 in the Long Prairie Area, and 5 in the Camp Ripley Area (Spector, 1992, 1993, 1994, 1995). These are described in detail in his reports.

Reevaluation of Geochemical Data from East-Central Minnesota

Under contract with the DNR, Shettel and O'Hara (1992) reevaluated four sets of geochemical data from east central Minnesota. More than one data set occurs in much of the study area (Fig. 2); however, all four data sets do not occur together anywhere in the area. Sample location maps and single-element geochemical maps (using a Canadian symbol scheme) were produced at a scale of 1:250,000 for all four surveys. Seven ore deposit models for Proterozoic and Archean terranes used in the evaluation were: gold, gold-cobalt-uranium-nickel-molybdenum, silver-nickel-cobalt-arsenic-bismuth, copper-lead-zinc-barium, manganese-iron, tin-tungsten, and beryllium-tantalum-niobium. The data were evaluated and target maps (the sum of the number of elements above a threshold value) were generated that indicate areas having mineralization potential. Patterns for available pathfinder elements such as arsenic, copper, and zinc are described. Discussed in the report are interpretation methods used in analyses, a definition of baseline hydrogeochemical data, single-element anomalies, inter-element associations, the most useful analytical techniques for contrasting and comparing major element associations, the effectiveness of the spatial distribution of sampling, and recommendations for follow-up.

Shettel and O'Hara (1992) identified 82 geochemical mineral potential target areas. Some of the target area information for base and precious metals is summarized on Table 9 which displays target number, 1°x2° sheet, summary map, lithology, structure, and anomalous elements in lake sediments.

Six summary target maps were produced at a scale of 1:250,000 for uranium, base and precious metals, and Algoma and Superior iron models. These covered surveys in the Brainerd, Duluth, and Stillwater 1°x2° NTMS quadrangles. They also made page-size reproductions of schematic target maps. In this report we have modified the page-size map for base and precious metals by adding target numbers to correspond with the those on Table 9. The shapes of these anomalous areas are different from those shown on the 1:250,000 scale maps, because the latter combine data from the different survey methods. A modified reproduction of the page-size schematic target maps for base and precious metals and lake-sediment data, is presented here as Figure 14.

Areas that have overlap of summary targets for different models include the Cuyuna district, Pelican Lake, Long Prairie basin, Animikie basin, Animikie unconformity, and the Keweenawan Supergroup rocks (Shettel and O'Hara, 1992).

Project Drilling Results

Of the six holes drilled 30 to 40 feet into bedrock to test estimated depth to magnetic basement and lithologic interpretations, four holes probably intersected magnetic basement; P295-4 intersected siltstone which may have mafic volcanics beneath it; and P295-6 intersected a quartz-pebble conglomerate interpreted to overlie a gneissic dome. The holes totaled 1,440 feet of drilling. Table 10 presents the results of this drilling. The holes were logged, sampled, and reported in drill core studies.

TABLE 9. GEOLOGIC AND GEOCHEMICAL DATA FOR SUMMARY MAPS OF BASE AND PRECIOUS METALS EVALUATION FROM LAKE-SEDIMENT DATA (modified from Shettel and O'Hara, 1992)

TARGET NUMBER[1]	1°x2° SHEET[2]	LITHOLOGY[4]	STRUCTURE	ANOMALOUS ELEMENTS IN LAKE SEDIMENTS
1	Brainerd	Amvs (Aqz)		F1[5] F2 F3 As Co Cu Fe Mn Ni Pb Ag U Zn
3	Brainerd	Pml (Pen & Pelv)		F1 F3 As Mn Ag U
7	Brainerd	North Range and Mille Lacs Groups (Pen Pems Pemv & Pelv)	Serpent Lake thrust + folded iron formation	F1 F2 F3 As Co Cu Fe Mn Mi Pb Ag U Zn
8	Brainerd	Animikie Group (Peg)		F1 F3 As Cu Fe Mn Ni Pb Ag U Zn
9	Brainerd	Psa/Pgvi (Pemq Pen & Pems)		F1 F3 As Co Mn Ni Pb Ag U
10	Brainerd	Mille Lacs Group (Pems)	Thrust	F1 As Mn
27	Duluth	Pgvi/Pdv/Pvdg (Pems & Pemb)		F1 F2 As Co Cu Fe Ni Ag U Zn
28	Duluth	Animikie Group (Peg)		F1 F2 F3 As Co Cu Fe Ni Pb U Zn
29	Duluth	Animikie Group/Psa (Peg Pemb & Pems)	Unconformity	F2 F3 Co Cu Pb Ni U Zn
30	Duluth	Psa/Pgui (Pems)		F2 As Co Cu Ni Pb U Zn
33	Duluth	Animikie Group/Pgs (Peg & Pems)	Unconformity	F2 F3 Co Cu Ni Pb Ag U Zn

[1]Target number refers to the targets displayed on Figure 14. Note that these are a sample of the work done by Shettel and O'Hara and do not include all the geochemical targets referred to in Table 11.

[2]These are the United States Geological Survey 1:250,000-scale maps.

[3]The summary map group chosen as an example of the geochemical reevaluation program for Central Minnesota is the base and precious metals evaluation.

[4]The lithology terms used by Shettel and O'Hara are from Southwick et al. (1988). The lithology terms in parentheses are from Morey (1994) as shown on Figures 6A and 6B.

[5]F1, F2, F3, F4, etc = specific factor scores precious and base metals. "Factor analysis is a statistical technique used to identify a relatively small number of factors that can be used to represent relationships among sets of many interrelated variables." (Shettel and O'Hara, 1992).

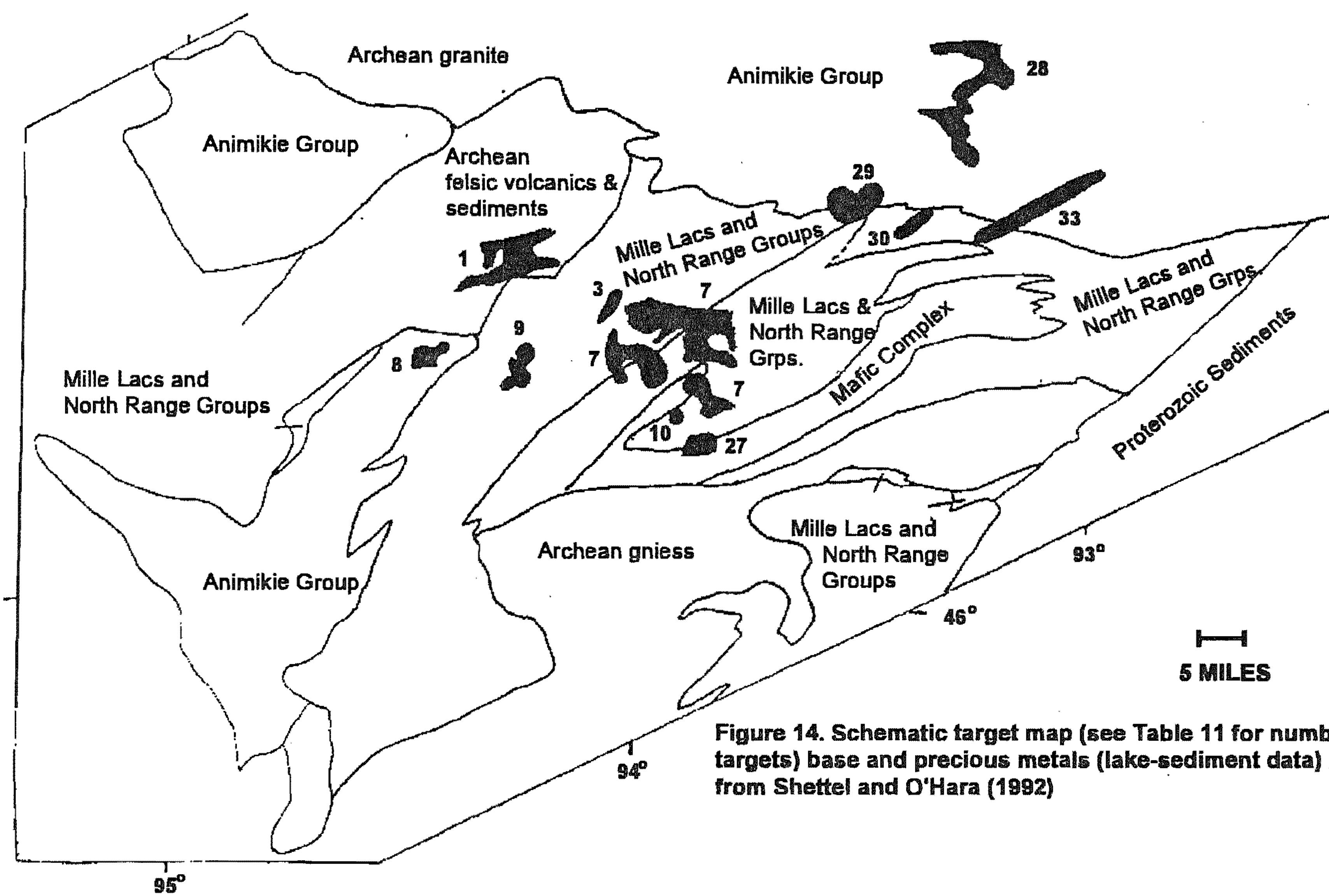


Figure 14. Schematic target map (see Table 11 for numbered targets) base and precious metals (lake-sediment data) modified from Shettel and O'Hara (1992)

The Project 295 drill hole data are summarized on Table 10 which compares the results of Spector's interpreted maps with data from the six holes drilled to test those results. Note that the depth estimates presented in Table 10 were taken from the open-file reports on the Shephard Area and the Shephard Area Extension. The depth contours on Plate 1 for these areas were taken from Spector and Lawler (1995), and were corrected to reflect drilling results. Comparing Spector's original depth estimates with data from the six holes drilled to test his results (see Table 10 for locations, also Plate 1), we see reasonably good correlation of the results in four of the holes. The expected error for depth estimates would be between 80 and 120 feet and the estimates for these four holes are within the expected error. The estimated error for hole P295-4 (>500 ft. compared with drilled depth of 311 ft.) could discourage an exploration effort, but more likely the mineral potential target would be magnetic bedrock beneath the siltstone, and this depth was not tested. The error for P295-5 (<100 ft. compared with drilled depth of 240 ft.) could be an error from equipment failure or complex, rapidly changing bedrock topography.

TABLE 10. COMPARISON OF SPECTOR'S INFERRED GEOLOGIC MAPS AND NEW DRILL HOLE DATA FROM SIX HOLES DRILLED AFTER THE MAPS WERE CREATED

HOLE NUMBER	LOCATION	ESTIMATED DEPTH TO MAGNETIC BASEMENT	DRILLED DEPTH TO LEDGE	SPECTOR ESTIMATED LITHOLOGY	DRILL CORE LITHOLOGY
P295-1	NE,NW, S.28 T47N, R22W	<200 Ft.	127 Ft.	Greenstone	Calcareous amphibolite
P295-2	NW,SW, S.21 T48N, R24W	<200 Ft.	144 Ft.	Greenstone	Iron stained siltstone
P295-3	NW,SE, S.18 T47N, R24W	<200 Ft.	94 Ft.	Quartzite	Sericitic quartz schist
P295-4	SW,SE, S.36 T44N, R30W	>500 Ft.	311 Ft.	Greenstone	Siltstone
P295-5	SE,SE, S.22 T44N, R28W	<100 Ft.	240 Ft.	Greenstone	Volcanics & Sediments
P295-6	SE,NE, S.30 T45N, R27W	~250 Ft.	285 Ft.	Gneissic dome	Qtz. pebble conglomerate

Spector uses the words greenstone or volcanics in his descriptions without further subdividing the belts into lithologic units. McMillan and Robinson (1985) describe a greenstone belt as: "These terrains are characterized by lowe rmost mafic and ultramafic tholeiitic and komatiitic flows, related intrusive rocks and lessor volumes of pyroclastic deposits, stratigraphically overlain by intermediate to felsic calc-alkaline tuff and ash deposits with minor flow material (felsic domes, etc.) and related epiclastic sedimentary rocks." This would constitute one complete volcanic cycle or supercycle which might be separated from other cycles by iron formation. Therefore Spector has not defined a lithology which can be tested by a drill hole, although the hole might test one or more of the lithologies in a greenstone belt. Holes P295-4 and P295-6 probably have depth problems where a lithologic unit not defined by geophysical methods overlies a lithology that is defined. V.W. Chandler (personal communication) suggests the term "greenstone" implies an arc-related metavolcanic sequence that might not fit the mapped terrane.

The holes were located to avoid areas interpreted as having specific mineral potential. However, hole P295-3 was logged as a sericitic quartz schist, and sericite is a common alteration mineral associated with gold and massive sulfide deposits. Hole P295-6 was logged as a quartz-pebble conglomerate, and native copper was observed in the core. The alteration suggests movement of mineralizing solution in the conglomerate.

Database and Computer File Use

The appendix contains a list of the 20 files on the diskettes at the back of this report. Additional digital database diskettes are available on an open-file basis from the contracts by Spector (1992, 1993, 1994, and 1995) and by Shettel and O'Hara (1992).

The reconnaissance logging and sampling provide a preliminary indication of geologic features such as lithology, structure, alteration, and mineral content. The format is designed especially for people intending to do further study in central Minnesota and should be of particular interest for mineral exploration. Core logging and sampling is meant to be used as a guide to specific Drill Core Library Index (DCLI) material that may warrant further examination or sampling. Most of the project data are on digital files designed to be accessed by computer.

The digital files provide for easy searching and management of the information. With geographic information system software, data points can be located on maps and reproduced at any scale. With relational database software the huge volume of digital data can be queried and sorted on a large number of parameters. Simple examples of how these databases can be used are: all samples and sample locations for copper analysis over 300 ppm can be recovered and displayed in both table and map format; statistical analysis and graphs can be quickly and easily drawn to display digital information; selected thin section data can be recovered and reviewed for in-depth lithologic and alteration information and then quickly cited in a report or proposal; density and magnetic susceptibility data can be used to plan geophysical surveys. These databases form an abundance of available information for synthesis by users.

Summary of Most Significant Results

Table 11 on the following pages summarizes some of the observed evidence of geologic processes sometimes associated with ore deposits. The table displays the location and drill hole inventory number, the mineral occurrence as defined by analytical results, the lithology of the host rock, observed alteration, observed structure, geophysical indications and geochemistry. Footnotes at the end of the table provide more information about the occurrence. The occurrences are grouped into descriptive ore deposit models. As more exploration takes place, it is very likely some of the occurrences will fit into different models than the designated model in Table 11.

TABLE 11. OBSERVED EVIDENCE OF GEOLOGIC PROCESSES ASSOCIATED WITH ORE DEPOSITS						
T-R-S, DH INV#	MINERAL OCCURR.	LITHOLOGY	ALTERATION	STRUCTURE	GEOPHYSICAL	GEOCHEM.[5]
Descriptive Model of Early Proterozoic Lode Gold (Berger *in* Cox and Singer, 1986)						
47-18-4, 10569	Zn 594, F 1,639 Hg 254[1&9]	Tuff and Sediments[1]	Quartz-Sericite[1]	Breccia-Veins[1]		Anom 37
48-17-32, 10588	Au 151[1]	Maf Int & Vol[1]	Qtz-Seri-Chl[1]	Brec Vein Qtz[1]		Anom 39
48-18-32, 10593	Au 152, Pd 30[1&13]	Phyllite[1]	Qtz-Sericite[1]	Fault-Antiform[10]	Targets ML3-106 & ML3-111[12]	Anom 37
Descriptive Model of Early Proterozoic Iron Formation Hosted Gold (Berger *in* Cox and Singer, 1986)						
47-29-33, 15471	Au 69[1&13]	Oxide IF[1]	Carb-Qtz[1]	Veins-Folds[1&3]		Anom 7
130-30-6, 12627	Au 102[1]	IF-Tuff-Grns[1&2]	Chl-Qtz-S[1]	Fold-Faulted[1&2]		
132-33-36, 12614	Au 61 Cu 276[1&13]	Silicate IF[1&2]	Chlorite-Qtz-Carbonate[1]	Schist-Folded Iron Fm[1&2]	IF in Qtzite (1994)[2]	
46-29-9, 15468	Au 112 Cu 1,622[1]	Oxide IF[1]	Carb-Qtz[1]	Veins[1&7]	IF in Grns(1992)[2]	Anom 7
47-26-17, 15503	Cu 1,328[1]	Oxide IF[1]	Chl-Qtz-S[1]	Breccia-Veins[1]	IF in Grns(1993)[2]	
48-26-36, 15722	As 753[1]	Oxide IF-Grns[1&3]	Chl-Qtz[1]	Veins-Fault[1&3]		
Descriptive Model of Early Proterozoic Iron Formation Hosted Gold and Platinum Group Elements (Thorman and Ladeira *in* Thorman et al., 1991)						
43-32-12, 18337	Au 1,383 & 2,341 Pd 1,339 Pt 1,156 F 1,100[1]	IF in Grns[2].	No Observations Churn Drill Cuttings	High Mag Flank of Maf/Fel Units[2&6]	MPA3 (1995)[2]	
46-29-9, 15468	Au 112 Pd 31[1&13]	Oxide IF-Grns[1&2]	Carbonate-Qtz[1]	Veins-Folds[1&2]	Mag IF, (1992)[2]	Anom 7
Descriptive Model of Sedimentary Exhaltive Zinc-Lead (Briskey *in* Cox and Singer, 1986)						
47-26-3, 10189	Ba>2,000 As 926 Y 966[1]	Graph-Ox-IF[1]	Carb-Qtz-S[1]	Grns-Sed Contact[2] Brec[1]	Mag Data Shows Contact (1993)[2]	
47-20-22, 16300	Zn >20,000 F 635 Au 57[1]	Phyllite-Schist-Tuff[1]	Qtz-Sericite-S[1]	Breccia-Fault[1&3]	StrongConductorMagHigh[11]	
48-18-32, 14697	Zn 3,009 Pb 325 Au 192[1]	Phyllite-Breccia[1]	Qtz-Seri-Carb-S[1]	Fault[1&10]	Target ML3-106[12]	Anom 37

TABLE 11. OBSERVED EVIDENCE OF GEOLOGIC PROCESSES ASSOCIATED WITH ORE DEPOSITS CONTINUED						
T-R-S, DH INV#	MINERAL OCCURR.	LITHOLOGY	ALTERATION	STRUCTURE	GEOPHYSICAL	GEOCHEM.[5]
Descriptive Model of Volcanogenic Massive Sulfides (Sangster, 1972)						
48-18-33, 10605	Au 132 & 146 Zn 979 & 1,038[1]	Graph-Schist & Sulfide IF[1]	Sericite-Qtz-S[1]	Fault[10]	Target ML3-107[12]	Anom 37
47-28-30, 10362	As 116 Zn 731[1]	Oxide IF[1]	Quartz[1]	Brec-Thrust Fault[1&3]		Anom 7
46-29-10, 15472	Cu 1,084 As 101[1]	Oxide IF- Seds[1]	Carb-Qtz-Sericite[1]	Thrust Fault[3]	Mag Anom[2&8]	Anom 7
Descriptive Model of Sediment Hosted Copper (Mosier et al. *in* Cox and Singer, 1986)						
45-27-30, 15852 DH P295-6[1]	Visible Copper[1]	Conglomerate[1]	Qtz-Sericite[1]	Contact Granite-Grns[2&3]	MPA1 (1992)[2]	Anom 25

[1]Lithology, alteration, structure, mineral occurrences and assay data from Central Minnesota Study, Au, Pt and Pd analysis units are ppb; all others are ppm (Frey and Lawler, 1993).
[2]Lithology, alteration, and structure as mapped by Spector (1992, 1993, 1994 and 1995).
[3]Lithology and structure as mapped by Morey (1994).
[4]Mineral Potential Area numbers refer to sequence of discussion (Spector, 1992, 1993, 1994 or 1995).
[5]Gold or base metal geochemical anomalies (Shettel and O'Hara, 1992). Note the anomalies listed here are from all of Shettel and O'Hara's work, not only the lake-sediment anomalies listed on Table 9 or shown on Figure 14.
[6]"MPA1, 2 and 3 are three localized zones of conspicuously high magnetization 500 to 3000 gammas in relief. They attract interest because they are located on the flank of Belt V1, a transition from mafic to more felsic igneous rocks." (Spector, 1992).
[7]Overthrust and intrusive contacts, fault zone contacts with mafic volcanics (Morey, 1994).
[8]This anomaly is also close to Spector's MPA8 which "focuses on the Serpent River Discontinuity, here depicted as an overthrust. According to Eckstrand (1984) this kind of structure is suitable for vein-type gold mineralization" (Spector, 1992).
[9]Fluorine, zinc and mercury are found in lode gold deposits, mercury is common where there is increased zinc (Berger *in* Cox and Singer, 1986), (Boyle, 1979).
[10]Geology and geophysics of the Denham-Mahtowa area, east-central Minnesota (McSwiggen, 1987).
[11]Mineral potential geophysical target mapped and described in Airborne geophysical survey Aitkin, Carlton county area Minnesota, surveyed & compiled by Geoterrex (1974).
[12]Mineral potential target area mapped and described in Interpretation Report Electromagnetic Survey Barringer Input System of the Moose Lake Area Minnesota, by Geoterrex Limited for Rocky Mountain Energy Company (Hetu, 1979).
[13]One of the paired reference samples has an analysis greater than two standard deviations above the zero accepted reference sample element content.

RECOMMENDATIONS

Perform additional descriptive logging, sampling, and chemical analysis on the available 2,600 sets of drill samples, from approximately 1,600 drill holes located in the central Minnesota study area. Many of these samples contain drill core worthy of further examination.

Use this database to perform GIS spatial analysis of the data, layer by layer and then with overlapping layers. For example, gold quartz veins are described by Berger *in* Cox and Singer (1986) as being associated with sericite and arsenopyrite. A search of the MASTLOG.DB, MASTCOM.DB, and P295CHEM.DB will probably yield several areas where these minerals are found. If these areas coincide with mineral potential areas as mapped by Spector and with areas of base and precious metal anomalies as mapped by Shettel and O'Hara, the combined data, done at a reconnaissance scale, have a good chance of representing mineralization which could be investigated with more detailed surveys. There are also more sophisticated statistical analyses using the lithochemical data available from the P295CHLA.DB file which would better indicate areas of mineral potential.

Perform more detailed airborne surveys using aeromagnetics, together with other methods such as electromagnetics surveys. Much work could be done at a modest cost with detailed ground magnetic, gravity, and electromagnetic surveys.

The various geochemical surveys cover parts of the study area. There is an opportunity to expand these surveys or use them to plan additional work using contemporary methods which are more sophisticated.

Structure is an important factor in several mineral deposit models (Cox and Singer, 1986). Several geophysical methods including magnetotellurics could be used to test mapped structures for better location and definition. These should be followed by core drilling to determine how extensive the deformation really is.

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APPENDIX—DESCRIPTION OF DIGITAL DATABASES

The digital data are on 3.5-inch DOS disks. Formats used are PARADOX database, QUATTO spreadsheet, WordPerfect word processor, and ASCII text files. Other digital formats can be obtained, and personnel of the Minerals Information Services Section of DNR Minerals should be contacted regarding conversion to other digital formats.

The **logging databases** were constructed using a data manipulation system called WATFILE/Plus and Software Carousel. Six databases can be open at one time, allowing very rapid database switching, queries, data entry, and editing. The six databases consist of the geographic portion of the Drill Core Library Index, the logging database, the logging comments database, the lithologic code database, the alteration code database, and the database containing sampling information. While not being truly "relational," the individual WATFILE databases were constructed with the common fields necessary for linking after importing into a relational database.

The methodologies for data synthesis and utilization will be dependent upon hardware and software limitations, and the ingenuity of the user. One hope for a future product will be a PARADOX run-time module that will make the data usable for those who do not have their own database software. However, this would limit the user to the queries written by the developer.

As in any database development procedure, certain ideas were used in this database formulation: (1) to convey to the user how data were put together and what the limitations are; (2) to be consistent in application and usage; (3) to create data that will support anticipated queries; (4) to convey uncertainty if present; (5) to make use of text string matches for lithology, alteration, and mineralization searches and queries; (6) to be consistent in the use of proper spelling and be cognizant of spelling variations; and (7) to be as quantitative as possible within the context of the data structure. Most important is to enable the user to make the most efficient use of the data.

As in the utilization of any database, the user should embrace certain concepts: (1) become familiar with the actual data; (2) make queries that are supported by the data; (3) in the case of descriptive data, be aware that there may be alternative language with similar meaning that should be included in making data queries; (4) be cognizant of the specificity of your queries relative to the specificity of our data; and (5) make queries on the "logging" database also on the "comments" database to obtain all the available information.

List of Files on Diskettes in this Report

The two diskettes with the report are labeled P295.EXE and P295a.EXE. PKZIP 2 software has been used on the computer files to make them fit on the diskettes. The files are self extracting. To extract the files type in the directory, file name, space, and directory you want the file directed to. For example A:P295.EXE C:
press **Enter**.

P295RPT.WP This is a WordPerfect file of the text of this report.

295MAST.DB 202,752 bytes This file contains the inventory number, sample number, project file number, drill hole number, location (township-range-section and forty). Using this file you can link with all the other files.

P295SAM.DB 3,969,024 bytes PARADOX database master sample number file for all P295 samples. Includes linking field of unique DNR Inventory number (INV) combined with footage.

LOCATE.DB 253,952 bytes PARADOX database of location information with linking field of unique DNR Inventory number (INV), and is a part of the DNR Drill Core Library Index (DCLI).

DRILLCRI.DB 1,299,456 bytes PARADOX database of drill hole information with linking field of unique DNR Inventory number (INV), and is a part of the DNR Drill Core Library Index (DCLI).

CHEM.DB 708,608 bytes PARADOX database of chemistry data needed in the assessment files with linking field of unique DNR Inventory number (INV), and is a part of the DNR Drill Core Library Index (DCLI).

MASTLOG.DB 2,638,441 bytes PARADOX database of the drill core logging information including footage intervals, lithology, lithologic descriptors, alteration mineralogy, mineralization, and mineralization type information with linking field of unique DNR Inventory number (INV) and footage. Codes for some fields are included to allow for additional linking of files.

MASTCOM.DB 299,008 bytes PARADOX database of comments associated with the logs for each drill hole with linking field of unique DNR Inventory number (INV).

P295CHEM.DB 2,869,248 bytes PARADOX database of chemical analyses for both the large and small analytical packages, excluding standards and miscellaneous chemistry samples (Brazilian samples). This chemistry contains averages for duplicated samples. Detection limit values (<) have been replaced by 3/5 of the detection limit value. Overlimit values have been replaced by a more arbitrary value. These changes will affect some statistics (mean, median, etc.), but not others (correlation coefficients). Each field has an associated field with < or >. Contains lithology information, and so does not need linking for some purposes. Sample numbers and unique DNR Inventory number (INV) with footage are linking fields.

P295CHSM.DB 1,069,056 bytes PARADOX database of chemistry analyses from the small analytical packages, including standards and duplicates. Each field has an associated field with < or >. Contains lithology information, and so does not need linking for some purposes. Sample numbers and unique DNR Inventory number (INV) with footage are linking fields.

P295CHLA.DB 657,408 bytes PARADOX database of chemistry analyses from the large analytical packages, including standards and duplicates. Each field has an associated field with < or >. Contains lithology information, and so does not need linking for some purposes. Sample numbers and unique DNR Inventory number (INV) with footage are linking fields.

MAGSUS.DB 108,544 bytes PARADOX database of magnetic susceptibility readings. Sample numbers and unique DNR Inventory number (INV) with footage are linking fields.

DENSITY.DB 82,944 bytes PARADOX database file of density readings. Sample numbers and unique DNR Inventory number (INV) with footage are linking fields.

JWPET93.WP 26,218 bytes WordPerfect file of 1,993 thin section petrographic summary by James Welsh. Additional information about thin sections can be found in files P295SAM.DB AND P295TS.DB.

JWPET95.WP 120,467 bytes WordPerfect file of 1,995 thin section petrographic summary and thin section descriptions by James Welsh. Additional information about thin sections can be found in files P295SAM.DB AND P295TS.DB.

JWDESC93.WP 147,220 bytes WordPerfect file of 1,993 thin section petrographic summary by James Welsh. Additional information about thin sections can be found in files P295SAM.DB AND P295TS.DB.

JWDES951.WQ2 13,263 bytes QUATTRO (DOS) spreadsheet file of thin section description table. Additional information about thin sections can be found in files P295SAM.DB AND P295TS.DB.

JWDES952.WQ2 18,952 bytes QUATTRO for Windows spreadsheet file of thin section mineralogy table. Additional information about thin sections can be found in files P295SAM.DB AND P295TS.DB.

P295TS.DB 280,576 bytes PARADOX database file of thin section information not found in P295SAM.DB, using sample number as the linking field. This is part of the DNR's thin section database.

P295FF.DB 1,351,680 bytes PARADOX database file with sample numbers, geologic age, orogen, formation name, lithology, alteration, mineralization, structure, and weathering.

INFERRED BEDROCK GEOLOGIC - MINERAL POTENTIAL MAPS
Modified from Spector (1992, 1993, 1994, and 1995)

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