Mineral Resource Assessment of the U.S. Portion of the International Falls $1^\circ \times 2^\circ$ Quadrangle, Northern Minnesota

U.S. GEOLOGICAL SURVEY BULLETIN 2044

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By Terry L. Klein, Warren C. Day, Robert J. Horton,
J. Robert Clark, *and* James E. Case

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This report summarizes the mineral resource assessment, the geologic framework, a high resolution aeromagnetic survey, and a surficial geochemical exploration survey of the International Falls $1^\circ \times 2^\circ$ quadrangle

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MINERAL RESOURCE ASSESSMENT OF THE U.S. PORTION OF THE INTERNATIONAL FALLS 1°×2° QUADRANGLE, NORTHERN MINNESOTA

By Terry L. Klein, Warren C. Day, Robert J. Horton, J. Robert Clark, *and* James E. Case

ABSTRACT

The International Falls 1°×2° quadrangle in northern Minnesota and southern Ontario has been studied in cooperation with the Minnesota Geological Survey as part of the U.S. Geological Survey Conterminous United States Mineral Assessment Program. This report summarizes the mineral resource assessment that was carried out between 1984 and 1990 by a team from the U.S. Geological Survey. New information, including geologic mapping, a high-resolution aeromagnetic survey, a surficial geochemical exploration survey, and a bedrock petrology and lithogeochemistry study, was combined with older data to locate and characterize the known metallic mineral resources in the quadrangle and to determine the potential for existence of undiscovered resources. The resource potential is considered only for economic, marginally economic, or subeconomic metallic resources of a conventional type that might be found in this area.

The study area straddles the international border separating Minnesota and Ontario and lies within the southern part of the Archean Superior province of the Canadian Shield. The Superior province is composed, in part, of several northeast-trending subprovinces of alternating greenstone-granite terranes and metasedimentary rock-gneiss terranes. Three of these major subprovinces, the Wabigoon, Quetico, and Wawa-Shebandowan occur within the study area. These subprovinces are separated by major east-west trending, high-angle faults (the Quetico, Rainy Lake-Seine River, Vermilion, and Silverdale faults) that have both a vertical and dextral strike-slip component.

The northernmost terrane is the Wabigoon subprovince, a greenstone-granite terrane that has undergone upper greenschist to lower amphibolite-facies metamorphism. Rocks of the Quetico subprovince, a metasedimentary rock-gneiss terrane that has been metamorphosed to upper amphibolite-facies, make up the middle terrane in the map area. The southern terrane, the Wawa-Shebandowan subprovince, is a granite-greenstone terrane that has undergone greenschist-facies metamorphism; the Vermilion district is located within this subprovince, southeast of the study area.

Most of the bedrock in the study area is represented by Late Archean supracrustal and plutonic rocks. The western part of the area has been intruded by an extensive northwest-trending, Early Proterozoic dike swarm that extends northwestward for several hundred kilometers.

Quaternary surficial deposits as thick as 60 m, composed of glacial till, glaciofluvial and glaciolacustrine sediments, flood-plain alluvium, and peat, unconformably overlie Precambrian bedrock or saprolite developed on bedrock during pre-Pleistocene weathering. The entire area was extensively glaciated by numerous glacial advances throughout the Pleistocene.

Three groups of magnetic surveys were merged to prepare a new aeromagnetic map of the International Falls quadrangle. Data for the eastern part of the area, were taken from a high-resolution aeromagnetic survey of St. Louis County, Minnesota (Chandler, 1983). This survey was flown along flight lines spaced at about 0.4 km at an elevation of 150 m above the surface. In Ontario, data were taken from north-south surveys flown along lines spaced about 0.7 km apart at an elevation of about 300 m by the Geological Survey of Canada. In the southwestern part of the area, data were obtained by the U.S. Geological Survey, in cooperation with the Minnesota Geological Survey, along north-south lines spaced 0.4 km apart at an elevation of 90 m above the ground. The magnetic data, supplemented with interpretations of gravity data, provided the basis for geologic interpretation of the bedrock where it is concealed by surficial deposits.

Geochemical analyses of B-horizon soils that were selectively leached using an enzyme-based leach were used to detect subtle patterns of hydromorphic trace element dispersion in areas where bedrock was covered by surficial deposits. Results of the geochemical survey indicated the extension of areas of possible gold mineralization along the Rainy Lake-Seine River fault and detected Ag-Co-As anomalies in soils that may indicate the presence of vein deposits in the underlying bedrock.

On the basis of projected known mineral occurrences and analogies with similar geologic environments, five types of deposits were assessed for their mineral resource potential. These deposits types are volcanogenic massive sulfide,

gabbro-hosted Ti, V, Ni, and Cu deposits, Algoma-type iron-formation, lode-gold, and chemical sedimentary rock-hosted gold. Five tracts, all within the volcanic rocks of the Wawa-Shebandowan and Wabigoon subprovinces, are thought to have moderate potential for volcanogenic massive sulfide deposits. Even though several occurrences of Ti-V and Cu-Ni and PGE enrichments in gabbro sills have been explored in the adjacent area of Canada, no appropriate host rocks were identified in the U.S. part of the in the U.S. portion of the International Falls 1°×2° quadrangle. One thin layer of Algoma-type iron-formation can be traced in the subsurface for more than 10 km but is probably too thin to be exploited. Potential for lode-gold deposits is high in two tracts along the Rainy Lake-Seine River fault, near International Falls and moderate along other segments of the Rainy Lake-Seine River fault and the Vermilion fault. Potential for chemical sedimentary rock-hosted gold deposits is moderate in metavolcanic rocks of the Wawa-Shebandowan and Wabigoon subprovinces.

INTRODUCTION

The International Falls 1°×2° quadrangle in northern Minnesota and southern Ontario has been studied in cooperation with the Minnesota Geological Survey as part of the U.S. Geological Survey Conterminous United States Mineral Assessment Program (CUSMAP). Multidisciplinary studies were used to evaluate the mineral resource potential of selected 1°×2° quadrangles throughout the country. This report summarizes the mineral resource assessment that was carried out between 1984 and 1990 by a team of scientists from the U.S. Geological Survey in cooperation with the Minnesota Geological Survey. New information, including geologic mapping (Day, 1990b; Day and others, 1990b), a high-resolution aeromagnetic survey (Bracken and Godson, 1987), a surficial geochemical exploration survey (Clark and others, 1990) and bedrock petrology and lithogeochemistry studies (Day, 1990a; Klein and Day, 1989; Klein, 1988; and Klein and others, 1987, 1988), were combined with older data to locate and characterize the known metallic mineral resources in the quadrangle and to determine the potential for existence of undiscovered resources. This report only considers the resource potential for economic, marginally economic, or subeconomic metallic resources of a conventional type that might be expected in this area. Products resulting from this study are intended to provide regional mineral resource assessment to aid in a long-range minerals resource management plans by federal agencies and local land-use planning; to provide data for mineral exploration; and to increase the geologic understanding of the area.

The International Falls 1°×2° (fig. 1) quadrangle includes an area of approximately 16,000 km^2 between lat 48° and 49° N. and long 92° and 94° W. Elevations range from approximately 330 to 490 m. Bedrock is exposed in the northeastern and east-central sections of the quadrangle, where a number of lakes fill depressions on the glaciated surface. Areas of black spruce forest and peatlands are developed on the poorly drained Quaternary glacial deposits which obscure the bedrock in the southwestern one-third of the quadrangle. The Big Fork and Littlefork Rivers flow northward into the eastward-flowing Rainy River, the major river in the western part of the quadrangle. The Rainy River flows into Rainy Lake, a large lake that straddles the United States-Canada border.

In areas of extensive glacial cover, the bedrock geology and structure were interpreted from aeromagnetic data, gravity data, and drill holes that penetrated to bedrock. Because of this Quaternary cover, information regarding deposit types, favorable host rocks and structures, and estimates of metallic concentrations was derived from descriptions of deposits in western Ontario, north of the study area. Weathering has produced a saprolite layer of varied thickness along the interface between the bedrock and the Quaternary deposits, further complicating the interpretation of bedrock characteristics.

The Canadian part of the quadrangle (roughly 40 percent of the land area) was not included in the mineral resource assessment. Approximately 10 percent of the land area within the eastern United States part of the quadrangle is within the Boundary Waters Canoe Area and the Voyagers National Park. No new field studies were undertaken in these areas. A large part of the remaining area in the eastern part of the quadrangle is in the Superior National Forest and the Kabetogema State Forest. A large area in the southwestern part of the quadrangle is in the Pine Island, Smokey Bear, and Koochiching State Forests.

This bulletin summarizes the results of the component geologic, geochemical, geophysical, and mineral resource investigations; presents the criteria on which the mineral resource assessment was made; and summarizes the results of the assessment.

GEOLOGIC SUMMARY

The International Falls 1°×2° quadrangle straddles the international border separating Minnesota and Ontario and lies within the southern part of the Precambrian Superior province of the Canadian Shield. As recently reviewed by Ayres and others (1985) and Card (1990) the Superior province includes several northeast-trending subprovinces of that alternate between greenstone-granite terrane and metasedimentary-gneiss terrane (fig. 2). The International Falls 1°×2° quadrangle overlaps three of these major subprovinces, which are also major lithotectonic terranes. Within the map area, these terranes are separated by high-angle faults that have both a vertical and dextral strike-slip component; these boundary faults are now broad shear zones (fig. 3).

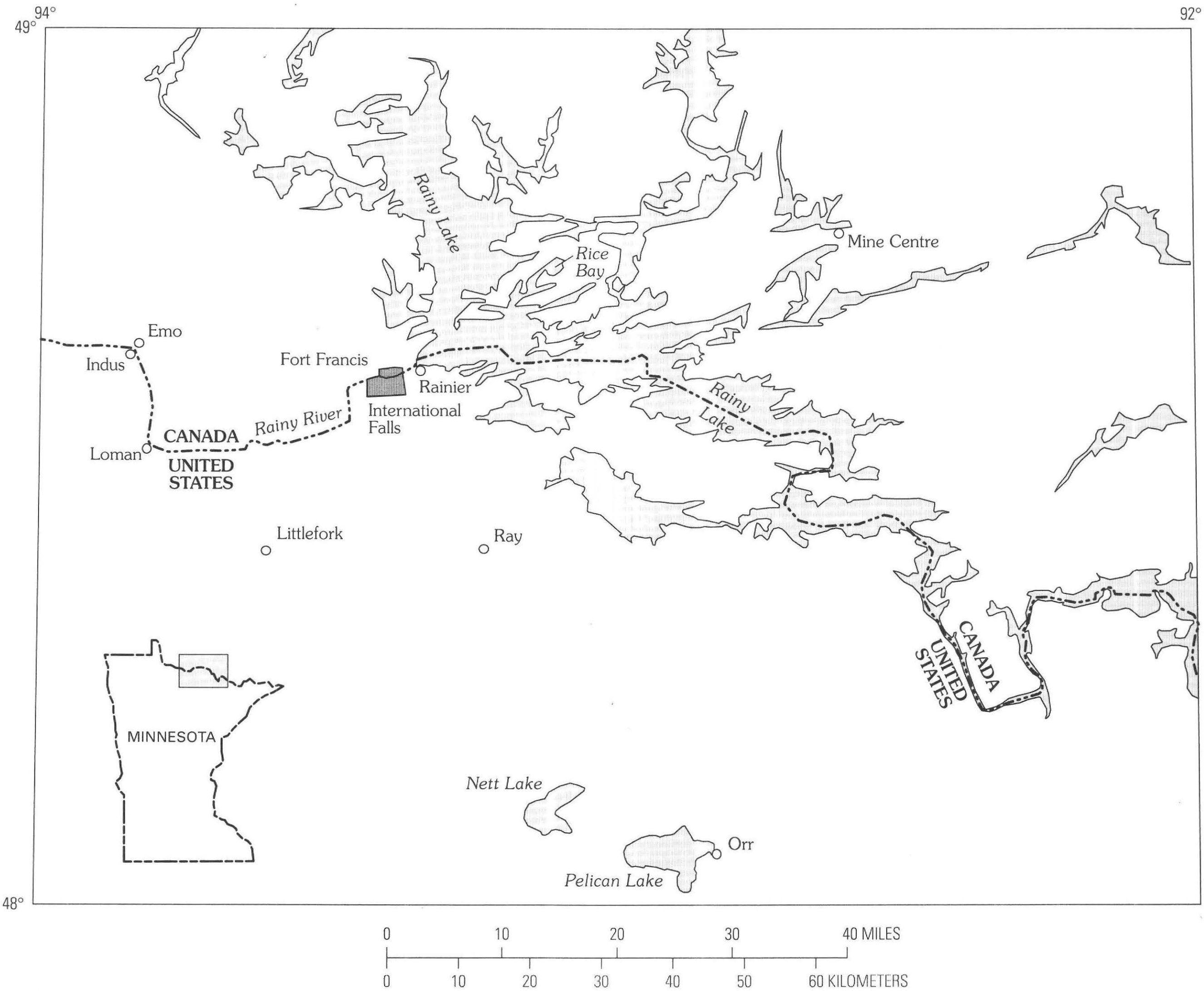


Figure 1. Location of the International Falls 1°×2° quadrangle showing selected geographic features.

The northernmost terrane in the quadrangle is the Wabigoon subprovince, a greenstone-granite terrane that has undergone upper greenschist- to lower amphibolite-facies metamorphism. Rocks of the Quetico subprovince, a metasedimentary rock-gneiss terrane that has been metamorphosed to upper amphibolite-facies, make up the middle terrane in the map area. The southern terrane, the Wawa-Shebandowan subprovince which includes the Vermilion district of Minnesota, is a greenstone-granite terrane that has undergone greenschist-facies metamorphism.

Most of the bedrock in the map area is represented by Late Archean supracrustal and plutonic rocks (pl. 1). The western part of map area has been intruded by an extensive northwest-trending, Early Proterozoic dike swarm that extends northwestward for several hundred kilometers (Southwick and Day, 1983; Day and other, 1990b).

GEOLOGY

WABIGOON SUBPROVINCE

The northern part of the quadrangle lies within the Wabigoon subprovince, a greenstone-granite terrane made up of metamorphosed volcanic, metasedimentary, and plutonic rocks ranging in age from 2,725 to 2,685 Ma (Davis and others, 1989). The terrane is bounded on the south by the Rainy Lake-Seine River fault. In the area bounded by the Quetico fault on the north and the Rainy Lake-Seine River fault on the south (fig. 3), the metavolcanic rocks, which Lawson (1913) termed the Keewatin volcanics, are the oldest of the supracrustal units. As noted by Goldich and Peterman (1980) volcanism in this part of the Wabigoon subprovince was predominantly bimodal. The mafic metavolcanic suite is predominantly tholeiitic in composition, with both depleted

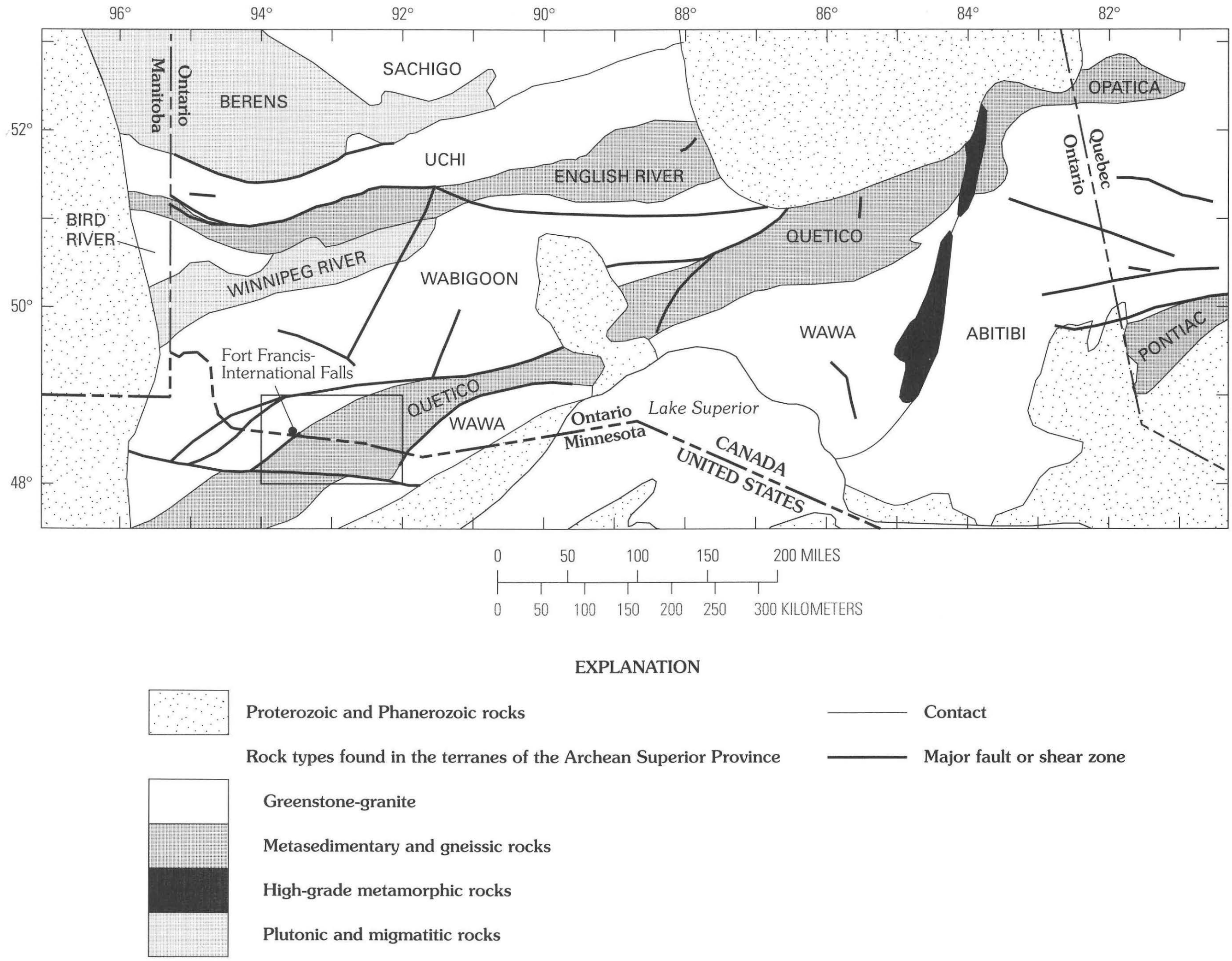


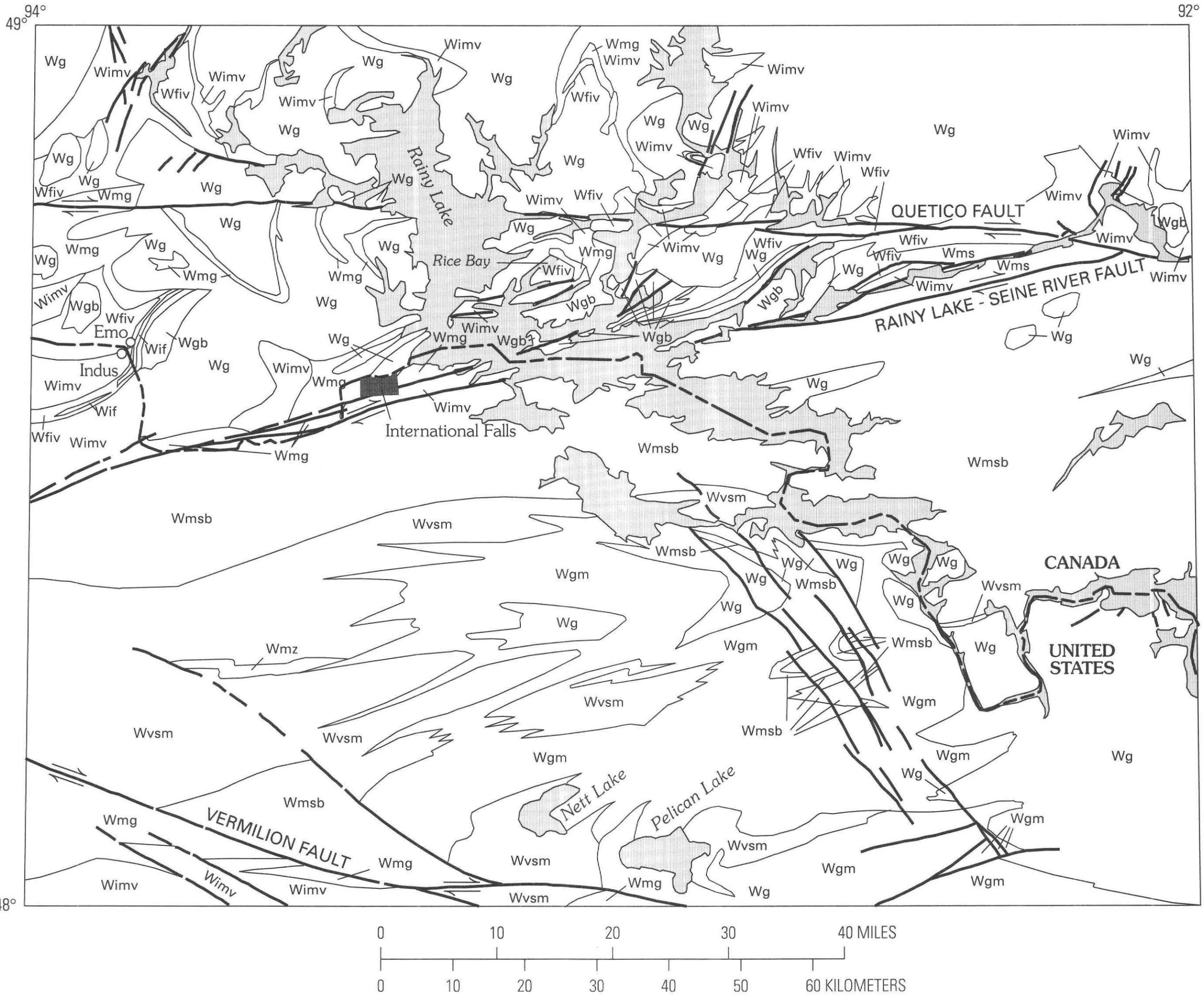
Figure 2. Sketch map showing major lithotectonic terranes, subprovinces, and the Archean Superior province (modified from Card and others, 1989). Sedimentary, volcanic, and most plutonic rocks are metamorphosed. International Falls 1°×2° quadrangle shown by box.

low-TiO_2 and enriched high-TiO_2 varieties (Day, 1990a). Although minor in abundance, calc-alkaline metabasalts have been identified in the Rainy Lake area (Day, 1990a). Ultramafic metavolcanic flows have been identified by Poulsen (1984) in a restricted area east of the Rice Bay in Ontario. The felsic metavolcanic suite is made up of both tholeiitic and calc-alkaline dacites, rhyodacite, and rhyolite. Andesitic metavolcanic rocks are conspicuously rare in the map area, although they do occur in a few locations in the extreme western part of the map area in Minnesota (Klein and others, 1987). Rocks mapped as intermediate metavolcanics a short distance to the east in Ontario are highly schistose and have an uncertain origin, although Shirey and Hanson (1984) reported two samples of high-magnesium trachyandesite near Rice Bay in Ontario.

The metavolcanic rocks have been intruded by coeval pretectonic gabbro and associated anorthosite, tonalite, and trondhjemite. In the eastern part of the map area (fig. 3), mafic intrusions occur as concordant sills interlayered with supracrustal rocks. In the western part of the map area, near Indus, Minn. and Emo, Ontario, deformation was less intense, and mafic intrusions are medium-sized stocks that crosscut lithologic contacts.

Lawson (1913) first described the stratigraphic relations in the Wabigoon subprovince rocks near Rainy Lake. He defined the pretectonic felsic plutonic rocks east of the Rainy Lake area as the Laurentian granite. They occur as concordant bodies that have been synkinematically deformed with the supracrustal country rocks. Geochemical data support the hypothesis that the mafic and felsic plutonic rocks are cogenetic with their effusive equivalents (Ashwal and others, 1983; Shirey, 1984; Day, 1990a).

The supracrustal rocks are primarily metagraywacke interlayed with minor amounts of mafic and felsic metavolcanic rocks and iron-formation. The metagraywacke is typically composed of fine- to medium-grained beds that



EXPLANATION

Wg	**Granitoid rocks**	Wmg	**Graywacke**
Wms	**Quartzite and conglomerate**	Wif	**Iron-formation**
Wgb	**Gabbro and anorthosite**	Wfiv	**Felsic to intermediate volcanic rocks**
Wgm	**Granite-rich migmatite**	Wimv	**Mafic to intermediate volcanic rocks**
Wvsm	**Schist-rich migmatite**		**Contact**
Wmsb	**Graywacke (biotite schist)**		**Fault**—Dashed where approximately located; half arrows show direction of movement

Figure 3. Simplified geologic map of Late Archean rocks in the International Falls 1°× 2° quadrangle (modified from Day and others, 1990b). Sedimentary, volcanic, and most plutonic rocks are metamorphosed. Wabigoon subprovince is north of the Rainy Lake-Seine River fault, the Quetico subprovince is between the Rainy Lake-Seine River fault and the Vermilion fault, and the Wawa-Shebandown subprovince (including the Vermilion district) is south of the Vermilion fault.

are locally graded. Ojakangas and others (1977) suggested that the metagraywacke was volcanogenic turbiditic sedimentary rocks deposited in tectonically active basins distal to contemporaneous volcanism.

The stratigraphic relations between the metavolcanic rocks (Keewatin greenstones) and the metagraywackes (Coutchiching series) of Lawson (1913) has been a focus of controversy since the turn of the century (Ojakangas, 1972).

Recent mapping (Ojakangas, 1972; Poulsen and others, 1980; Poulsen, 1984; Day, 1990b) has shown that most of the contacts between metavolcanic rocks and metagraywackes are faults, and therefore, the relative age of the two groups is ambiguous. However, Poulsen and others (1980) did recognize an area where the metagraywacke is clearly stratigraphically younger than the metavolcanic rocks.

Iron-formation is interlayered with both metavolcanic rocks and metagraywacke throughout the area north of the Rainy Lake-Seine River fault. The iron-formation is generally oxide-facies (chert-magnetite), but silicate-facies (cummingtonite-grunerite-actinolite) and sulfide-facies (pyrite-pyrrhotite) varieties do occur. The layers of iron-formation are enfolded and synkinematically deformed with the host supracrustal rock.

Following deformation of the supracrustal rocks and pretectonic intrusive rocks (see below), quartz arenite and polymict conglomerate of the Timiskiming type (which Lawson (1913) termed the Seine Group) were deposited. Both Ojakangas (1972) and Wood (1980) established that the quartz arenite is feldspathic and immature, commonly exhibits trough crossbedding, and probably was deposited in a fluvial environment (Ojakangas and Olson, 1982). Clasts within the conglomerate are thought to be locally derived.

After deformation of the supracrustal and pretectonic intrusive rocks, the conglomerate was invaded by large volumes of granitoid rocks and monzodiorite (Algoman Group of Lawson(1913)) at about 2,686 Ma (Davis and others, 1989). The weakly foliated, post-tectonic intrusions formed composite batholiths that generally have an early intermediate phase (monzodiorite to monzonite) that is cut by a later, more felsic phase (granodiorite to granite). Internal foliation within the batholiths generally cuts the regional foliation of the country rock, which commonly occur as roof pendants.

QUETICO SUBPROVINCE

Metasedimentary, migmatitic, and granitic rocks of the Quetico subprovince lie south of the Wabigoon subprovince. This terrane is bounded on the north by the Rainy Lake-Seine River fault and on the south by the Vermilion fault (fig. 3). The northern part of the terrane is composed of a broad unnamed belt of folded graywacke that has been metamorphosed to sillimanite-bearing biotite schist, and intruded by small bodies of leucogranite and monzonite. This belt of biotite schist passes southward into rocks of the Vermilion Granitic Complex (pl.1). The contact between the biotite schist belt and the migmatite to the south is gradational and, as defined by Southwick (1978), "is arbitrarily placed where granitic rocks become sparse or absent from the flanking unnamed biotite schist."

Day and Weiblen (1986) described the Vermilion Granitic Complex as "a granite-migmatite terrane consisting of supracrustal rocks (metagraywacke and amphibolite) that have been intruded by granitoid." Large intrusions of massive Lac La Croix Granite occur in the eastern and central part; elsewhere, the Lac La Croix Granite has invaded the supracrustal rocks, forming a granite-rich migmatite that consists of a neosome of primarily Lac La Croix Granite and a paleosome that itself is an early migmatite formed by the intrusion of older tonalite, trondhjemite, and granodiorite into supracrustal rocks [graywacke], minor granofels, and amphibolite (pl.1).

Schist-rich migmatite in the outer margins of the complex has a paleosome of graywacke (now biotite schist) and a neosome of leucogranite and granodiorite. The leucogranite, a garnet-bearing two-mica granite, commonly occurs as thin stringers in the graywacke, forming a stromatic migmatite. The leucogranite is synkinematically enfolded with the biotite schist and forms boudins and pods that coalesce into small irregularly shaped bodies. Day and Weiblen (1986) suggested that the leucogranite bodies were anatectic melts remobilized into their present position within the graywacke.

The oldest plutonic phases in the Vermilion Granitic Complex include small tonalitic, trondhjemitic, and granodioritic bodies that invade the metagraywacke host rock and form migmatite (Southwick, 1972). This early migmatite was deformed (see below) and then intruded by large bodies of Lac La Croix Granite. The Lac La Croix Granite, which is a magnetite-bearing biotite granite, has invaded both the graywacke and early migmatite and forms the neosome of late migmatite. In the eastern and central part of the map area the Lac La Croix Granite forms large plutons in the cores of regional folds (pl. 1). The late migmatite, termed a granite-rich migmatite by Southwick and Ojakangas (1979), is formed along the edges of the plutons (fig. 3).

WAWA-SHEBANDOWAN SUBPROVINCE

The rocks in the southwestern corner of the International Falls 1°×2° quadrangle lie within the Vermilion district, a southwest extension of the Wawa-Shebandowan subprovince. These rocks are separated from the rocks of the Quetico subprovince by the Vermilion fault. This subprovince constitutes a small, poorly exposed part of the quadrangle (fig. 3).

Rocks in the Vermilion district (Sims, 1976), typical of greenstone-granite terranes throughout the Superior province consist of metamorphosed bimodal volcanic rocks and sedimentary rocks, and post-tectonic plutonic rocks. The mafic metavolcanic rocks (flows in part) range in composition from ultramafic to tholeiitic with some calc-alkaline basaltic flows and pillow lavas. The felsic metavolcanic rocks are calc-alkaline dacite, rhyodacite, and rhyolite (Schulz, 1980). The metasedimentary rocks are chemical sedimentary rocks (for example, iron-formation) and epiclastic sedimentary rocks (for example, graywacke). Unlike in the Wabigoon subprovince, the stratigraphic relations between the supracrustal metasedimentary rocks and metavolcanic rocks are fairly well preserved. In general the metavolcanic rocks are the oldest units, but interfinger with and are overlain by the metasedimentary units (Sims, 1972b).

The metavolcanic and metasedimentary rocks in the Vermilion district have been extensively invaded by post-tectonic granitoid rocks. The most voluminous intrusion is the composite Giants Range batholith which contains tonalitic, granodioritic, and granite phases (Sims and Viswanathan, 1972; Arth and Hanson, 1975).

In the study area, the dominant rock type in the Vermilion district is metagraywacke; lesser amounts of mixed mafic metavolcanic and metasedimentary rocks are present. The metagraywacke south of the Vermilion fault may be stratigraphically equivalent to the metagraywacke (now biotite schist) north of the fault in the Vermilion Granitic Complex (Bauer, 1986). This implies that the amphibolite-facies metagraywacke and migmatite north of the Vermilion fault were once at a deeper structural level in the crust than those south of the fault, which are metamorphosed only to the greenschist-facies, and that the rocks on the north side of the fault have been uplifted relative to those on the south side.

STRUCTURAL HISTORY

The rocks in each of the three lithotectonic terranes or subprovinces in the International Falls 1°×2° quadrangle were complexly deformed during the Archean. Correlation of the early tectonic events from one terrane to another, is ambiguous. However, the effects of the latest episodes of deformation are recognized throughout the entire map area.

WABIGOON SUBPROVINCE

Rocks in the Wabigoon subprovince have undergone at least three episodes of deformation. The earliest (D_1), in response to a regional northwest-southeast directed compression, produced isoclinal and recumbent folds, a strong bedding-parallel schistosity, and mineral lineations (Poulsen and others, 1980; Day, 1987,1990b,). The D_1 fabrics are best preserved in the graywacke units between the Quetico and Rainy Lake-Seine River faults (fig. 3).

The second episode of deformation (D_2) was in response to a regional, dextral, transpressive, ductile-shear regime. The major wrench faults, represented by the Quetico and Rainy Lake-Seine River faults, were established during D_2. The D_2 episode produced numerous upright folds (both large and small scale), a strong penetrative, ductile shear planar fabric, and mineral and intersection lineations.

Ductile deformation during D_2 along the boundary faults, which now are broad shear zones (as wide as 1 km wide), produced schist, phyllonite, and mylonite. Within these wrench zones, many faults are subparallel to the major boundary faults but then "horse-tail" as they diverge from the shear zone boundary (fig. 3).

The regional D_2 shearing produced numerous fault-bounded structural panels throughout the wrench zone (Ojakangas, 1972; Poulsen, 1984) that have an internally consistent stratigraphy and metallogeny. Near the major shear zones, however, the stratigraphic relations within the panels are obscured by transportation of units along small, internal shear zones that formed along lithologic boundaries.

The third episode of deformation (D_3) within the Wabigoon subprovince caused reactivation of the major shear zones. The latest movement occurred during the Early Proterozoic (Peterman and Day, 1989), at about 1,947 Ma, causing brittle deformation along the earlier ductile or brittle-ductile fault zones. Pseudotachylite, developed as a result of frictional heating and fusion of the wallrock within the fault zone, is present along both the Rainy Lake-Seine River and the Quetico fault zones.

QUETICO SUBPROVINCE

The metasedimentary rocks and migmatite of the Quetico subprovince have undergone three episodes of regional ductile deformation. D_1, the earliest, produced a bedding-parallel S_1 foliation, isoclinal and large-scale recumbent folds, and small-scale intrafolial folds in the metagraywacke. Early stringers and small bodies of tonalite, trondhjemite, and leucogranite were emplaced syntectonically into the supracrustal country rocks during D_1, forming an early migmatite (Southwick, 1972).

D_2, which was in response to a regional north-south directed compressional regime, produced F_2 folds and strong S_2 foliation (Bauer, 1986). Regional upper-amphibolite-facies metamorphism climaxed during D_2, causing peak metamorphic minerals, as well as producing interlayered leucogranite stringers aligned parallel to the S_2 foliation. L_2 lineations, which formed at the intersections of S_0-S_1 and S_1-S_2 planar elements, are coaxial with the F_2 folds (Bauer, 1986). The major plutons of the Lac La Croix Granite were emplaced syn- to post-D_2 deformation (Southwick, 1978; Bauer, 1986).

D_3 folded the D_2 structural elements along broad, open folds that have east-west axial traces as much as 85 km long (fig. 3). As described by Bauer (1986), these F_3 folds have a locally developed axial-planar foliation, fold the S_2 foliation, and fold the regional metamorphic isograds (Percival and others, 1985) in the biotite schist belt in Ontario (Day and others, 1990a).

Bauer (1985, 1986) has shown that the D_2 and D_3 events were caused by the same regional transpressive dextral shear regime. The predominant D_2 structural fabric was refolded during emplacement of the Lac La Croix Granite during late D_2. Progressive ductile deformation during D_3 caused reorientation of the D_2 fabric and developed a mineral foliation within parts of the plutons of Lac La Croix Granite, which are along the axis of the east-trending F_3 folds (fig. 3).

WAWA-SHEBANDOWAN SUBPROVINCE

The metasedimentary and metavolcanic rocks in the Vermilion district of the Wawa-Shebandowan subprovince record two major episodes of ductile deformation. The oldest (D_1) was produced by a north-south compression that produced large-scale recumbent, isoclinal, and small-scale sheath-like folds (Hudleston and others, 1988). In a detailed study of the strain history of the southern part of the Vermilion district, Hudleston (1976) determined that the metasedimentary rocks have been folded, but have no penetrative D_1 fabric and record no associated strain. He concluded that D_1 affected unlithified sediments and resulted in soft-sediment deformation. In the northern part of the Vermilion district, Bauer (1985) has shown that D_1 did produce folds with a penetrative fabric and that rocks in the northern domain were structurally downward-facing, whereas those in the southern domain were upward-facing. Bauer (1985) suggested that a large-scale F_1 nappe structure could account for the discrepancy in the strain history, the southern domain rocks being on the upper limb and the northern domain rocks being on the lower limb of a south-verging F_1 nappe.

D_2, in the Vermilion district, produced a strong foliation and lineation and ductile shear zones with sigmoidal foliation patterns. D_2 structural fabrics developed in a regional transpressive dextral-shear regime, which refolded D_1 and early D_2 structural fabrics and produced dextral wrench faults (Hudleston and others, 1988).

SUMMARY OF THE STRUCTURAL HISTORY

The structural history of the three lithotectonic terranes in the map area is complex, but the terranes are related in a coherent regional pattern. Direct correlation of the oldest tectonic events across the terrane boundaries is ambiguous; however, each terrane did experience an early deformation in response to a northwest-southeast to north-south axis of maximum compression. In the Wabigoon subprovince and in the Vermilion district of the Wawa-Shebandowan subprovince, D_1 resulted in isoclinal folds and nappe structures. In the Quetico subprovince, D_1 resulted in isoclinal and intrafolial folds and the development of a nappe fold along its southern boundary.

D_2 was an event of regional transcurrent dextral shearing, that can be correlated among each of the terranes. Drag folds, small-scale folds of Z-symmetry, mylonite and shear zones with sigmoidal foliation patterns are well developed in parts of the Wabigoon subprovince and the Vermilion district. Within the Quetico subprovince, D_2 produced large-scale folds and was accompanied by the regional upper greenschist-facies metamorphism. Continued transpressive deformation resulted in the major east-west- trending F_3 folds, which reoriented the D_2 structural elements and produced dextral wrench faults.

The final Archean tectonic episode in each of the terranes involved dextral slip on the major faults, which formed the terrane boundaries. The metasedimentary rocks and migmatite of the Quetico subprovince were uplifted relative to the flanking greenstone-granite terranes.

The rocks within the map area were also affected by Proterozoic deformation. After stabilization of the Archean terranes, high-angle northwest-trending faults cut the Archean rocks within the southern part of the map area (fig. 3). These faults are filled, in places, with Proterozoic diabase dike swarms (Southwick and Day, 1983). Subsequent movement along these faults locally produced pseudotachylite, which has been dated at about 1,947 Ma by Peterman and Day (1989).

QUATERNARY GEOLOGY

Quaternary surficial deposits in the International Falls quadrangle, composed of glacial till, glaciofluvial and glaciolacustrine sediments, flood-plain alluvium, and peat, unconformably overlie Precambrian bedrock or saprolite developed on bedrock during pre-Pleistocene weathering. This area was extensively glaciated by numerous glacial advances throughout the Pleistocene. However, only surficial deposits from the lastest glacial events are exposed.

Within the quadrangle, Quaternary deposits of late Wisconsinan and Holocene age are the product of the advances of two lobes of the Laurentide ice sheet (Horton and others, 1989). Most of these lobes were fronted by proglacial lakes. The area's oldest glacial deposits, composed of noncalcareous till and glaciofluvial sediments, were produced by an advance of the Rainy lobe from the northeast, which spread from the Labradorian ice center in Quebec and Labrador (Johnson, 1915). Rainy lobe till is composed of loose, unsorted stony material in a sandy and silty matrix which generally represents 50 percent of the volume. The stony component of the till is composed of angular, subangular and subrounded material ranging in size from pebbles to boulders that were derived almost entirely from local Precambrian rocks.

The next advance was by the Koochiching lobe (Martin and others, 1989), which spread from the Keewatin ice center located northwest of Hudson Bay (Johnson, 1915). Calcareous till was deposited by this advance, which came from the west and north as shown by glacial striae. During the advance and subsequent retreat of the Koochiching lobe, glaciolacustrine sediments were deposited in a proglacial lake that formed along the front of the ice sheet. The Koochiching till is predominantly composed of silt and clay containing small amounts of stony material. The silt and clay component of the till were derived from glaciolacustrine sediments deposited in front of the advancing ice sheet and then incorporated into the till as the glacier overrode them. The stony component of the till, generally less than 15 percent, consists of angular, subangular, and subrounded material ranging in size from pebbles to boulders of locally derived Precambrian rocks and Paleozoic and Mesozoic sedimentary rocks derived from the northeastern flank of the Williston basin.

The final glacial event was a re-advance of the Rainy lobe from the northeast. The terminal moraine of this advance is marked by several ice-contact deposits in the northwest quarter of the quadrangle. Locally, deglaciation began with a retreat of the Rainy lobe to the northeast corner of the quadrangle, where it remained for a considerable length of time, forming the Eagle-Finlayson moraine (Zoltai, 1961). Meltwater, dammed by the Koochiching lobe to the northwest and the Rainy lobe to the northeast, formed glacial Lake Agassiz. Lacustrine clays from 1 to 10 m thick (G.N. Meyers, oral commun., 1990), were deposited from the Beltrami arm of Glacial Lake Agassiz over much of the quadrangle (Wright, 1972; Martin and others, 1989; Horton and others, 1989).

The lake level of glacial Lake Agassiz dropped in stages, creating numerous shoreline and beach deposits, as successively lower outlets were created by melting ice and erosion by lake water discharge. As the water level receded, waves eroded large areas of the lake plain down to bedrock, leaving isolated pockets of sediment and till. Peat bogs formed in shallow, undrained depressions and over large flat-lying parts of the lake plain which, had insufficient grade to drain precipitation.

Glacial overburden ranges in thickness from less than 1 m to as much as 60 m. In the northeast part of the quadrangle, dominated by bedrock outcrops, overburden consists of a thin, discontinuous veneer of till. However, it is not uncommon to find 30 m or more of sediment filling narrow valleys between bedrock exposures. The overburden is thinnest in the northeast part of the quadrangle and becomes thicker to the southwest (Horton and others, 1989). This distribution is attributed to the regional northeast-to-southwest slope of the bedrock surface, which exposed the higher northeast part to more erosion and less deposition.

GEOPHYSICAL SUMMARY

As part of the mineral resource assessment of the International Falls quadrangle, geophysical data was compiled by the U.S. Geological Survey to produce magnetic (Bracken and Godson, 1987) and gravity (Chandler and Horton, 1988) maps. Most of the bedrock in the Minnesota part of the quadrangle is covered by Quaternary glacial deposits, swamps and lakes. Information from available drill holes (Klein, 1988; Klein, 1991; and Klein and Day, 1989) and sparse outcrop data were inadequate for regional-scale geologic mapping and mineral resource assessment. Therefore, the geophysical data provided a critical element in the interpretation of the bedrock geology and mineral resource assessment of the quadrangle.

Magnetic and gravity surveys are commonly used to evaluate large tracts of land to identify favorable areas for the occurrence of mineral deposits. Magnetic anomaly maps reflect the spatial distribution of magnetic minerals present, whereas gravity anomaly maps reflect variations in the densities of surface and subsurface lithologic units. Geophysical surveys provide information about subsurface structure and lithology, and may be used to locate potential mineral deposits that have physical properties significantly different than those of the host rock.

AEROMAGNETIC STUDIES

The aeromagnetic map of the International Falls quadrangle (fig. 4) was produced by compiling data from three different areomagnetic surveys (Bracken and Godson, 1987). Data for the Ontario part of the study area, approximately the northern half of the quadrangle, was obtained from the Geological Survey of Canada. The Ontario survey was flown in 1961 along north-south flightlines, spaced about 680 m apart at an altitude of 305 m. Data for the Minnesota part of the study area, approximately the southern half of the quadrangle, was obtained from the Minnesota Geological Survey (MGS) and the U.S. Geological Survey. The southeastern part of the quadrangle was flown in 1979 and 1980 for the MGS along north-south flightlines spaced 400 m apart at an altitude of 150 m (Chandler, 1983). The southwestern part of the quadrangle was flown in 1984 and 1985 by the U.S. Geological Survey along north-south flightlines spaced 380 m apart at an altitude of about 90 m (Bracken, 1991; and Bracken and Petrafeso, 1991).

Due to the different survey altitudes, data reduction techniques, and variations in geomagnetic reference fields, gridded data from the individual surveys were leveled for merging purposes to produce the best fit across survey boundaries (Bhattacharyya and others, 1979). The merged grid has a 0.25 km spacing interval. A shaded relief aeromagnetic map (fig. 4) was generated using an unpublished U.S.Geological Survey computer program (R. J. Horton, unpub. program).

It is important to note that the wavelengths of observed magnetic anomalies are proportional to the distance between the magnetic measurement and the magnetic source. Anomaly wavelength increases as the distance from the source increases. Therefore, aeromagnetic data collected at 300 m will have broader, longer wavelength anomalies than data collected over similar geology at 90 m.

Variations in the observed magnetic field are produced by magnetic minerals, primarily magnetite and ilmenite, present in the different rock types. The anomalies observed on the aeromagnetic map reflect variations in the content and distribution of magnetic minerals, and the size, shape and depth of the magnetic source rocks. At this latitude, approximately 48° N., normally polarized magnetic bodies produce dipole (paired negative-positive) anomalies with the negative pole of the anomaly on the north side of the body.

Within the mapped area, most of the magnetic anomalies are produced by normally polarized magnetic bodies. However, a few negatively polarized magnetic units are present, most notably a few mafic dikes, that produce reversed anomalies with the negative magnetic response on the south side of the body. These negatively polarized dikes were emplaced during a period when the Earth's magnetic field was reversed from the present polarity.

The magnetic properties of rock units in the mapped area varies widely with rock type. Physical properties, including magnetic susceptibility and density, were measured for numerous rocks samples collected within and adjacent to the mapped area (J.E. Case, unpub. data). Locally, iron-formation has the highest concentration of magnetic minerals resulting in extremely high (>10,000 cgs units) magnetic susceptibilities. Iron-formation produces positive, very high-amplitude magnetic anomalies (>20,000 nanoTesla). Metamorphosed mafic and ultramafic rock units have the next highest magnetic mineral content with resulting magnetic susceptibilities as high as about 3000 cgs units. The mafic and ultramafic units generally produce positive, high-amplitude anomalies greater than 1000 nanoTesla.

In general, granitic plutons and migmatite terranes have relatively low magnetic mineral compositions, compared to iron-formations, mafic and ultramafic rocks. Within the mapped area, granitic bodies usually produce positive, low-amplitude magnetic responses. Migmatite terranes have variable magnetic properties depending on the percentage and composition of paleosomatic inclusions. Amphibolite migmatite phases with magnetite-rich paleosomatic inclusions can produce positive, intermediate-amplitude magnetic responses. Granite-rich migmatite phases generally have low amplitude magnetic expressions.

Felsic to intermediate metavolcanic rocks generally have a low magnetic mineral content and commonly produce low-amplitude magnetic anomalies. However, some felsic metavolcanic rock types, such as rhyolite, can have a relatively high magnetite content and may produce moderate, positive magnetic features. Schistose and metasedimentary rock units generally have low magnetic mineral contents, and therefore produce low-amplitude magnetic features or have no magnetic expression at all.

GRAVITY STUDIES

The International Falls complete Bouguer gravity anomaly map (fig. 5) was compiled from data obtained from the Minnesota Geologic Survey, the Geological Survey of Canada, the U.S. Department of Defense, and the U.S. Geological Survey (Horton and Kucks, 1988). The complete Bouguer anomaly was calculated using a reduction density of 2.67 g/cm^3, the 1967 gravity formula (International Association of Geodesy, 1967) and observed gravity values relative to the IGSN-71 datum (Morelli, 1974). Terrain corrections were made using the method of Plouff (1977) in conjunction with U.S. Department of Defense digital terrain data.

For the purposes of computer contouring, a data grid with a 1 km interval was generated from the irregularly distributed field data using a computer program (Webring, 1981) based on a minimum curvature algorithm (Briggs, 1974). The gridded data set was used to produce the gravity anomaly map (fig. 5) using a computer program by Godson and Webring (1982).

Variations in the observed gravity field are produced by density contrasts within the underlying rock units. Sedimentary rocks have relatively low densities, controlled primarily by their porosity and degree of compaction. Igneous rocks are generally more dense than sedimentary rocks. Igneous rocks with mafic compositions usually have higher densities than those with felsic compositions. Metamorphic rocks generally have higher densities than their protoliths due to pore-filling and recrystallization. The density of metamorphic rocks usually increases with metamorphic grade.

Gravity anomalies reflect the size, shape, and depth of the source rocks. However, it is important to note that the shape of a mapped gravity anomaly is a function not only of the density and shape of the geologic source, but also the relative spacing of the gravity observations. Therefore, where gravity stations are poorly distributed the shape of the anomalies may not accurately represent the underlying geology.

Densities of rock units in the mapped area vary widely. Mafic and ultramafic rocks have the highest densities ranging from 2.82 to 3.30 g/cm^3. Iron-formations also have relatively high densities, averaging about 3.00 g/cm^3. These dense rock types produce positive, high-amplitude gravity anomalies. The dikes, composed of gabbro, diorite, and diabase, have an average density of 3.01 g/cm^3. These dense intrusive units can significantly increase the bulk density of the host rock terrane. Gravity observations made on or near dikes may result in relatively high readings due to the dikes high density composition.

Felsic to intermediate metavolcanic rocks and schistose rocks have moderate densities averaging about 2.75 g/cm^3. These rock units produce positive moderate-amplitude gravity anomalies. Migmatites have variable densities ranging from 2.57 to 2.89 g/cm^3. The density of the migmatites are thought to be dependent on the percentage and composition of the paleosomatic inclusions, resulting in the amphibolite-rich phases being considerably denser than granitic-rich phases.

Metasedimentary rocks generally have low densities and produce broad areas with a low-amplitude gravity response. Granitic rocks are the lowest density bedrock units located within the quadrangle. Density measurements indicate these rocks range from 2.57 to 2.90 g/cm^3. Granitic bodies generally produce broad, low-amplitude gravity anomalies.

GEOPHYSICAL DESCRIPTION

The International Falls quadrangle can be divided into three distinct geophysical terrains that correspond to the geologic subprovinces. The Wabigoon subprovince,

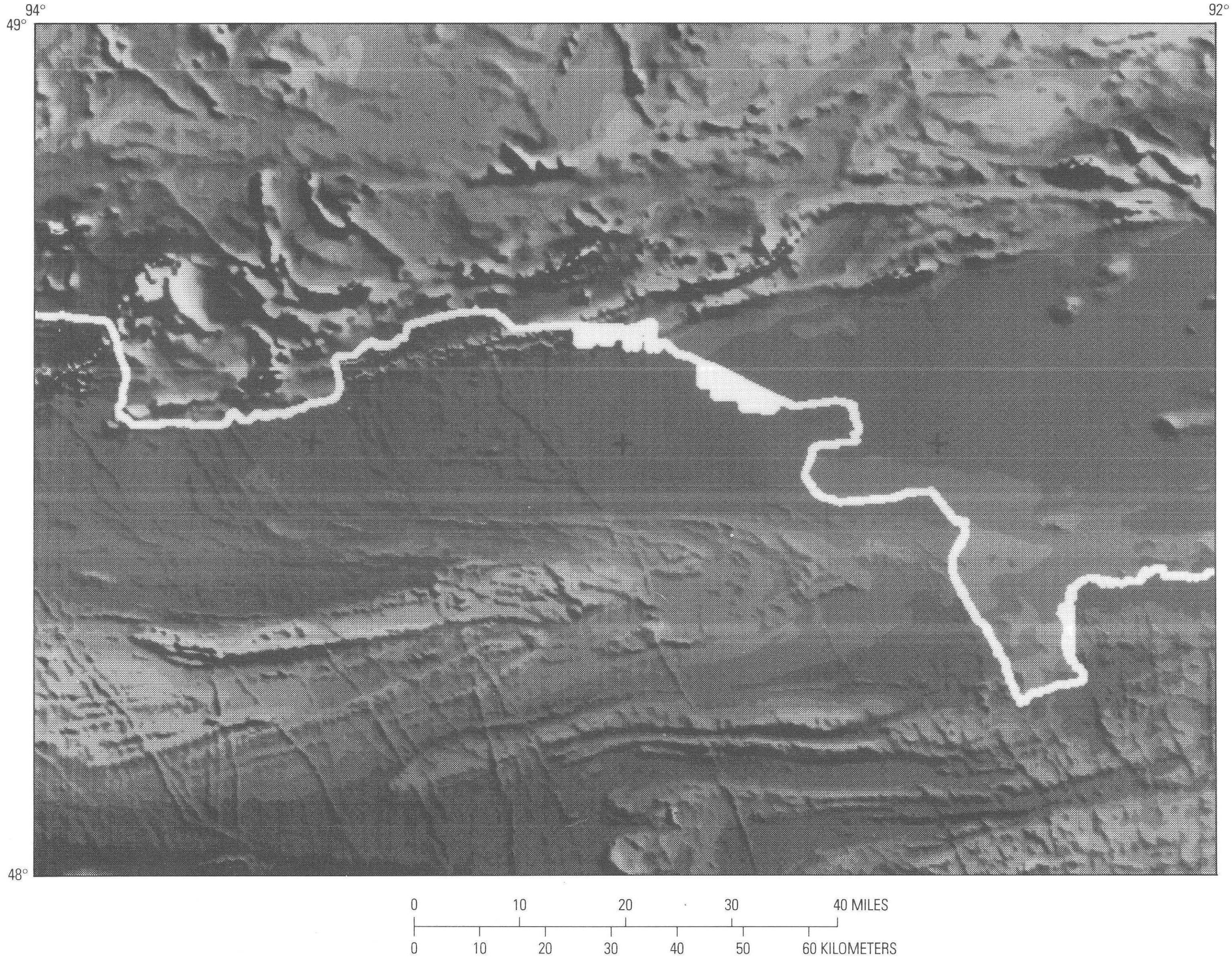


Figure 4. Shaded relief aeromagnetic map of the International Falls 1°×2° quadrangle. The light areas indicate magnetic field highs, whereas the dark areas represent magnetic field lows. The apparent relief is computer generated. Illumination direction is from the northeast. White area indicates the Canada-United States border and (or) other areas of no data.

located north of the Rainy Lake-Seine River fault zone across the northern part of the quadrangle (fig. 3), is characterized by high-amplitude anomalies over greenstone belts and relatively low-amplitude anomalies over metasedimentary and granitoid rocks. The Quetico subprovince, located between the Vermilion and Rainy Lake-Seine River fault zones in the central and southeastern parts of the quadrangle (fig. 3), is characterized by relatively low density and nonmagnetic to moderately magnetic metasedimentary, granitoid, and, locally, migmatitic rocks. The Wawa-Shebandowan subprovince, located south of the Vermilion fault in the southwestern corner of the quadrangle (fig. 3), is characterized by metavolcanic rocks that produce relatively high-amplitude anomalies.

WABIGOON SUBPROVINCE

The Wabigoon subprovince (fig. 3), composed of granitoid plutons and greenstone belts, has a wide range of geophysical characteristics. The granitic rocks generally produce broad, low-amplitude magnetic and gravity anomalies. The Wabigoon greenstone belts produce relatively long, narrow high-amplitude magnetic and gravity anomalies. Mafic and ultramafic bodies produce irregular-shaped high- to moderate-amplitude geophysical anomalies.

Granitic bodies in the Wabigoon subprovince range in size from small plutons, a few kilometers in diameter, to immense batholithic complexes encompassing several hundred square kilometers. These granitic bodies have relatively low magnetic mineral content and generally have low densities. This results in broad, low-amplitude magnetic and gravity anomalies. In the north central and northeast parts of the quadrangle two large granitic batholiths, the Rainy Lake and Irene-Eltrut Lake respectively, produce the extreme gravity lows (fig. 5).

The greenstone belts of the Wabigoon subprovince are characterized by short wavelength, high-amplitude geophysical anomalies. Within the greenstone belts, narrow and extremely high-amplitude magnetic anomalies are produced by iron-formations. Greenstone belt rocks of relatively high density produce the associated positive, moderately high-amplitude gravity anomalies. Across the southern edge of the Wabigoon a wedge-shaped feature, characterized by east-northeast striking, positive magnetic anomalies (fig. 4) and associated gravity highs (fig. 5), is produced by a greenstone terrain bound between the Rainy Lake-Seine River and Quetico faults (fig. 3). In general, the amplitude of the magnetic and gravity anomalies decrease from west to east as the composition of the greenstone rocks change from dense mafic and intermediate metavolcanic rocks in the west to monzonite, metasedimentary, and felsic metavolcanic units in the east-central portion of the quadrangle. The eastern portion of this greenstone wedge is composed of quartzite and felsic metavolcanic rocks where it pinches out between the Rainy Lake-Seine River and Quetico faults.

QUETICO SUBPROVINCE

Metasedimentary and migmatitic rocks of the Quetico subprovince (fig. 3) have a low density, are relatively nonmagnetic, and produce a broad gradient, low-amplitude magnetic and gravity expression across the southern part of the quadrangle. The Vermilion Granitic Complex is the dominate feature in this subprovince. The extreme gravity low in the southeast corner of the quadrangle (fig. 5) is produced by the Lac La Croix Granite, which generally contains less than 5 percent inclusions and appears to be the core of the granitic complex. The Lac La Croix Granite grades westward into granite-rich migmatite, which becomes more magnetic and slightly denser due to 5-25 percent paleosomatic inclusions. The magnetic mineral content and density of the complex continues to increase westward as the granite-rich migmatite grades to schist-rich migmatite with as much as 75 percent biotite schist inclusions. In the center of the complex, moderate-amplitude magnetic anomalies indicate fold hinges of a large antiform structure in the migmatite terrane (fig. 4). The western part of the complex, composed primarily of schist-rich migmatite, has a relatively high gravity response. Here, dense amphibolite migmatite phases contained in the schist-rich migmatite, contributes to the high bulk density and resulting high gravity response.

The contact between the Vermilion Granitic Complex and the metasedimentary units to the north is gradational. In the east, the contact between the Lac La Croix Granite and metasedimentary rocks forms the broad gravity and magnetic gradients seen across the east central part of the quadrangle (figs. 4, 5). In the western portion of the quadrangle, the contact between the dense schist-rich migmatite and the metasediments to the north produces much steeper gradients than seen in the east.

WAWA-SHEBANDOWAN SUBPROVINCE

Rocks of the Wawa-Shebandowan subprovince (fig. 3) are located in the southwest corner of the International Falls quadrangle. Within the quadrangle, the Wawa rocks are composed primarily of metavolcanic rocks. These metavolcanic rocks produce the relatively high-amplitude magnetic anomalies seen in the extreme southwest corner of the quadrangle (fig. 4). The relatively high density of the Wawa metavolcanic rocks also produces the positive gravity response in the southwest corner of the quadrangle (fig. 5).

STRUCTURAL FEATURES

Several prominent structural features are apparent in the geophysical data. The Quetico fault (fig. 3) can be seen in the aeromagnetic data (fig. 4), striking east-west through the Wabigoon subprovince rocks across the northern part of the quadrangle. The Rainy Lake-Seine River fault (fig. 3)

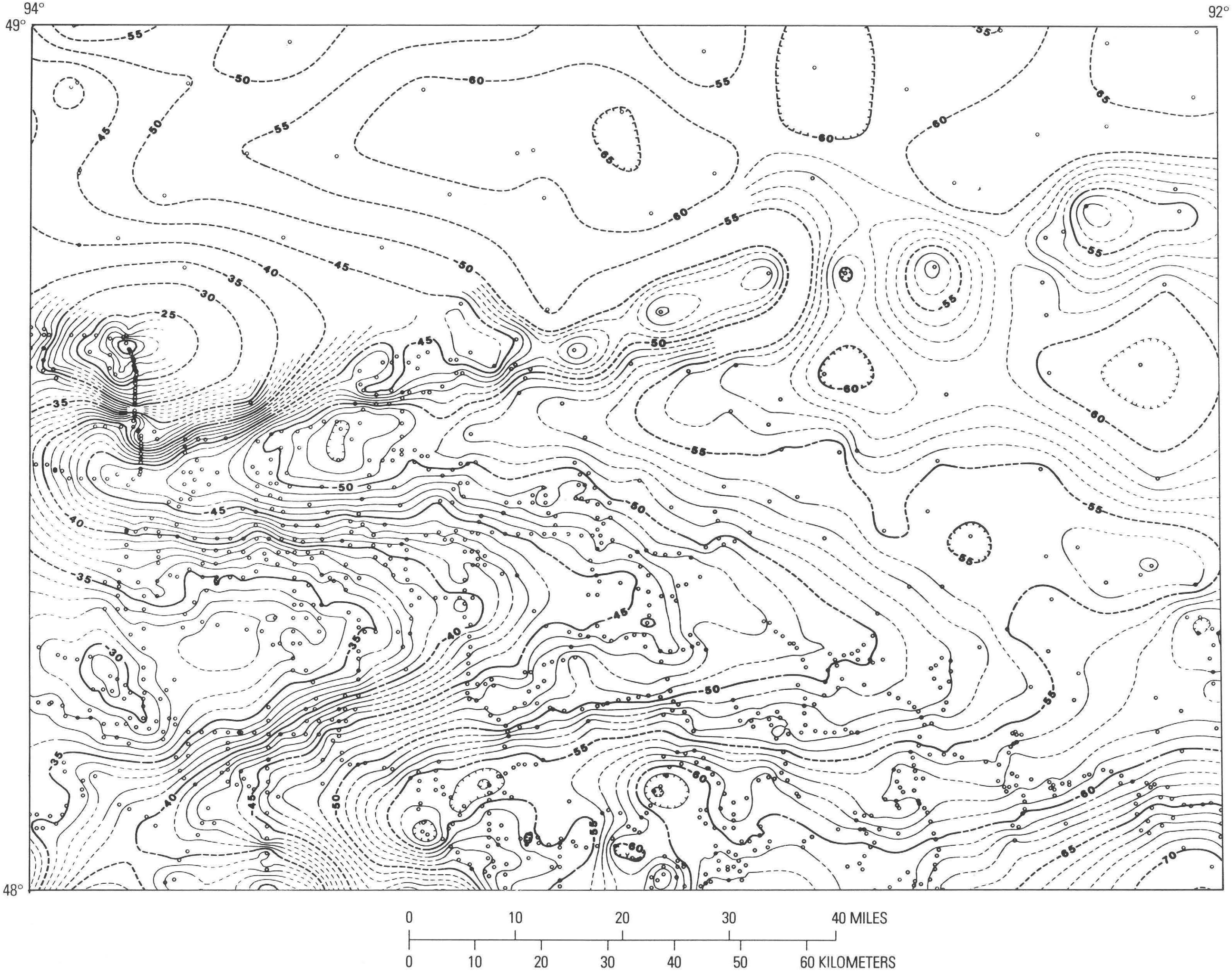


Figure 5. Complete Bouguer gravity anomaly map of the International Falls 1°× 2° quadrangle. The contour interval is 1 and 5 milligals. Contours are hachured when enclosing a gravity low. Gravity stations are indicated by small dots. Contours 5 km or more from a gravity station are dashed.

separates the Wabigoon from the Quetico subprovince rocks, and can be seen striking east-northeast across the northern third of the aeromagnetic map (fig. 4). The Rainy Lake-Seine River fault is also apparent in the gravity data (fig. 5), expressed as a steep, east-northeast-trending gradient seen in the western part of the quadrangle.

Less apparent is the Vermilion fault (fig. 3), striking west-northwest across the southwest corner of the quadrangle. The Vermilion fault separates the relatively low density, non-magnetic Quetico subprovince rocks from the high density, magnetic rocks of the Wawa subprovince (figs. 4, 5).

Several fold structures are also observed in the geophysical data. In the south-central part of the quadrangle, a large fold is apparent in the aeromagnetic data (fig. 4). Located within the Vermilion Granitic Complex of the Quetico subprovince, this large, open-fold antiform plunges gently to the east.

Fold structures are also observed in the Wabigoon subprovince, located in the greenstone wedge bound between the Rainy Lake-Seine River and Quetico faults. Wrench faulting has produced s-shaped drag folds in the steeply dipping greenstone units. S-shaped magnetic anomalies are produced by folded, mafic to intermediate metavolcanic units (fig. 4).

Early Proterozoic mafic dikes, composed of gabbro, diorite, and diabase, cut across major structural features in all three subprovince terranes, producing narrow, northwest-tending linear magnetic anomalies (fig. 4). These dikes are commonly tens of kilometers long and range in thickness from less than 1 to 30 m. Due to their relatively long length, an individual dike may cut a number of different terrains having different compositions. The amplitude of the linear, dike-related, magnetic anomalies appears to vary considerably along strike. This amplitude variation may result from several different factors including variable width and composition of the dike, variable alteration of the dike and surrounding host rock, and variable magnetic properties of the different host rocks along strike.

INTERPRETATION OF THE SOIL GEOCHEMISTRY

The complexity of the Quaternary overburden, which was summarized previously, makes it difficult to adequately evaluate the mineral potential of the bedrock in the International Falls quadrangle. The overburden at a given location may consist of two sheets of basal (lodgement) till, multiple layers of outwash, lake sediments, and perhaps Holocene flood-plain alluvium and peat bogs.

Hummocky terrain, numerous lakes and streams, and relatively shallow bedrock characterize the eastern half of the International Falls quadrangle. The western half is part of a largely featureless, poorly dissected lake bed formed by glacial Lake Agassiz (Eng, 1980). Natural drainage is poorly developed (Wright, 1972), and the water table is shallow throughout most of the study area.

To assess the mineral resource potential in the International Falls quadrangle, it was necessary to develop a method for conducting regional-scale geochemical surveys in areas where bedrock is buried beneath complex glacially derived overburden. Where mechanical dispersion trains of mineralized bedrock in basal tills are smeared down-ice, soils that developed on moraines commonly can be used as sample media for mineral exploration (Alminas, 1984; Miller, 1984). However, an overlying variable sequence of outwash and lake sediments, similar to that in the study area, will mask both the underlying bedrock and basal till from most conventional methods of geochemical exploration. Overburden drilling has been used in this area to collect geochemical samples from basal tills as part of a pilot program by the Minnesota Department of Natural Resources (Martin and others, 1988, 1989) to determine their suitability as a sampling media in this area and to better define the glacial history of the area. These studies assessed the suitability of basal till as a sampling media and better defined the glacial history of the area. This method is somewhat successful in detecting anomalies that may be related to metallic mineralization but was not possible within the fiscal constraints of this assessment.

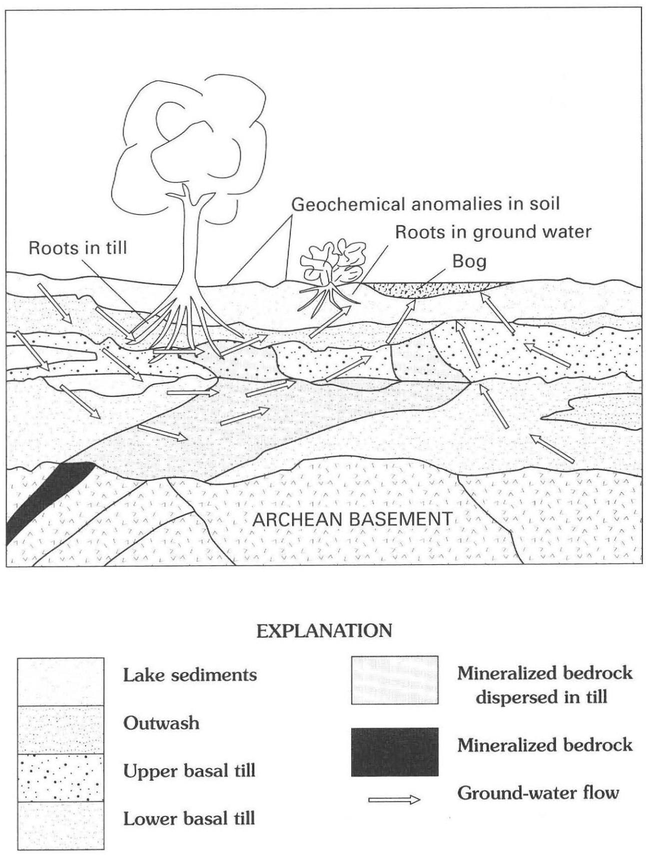


Figure 6. Diagram showing probable relationships between till, ground-water flow, and vegetation, that can form geochemical anomalies in B horizon soils. Modified from Clark and others (1990).

Secondary dispersion of metals from anomalous till trains or bedrock can produce anomalies at or near the surface, where geochemical traps or barriers often occur. Ground-water flow is probably the most important process for dispersing metals. Ground-water transport has a significant component of vertical flow (Clark and others, 1990) and, consequently, provides a pathway of communication between the bedrock and surficial deposits. The result is a hydromorphic component in the overlying soils that may reflect the geochemistry of the buried bedrock. Although the silty clays of the ubiquitous glaciolacustrine sediments have relatively low permeabilities, they are not impermeable to flowing ground water and, thus, allow hydrologic communication between bedrock and surficial materials. Metals that are transported to the surface by ground water are entrained into a complex cycle between the soil, plants, and ground water during soil formation to produce surficial geochemical anomalies (fig. 6). B horizon soils can serve as long-term integrators for vegetation anomalies where the metals are trapped in manganese- and iron-oxide coatings on mineral grains (Clark and others, 1990).

Selectively leached elements from B horizon soils can be used to detect subtle patterns of hydromorphic trace element dispersion by enhancing the contrast between background and anomalous samples (Chao, 1984). An enzyme-based leach was developed for this study, that selectively removes metals from oxide coatings on soil materials without attacking the soil matrix (Clark and others, 1990).

METHODS

SAMPLING

During the early stages of the project, orientation studies were conducted to find an effective sample medium and a suitable analytical method. Lake sediments, till, plants, soil gases, and soils were all considered as possible media. Plants, soil gases, and soils were collected throughout the area and analyzed during the pilot phase of the project. Plants and soil gases were found to be effective sample media, but budgetary constraints of a regional-scale mineral assessment project prohibited their use. Results from early partial analyses for both A horizon and B horizon soil samples were encouraging. Subsequently, B horizon samples were found to produce more predictable results than A horizon samples and were chosen as the primary sample medium.

Samples were collected at approximate 1.6 km intervals or at sites where B horizon soils were available along accessible roads in most of the International Falls quadrangle. Swamps in many areas precluded access, so that sample coverage is not uniform throughout the study area. Samples were collected at approximately 750 sites in the U.S. portion of the International Falls 1°×2° and the adjacent Roseau 1°×2° quadrangles. At each site the soil profile was exposed, and the sample was collected from the upper 0.3 m (1 ft) of the first soil horizon that contained visible oxides of ferric iron. Samples were sieved for the -0.25-mm fraction (-60-mesh fraction, fine sand and smaller) before analysis.

ANALYTICAL CHEMISTRY

Three different leaches were used for soils at each location. Each successive leach accomplished progressively stronger dissolution of the surface coatings on the mineral grains in the samples. The concentrations of elements released in the first leach were those that are merely water soluble. The second leach released metals that were bound by more reactive manganese-oxide phases on the constituent mineral grains. The third leach removed metals that were buried slightly deeper in oxide coatings.

For the first leach (the "water" leach), 1 g of sieved sample material was washed with 15-mL of 16 MW/cm of water for 1 hour. In the second leach (the "enzyme" or ENZ leach), 1 g of sample was leached for 1 hour with 15-mL of 1 percent (w/v) dextrose and 0.1-mL of 5 percent (w/v) glucose oxidase powder. In the third leach (the "enzyme and ascorbic acid" or ENZ+ASC leach), 1 g of sample was leached for 24 hours with 15-mL of 1 percent (w/v) dextrose and 0.1 percent ascorbic acid and 0.1-mL of 5 percent glucose oxidase powder. All stock solutions were prepared in 16 MW/cm water. After the prescribed leaching time, the samples were stirred and centrifuged, and 10 mL of the solution was removed with a pipette and set aside. These 10-mL portions of the leach solutions were immediately stabilized with 0.1-mL ultrapure nitric acid, and 0.1-mL of formaldehyde was added to prevent the growth of fungi. A spike consisting of 1 mg each of terbium and scandium was also added to serve as an internal standard for the inductively coupled plasma/mass spectrometry (ICP/MS) determinations. Determinations were made by ICP/MS for V, Cr, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Rb, Mo, Ag, Cd, In, Sn, Sb, Te, W, Tl, Pb, Bi, and U. Inductively coupled plasma/atomic emission spectrometry (ICP/AES) was used to determine Al, Ca, Fe, Mg, K, Mn, Na, Ba, La, P, Sr, Ti, and Y. Detailed descriptions of these analytical procedures are in preparation by J.R. Clark. The data from these analyses are given by Riddle and others (1992).

STATISTICAL EVALUATION

Probability plots of each of the 108 geochemical variables were studied to determine the breaks between populations, using the procedures of Sinclair (1976) and the Probplot program (Stanley, 1987). Most of the elements determined in each of the three leaches did not fit either a normal or lognormal ideal distribution.

Next, each variable was power transformed, using an unpublished program written by Cole L. Smith, as set forth by Chambers and others (1983). The purpose of the

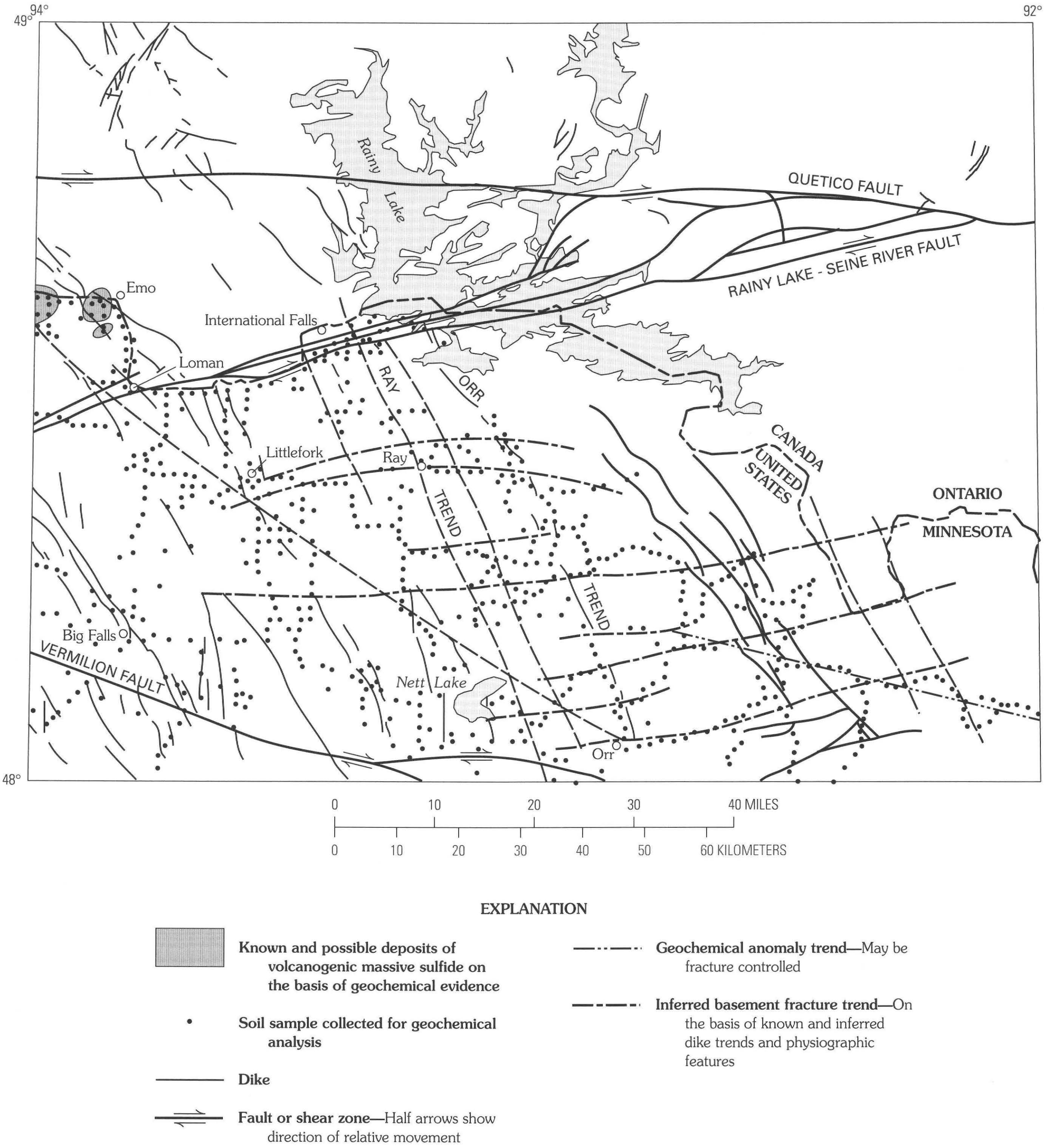


Figure 7. Known and possible deposits of volcanogenic massive sulfide deposits in the International Falls 1°×2° quadrangle on the basis of geochemical evidence. Faults and dikes shown are modified from Day and others (1990b).

transformation is to shift the central body of the data to approximate a normal distribution. Defining background populations for nearly all of the 108 geochemical variables was substantially facilitated when power transformed data were used, and many variables gave the most useful probability plots when the power transformed data were truncated. Truncation prevented highly skewed anomalous populations from interfering with the definition of background populations. Thresholds were chosen at two standard deviations above and below the mean of each population for each variable, and in many cases the upper one or two populations were identified as being anomalous. The most distinctly anomalous populations for most elements were found with the ENZ leach.

RESULTS AND INTERPRETATION

ARCHEAN MINERALIZATION

VOLCANOGENIC MASSIVE SULFIDE OCCURRENCES

Geochemical anomalies thought to be related to massive sulfide occurrences in the volcanic rocks of the Wabigoon subprovince are shown in figure 7.

Occurrences of volcanogenic massive sulfide produce the weakest geochemical soil anomalies of the three types of metallic mineralization that have been identified in the U.S. part of the International Falls quadrangle. Several occurrences of massive sulfide present in the Wabigoon subprovince along the United States-Canada border near the western edge of the quadrangle (fig. 7) are dominated by iron sulfide minerals and, accordingly, are of little economic interest. The low geochemical contrast of the soil anomalies associated with bedrock containing volcanogenic massive sulfide deposits may be the result of their low base metal content.

During the pilot phase of this study, closely spaced samples were collected over an exhalative sulfide occurrence approximately 3 km south of the old school at Indus, Minn. We found very weak Cu, Zn, and Sb anomalies in B horizon soil ENZ-leach together with anomalies of In, Sn, and Bi in B horizon ENZ+ASC-leach. Trace element anomalies in B horizon soils occur in a cluster of four sample sites located south, southwest, and west of, as well as, at the old Indus school. Analyses of bedrock from drill hole IND-3 which was drilled in this area, show concentrations as high as 750 ppm Zn, 345 ppm Cu, and 0.26 ppm Ag in magnetite-pyrrhotite iron-formation and cherty, pyrrhotite-rich massive sulfides (Klein, 1988; Klein and Day, 1989). These analyses indicate the apparent low-grade nature of the mineralized zone.

Another area of B horizon anomalies occurs at the west edge of the quadrangle, west of Indus, Minn. Soil anomalies in this area are interpreted as indicating metal enrichment in the underlying greenstone. Similarly, in nearby drill hole MR-86-1, several intercepts of approximately 1,600 ppm of Zn were encountered in pyrite-rich veins and massive sulfide layers (see, Klein (1989), for location; Klein (1988, pp. 38 and 77), for assay data; and Klein and Day (1989), for a lithologic summary of the drill core).

SHEAR ZONE ANOMALIES

Sample sites along the zone of shearing associated with the Rainy Lake-Seine River fault are typically anomalous in one or more chalcophile elements. Zinc and a suite of other metals that may substitute for Zn in sphalerite (Cd, Ga, Ge, and Sn) are most often found in anomalous concentrations (fig. 8). Although these metals are also anomalous in soils in other parts of the quadrangle, the area that is most consistently anomalous is along the Rainy Lake-Seine River fault. Anomalous amounts of Cu, Mo, Co, Ni, V, As, Sb, Bi, and Tl also are found at many locations along the fault zone. Analyses of bedrock samples along the fault zone were reported by Klein and others (1987) and Klein (1988).

Two types of mineralization exposed along the shore of Rainy Lake may account for the B horizon soil anomalies associated with the Rainy Lake-Seine River fault zone. A lode-gold deposit on Little America Island (pl. 1), located in the fault zone, contains bedrock enrichments in Zn and other chalcophile metals (Klein and others, 1987, samples LAMV, LAMVH) and is characterized by similar enrichments in the overlying soils. The second possibility, a massive sulfide occurrence located in a tectonic slice of the shear zone on Bushy Head Island (pl. 1), also contains bedrock enrichments in chalcophile elements (Klein and others, 1987, samples BUSHDS, BUSHHW). Because soil anomalies occur where projected Proterozoic fractures cross the fault, some of the B horizon anomalies along the fault may be the result of Proterozoic vein mineralization at the structural intersections. However, the distribution of these chalcophile element anomalies along the fault zone are expressions of either lode-gold deposits associated with shear zones or massive sulfide occurrences. The area where soil geochemistry may reflect mineralization along the Rainy Lake-Seine River fault is shown in figure 8.

A broad geochemical trend found in the area around and east of Ray, Minn. (fig. 3) may reflect an east-west trending Archean shear zone in the Quetico subprovince (fig. 8). This structure could extend as far west as the area around Littlefork, Minn., and could explain some of the B horizon

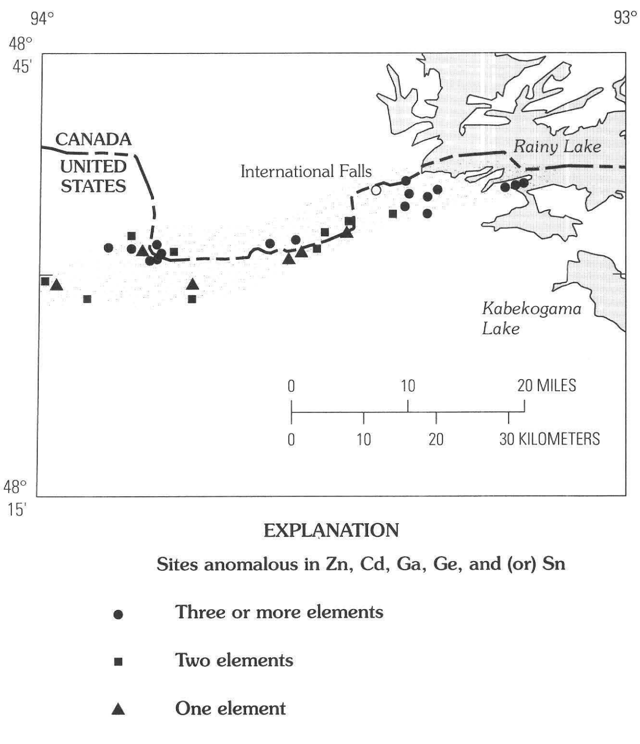
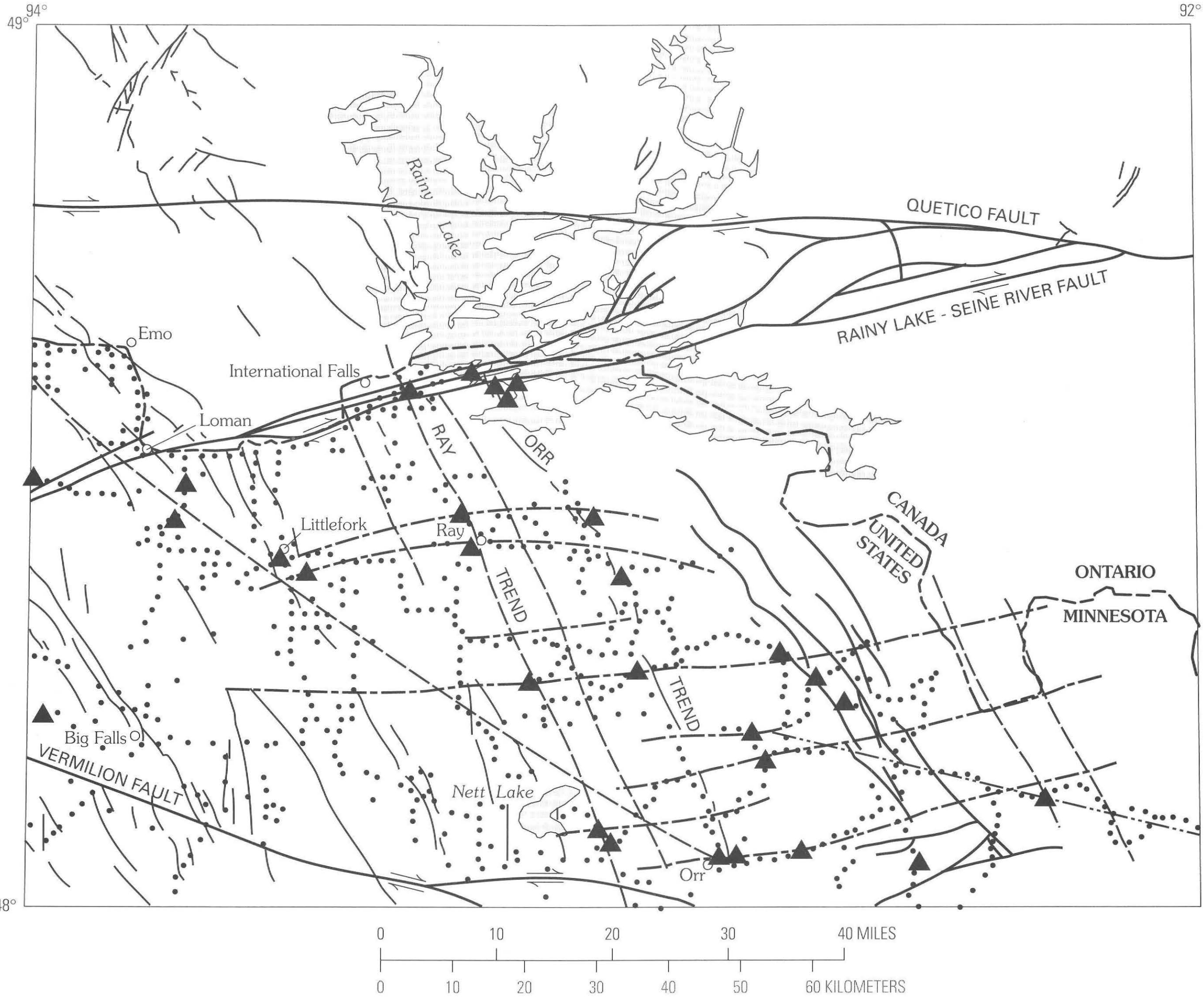


Figure 8. Selected B-horizon soil anomalies along the Rainy Lake-Seine River fault in area of geochemical anomalies apparently influenced by the Rainy Lake-Seine River fault (stippled). Modified from Clark and others (1990).



EXPLANATION

- Cobalt content ≥ 61 parts per billion
- Soil sample collected for geochemical analysis
- Dike
- Fault or shear zone—Half arrows show direction of relative movement
- Geochemical anomaly trend—May be fracture controlled
- Inferred basement fracture trend—On the basis of known and inferred dike trends and physiographic features

Figure 9. B-horizon soil samples with largest Co anomalies as determined by enzyme leach from the International Falls 1°×2° quadrangle. Faults and dikes shown are modified from Day and others (1990b).

anomalies and an isolated occurrence of native gold in basal till reported by Martin and others (1989).

PROTEROZOIC MINERALIZATION

Evidence for possible Proterozoic vein systems in the International Falls 1°×2° quadrangle was first recognized when spatial plots of Co, Tl, and Ag anomalies found with the ENZ leach showed linear anomaly trends where the bedrock was obscured by overburden. Logarithmic probability plots that were done prior to power transformation of the geochemical data revealed an alignment of sites enriched in ENZ leach Co was found (figs. 9, 10). One trend (Orr trend) strikes approximately N. 30° W. from Orr, Minn. to Island View, about 16 km east of International Falls. It appears to follow a set of diabase dikes in the basement that were located on the basis

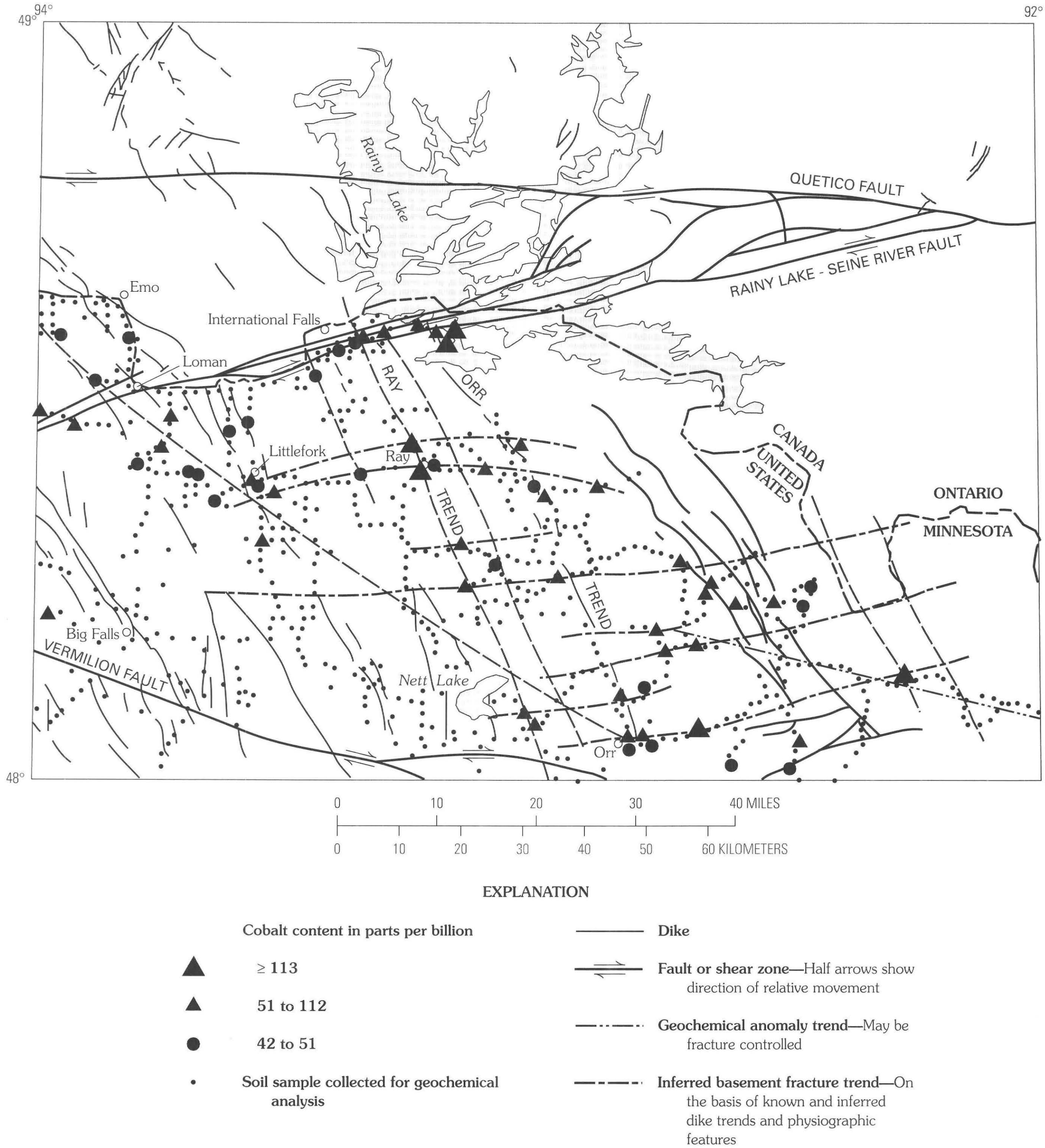


Figure 10. All B-horizon soil samples with anomalous Co concentrations as determined by enzyme leach from the International Falls 1°×2° quadrangle. Faults and dikes shown are modified from Day and others (1990b).

of their aeromagnetic signature (Day and others, 1990b). A second trend (Ray trend, fig. 10), parallel to the first, passes from just east of Nett Lake, northwestward through Ray, Minn. to just east of International Falls (fig. 10). Diabase dikes were not detected along that trend in the regional aeromagnetic data. However, a diabase dike with no magnetic expression is exposed on strike with this trend 10 km to the northwest in Ontario suggesting that there may be buried nonmagnetic diabase dikes along the Ray trend. The linear nature of the anomalies and their coincidence with either recognized dike trends or possible nonmagnetic dikes suggest that the geochemical anomalies are fracture controlled.

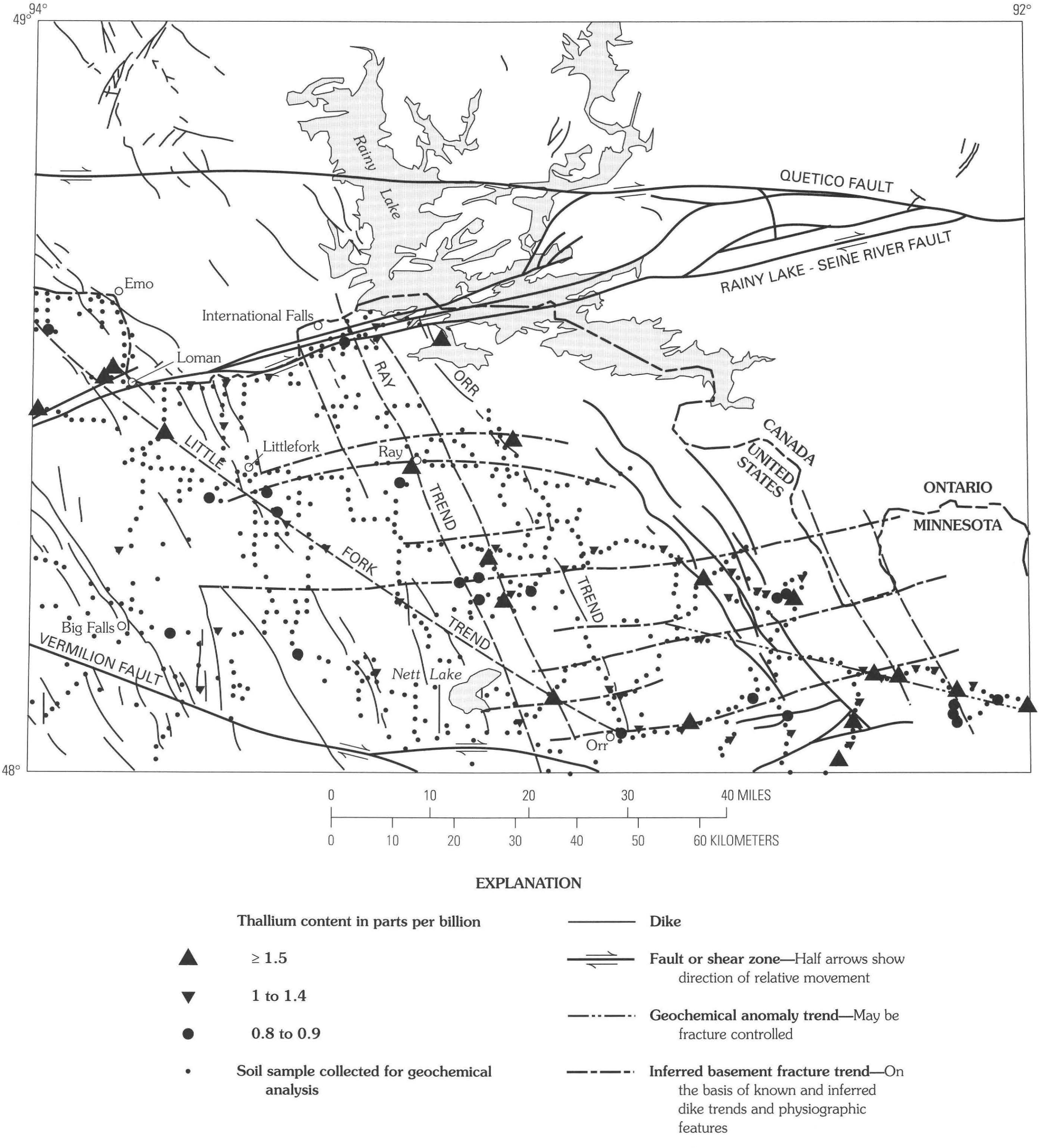


Figure 11. B-horizon soil samples showing anomalous Tl as determined by enzyme leach from the International Falls 1°× 2° quadrangle. Faults and dikes shown are modified from Day and others (1990b).

Along the Orr trend, the Co anomalies tend to be localized near the recognized terminations of dike segments. Elsewhere in the quadrangle, anomalies also tend to occur near the terminations of dikes, or they may possibly be associated with known basement faults, such as those found in the eastern part of the area (fig. 3). The anomalous Co found in the B-horizon soil samples by the ENZ leach does not appear to be derived from the diabase dikes. Population studies of the data set (Clark and others, 1990) indicate that the sample sites anomalous in Co are from a strongly anomalous population that is unrelated to any lithophile association. Furthermore, if they had resulted from a lithophile association, these Co anomalies should occur along the entire lengths of the dikes. Instead, the location of the Co

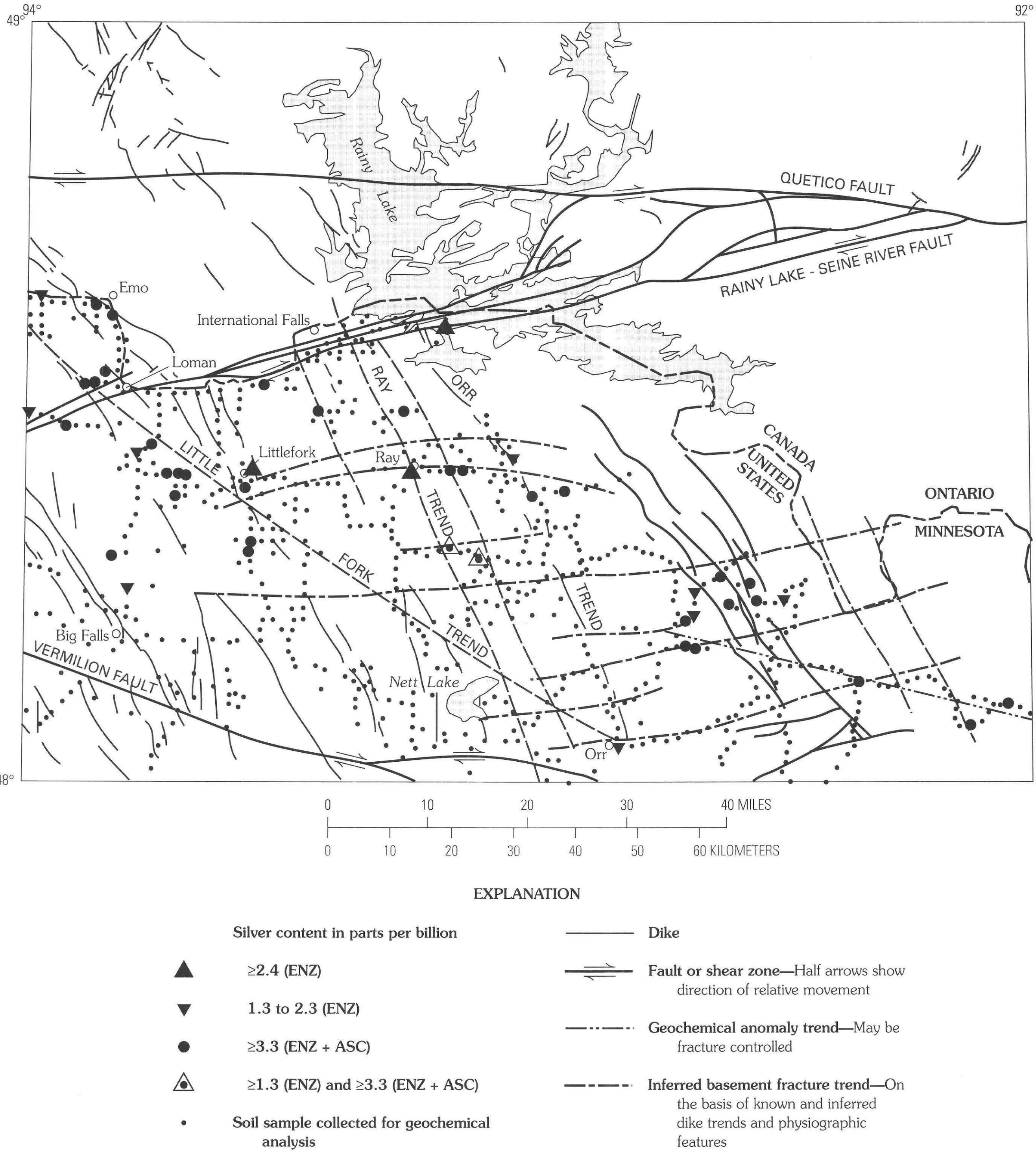


Figure 12. Ag anomalies in B-horizon soil samples as determined by enzyme leach (ENZ) and enzyme and ascorbic acid leach (ENZ+ASC) from the International Falls 1°× 2° quadrangle. Faults and dikes shown are modified from Day and others (1990b).

anomalies along the Ray and Orr trends seem to correspond to intersections of northeast-striking trends with these northwest trends (fig. 10).

A fracture system is reflected in the rectangular configuration of lakes and the Loon River at the Ontario-Minnesota border along the eastern side of the International Falls quadrangle. Diabase dikes in much of the International Falls quadrangle follow the northwest-striking fractures and commonly terminate at what may be northeast-striking structural features. These northeast-striking features are probably either the Archean foliation or structures that trend parallel to that foliation in the basement. The northwest-trending Proterozoic diabase dike swarm was intruded at about 2.1 Ga (Southwick and Day, 1983). Keweenawan rifting and

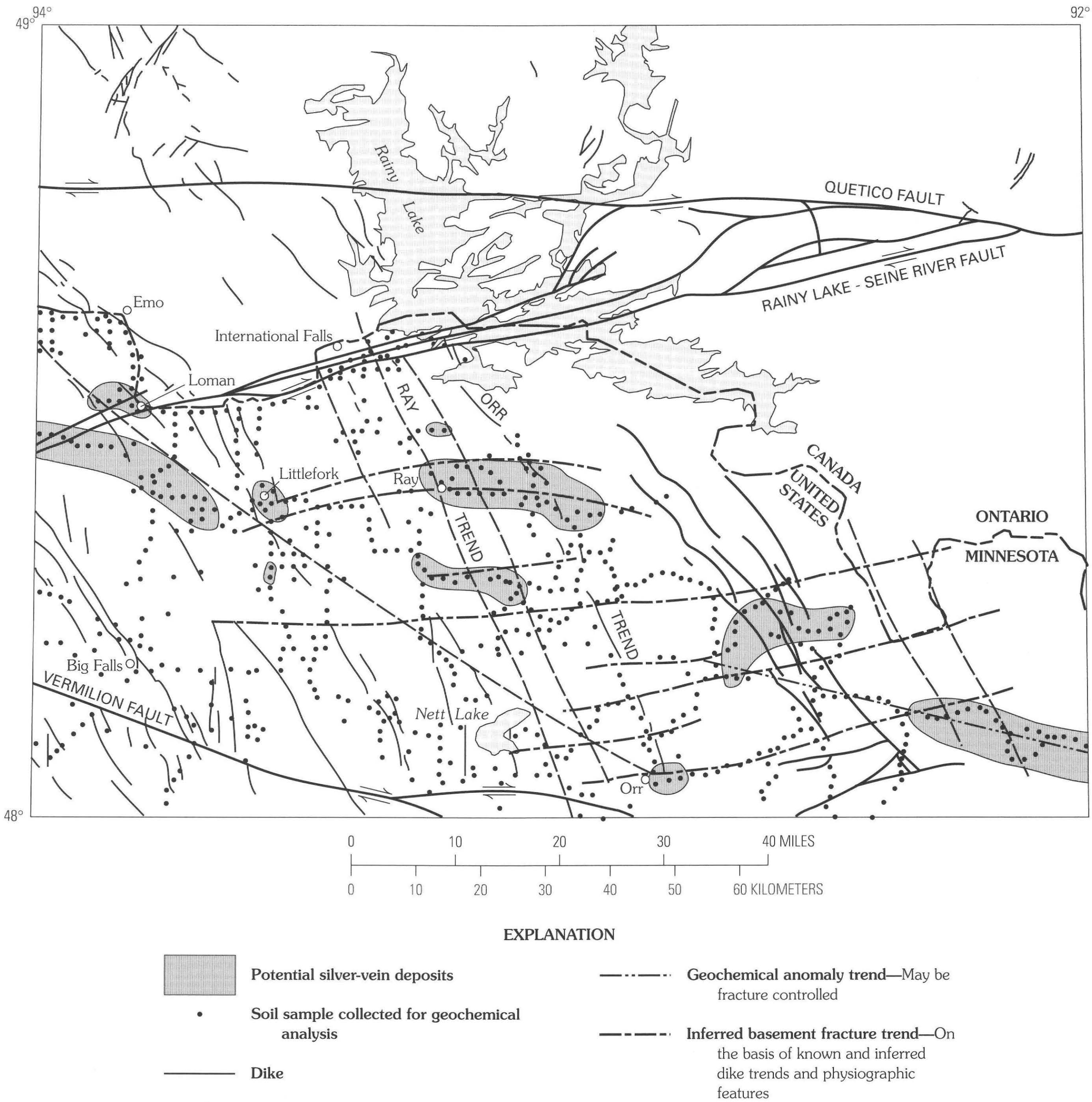


Figure 13. Areas of potential Proterozoic silver-vein deposits on the basis of soil geochemistry in the International Falls 1°×2° quadrangle. Faults and dikes shown are modified from Day and others (1990b).

igneous activity in the general region took place between about 1.2 and 1.0 Ga (Goldich and others, 1966, p. 5404). Hydrothermal activity associated with this rifting produced silver-vein deposits in the Thunder Bay, Ontario, mining camp, located 210 km east of the quadrangle. These veins were emplaced along northwest- and northeast-striking faults (Franklin and others, 1986). Similar Ag-rich veins at Cobalt, Ontario, about 800 km to the east, formed at approximately the same time as the intrusion of the Nipissing Diabase at 2.2 Ga (Andrews and others, 1986). Two mineralogical suites that characterize the deposits from both of these areas are (1) Ni, Co, Fe, and Sb in sulfarsenide minerals and native Ag and (2) Pb and Zn sulfides and Ag sulfosalts. The geochemical association of Ag, As, Bi, Co, Cu, Ni, Pb, S, Sb, and Zn can therefore be indicative of these deposits.

Similar Ag-Co-As vein system were deposited world- wide and have many different ages ranging from middle Proterozoic to Mesozoic (Boyle, 1968). All are characteristically fracture controlled and are usually found in shale-graywacke and (or) volcanic sequences. Extensional tectonics and the association of mafic intrusions have been linked to Ag-Co-As deposits in Kongsberg, Norway; Chalcanches, France; possibly the Freiberg district, Germany; Great Bear Lake, Northwest Territories, as well as the deposits at Thunder Bay, Cobalt, and Gowganda, Ontario. The soil anomalies that have been observed at apparant structural intersections in the quadrangle may have resulted from dispersion of similar vein deposit.

Co anomalies, as defined by the ENZ-leach, alignment of dike terminations, and physiographic features were used to predict the location of basement fracture trends (fig. 10). Other elements either confirm the trends predicted with Co, or they define new trends. Tl anomalies, as defined by the ENZ-leach are commonly found along known dikes, basement fractures, and Co trends (fig. 11). One such trend closely parallels the Ray trend and passes near Ranier, 5 km east of International Falls. A long Tl trend apparently extends from near Orr, N. 55° W., passing south of Littlefork and Loman, Minn. Another Tl trend passes from Littlefork, N. 35° W., into Ontario.

Many of the Ag anomalies, determined with the ENZ and ENZ+ASC leaches, correspond with mapped dikes and fractures, and projected Co and Tl trends (fig. 12). The association of Ag with mapped or predicted basement fractures suggests that the fractures may have been the locus for Ag mineralization. Shifts in locations and strikes of geochemical trends from one element to another may reflect a complex hydrothermal history, as was found at Thunder Bay (Franklin and others, 1986). The most significant cluster of soil anomalies in the International Falls quadrangle occurs in a band of sample sites that extends from just west of Ray, eastward to the Orr-anomaly trend (fig. 13). Almost every sample site in that area is enriched in at least one leachable chalcophile metal. This east-west band may represent a broad Archean shear that localized Early or Middle Proterozoic hydrothermal activity.

East of the International Falls quadrangle, the Ag veins that are observed are commonly quite small but may be rich in sulfide minerals. Because of the extremely high metal concentrations in many of these veins, a very small occurrence can dominate the geochemistry of the leachable trace elements in the overburden for possibly as much as 1.5 km down-ice. Therefore, possible Proterozoic vein occurrences may account for the largest number of soil-geochemistry anomalies and most of the high-contrast soil anomalies in the International Falls quadrangle. Small occurrences of Proterozoic vein-silver mineralization might be found along any of the detected fractures. Areas with persistent mult-element anomalies that may have potential for Proterozoic silver-vein deposits are summarized in figure 13. Logistical problems precluded sampling in larger swampy areas, but many prospects for this type of mineralization may occur in the unsampled regions.

MINERAL RESOURCES

METHODOLOGY OF THE MINERAL RESOURCE ASSESSMENT

The approach and criteria used to assess the potential for metallic mineral resources in the International Falls 1°×2° quadrangle are summarized in this section. The general approach, based on the methods summarized by Shawe (1981), is a variant of the three-step approach of mineral resource assessment.

The first step is to identify the genetic types of deposits that are found or are likely to occur within the geologic terranes present in the study area. These permissive genetic deposit types were defined by extrapolation from similar, adjacent terranes in Canada and by inference from terranes with similar geologic history and age elsewhere in the world.

Second, the geologic, geochemical, and geophysical features of the identified analogous mineral deposits were used to delineate areas or domains that may contain a particular deposit. The selection of these areas is based on recognition criteria that are established from published genetic models of mineral deposits. These criteria, which were used to delineate areas where mineralization may have taken place, allowed assessment of the mineral resource potential. The genetic models used in this study were largely based on those summarized by Ekstrand (1984), which include all of the major categories of mineral deposits found in the Superior province. In all cases during this study, published genetic models were supplemented or updated with the results of recent studies.

In the three step approach, the final step is the estimation of the number of undiscovered deposits. However, we have neither estimated the number of undiscovered deposits nor attempted to quantify the mineral resources because the amount of bedrock exposure is small in much of the U.S. part of the International Falls 1°×2° quadrangle. Also, relatively little subsurface exploration has been carried out in the glacial-drift covered areas, and the amount of metal production has been minor in this area and the immediately adjacent areas in Ontario.

Most of the mineral-deposit models used in this study were derived from examining the characteristics of mineral occurrences and deposits found elsewhere in the Superior province in rocks of similar composition, tectonic history, and age. The principal sources of information used in selecting the models were the numerous mineral occurrences and some small, formerly producing mines in the adjacent Fort Frances-Mine Centre area in Ontario where rock exposures are relatively good, as summarized by Poulsen (1984) and Beard and Garrat (1976). The metallic mineral commodities contained in the immediately adjacent areas of Canada are typical of those found elsewhere in the Canadian Shield. The principal criteria for selection were similarities in host rock lithology, alteration style, ore mineralogy, structural setting, and stratigraphic relations. The permissive mineral deposit types based on our extrapolations are summarized in table 1.

We have used the defined the term "mineral resource" that was previously adopted by the U.S. Bureau of Mines and the U.S. Geological Survey (1980). The terminology that describes the various categories of known and inferred mineral resources is summarized in figure 14. Because of the small number of mines and well-explored prospects in this area and the sparse production and reserve data, we have only attempted to assess the potential for undiscovered conventional metallic mineral resources. Although the number of permissive mineral deposit types is large (table 1) we have only considered those that are hypothetical resources, for example deposit types which are known to occur in nearby, similar geologic terrains. We also did not evaluate the mineral resource potential for industrial commodities or unconventional "low grade" resources.

The assessment, as presented here, is based on the level of knowledge as of December, 1993. Because all assessments are time and data dependent, new data and geologic concepts of ore genesis and the stratigraphic and structural framework of the area could significantly alter future mineral assessments.

Table 1. Permissive mineral deposit types identified in the International Falls 1°×2° quadrangle, Minnesota.

Syngenetic-diagenetic mineral deposits
Volcanogenic base- and precious-metal massive sulfide deposits[1]
Algoma-type iron-formations[1]
Epigenetic mineral deposits
Lode gold deposits[1]
Mo-vein deposits
Ag-, Co-, As-vein deposits[1]
Magmatic mineral deposits
Intrusion-hosted deposits
Chromite in ultramafic intrusive rocks
Gabbro-associated deposits
[1]Cu, Ni, and PGE
[1]Gabbro-hosted Ti and V
Felsic intrusive rocks
Cu and Mo porphyry deposits
Alkalic intrusive rocks
Kimberlite-hosted diamonds
Ultramafic copper, uranium
Nephelinitic carbonatite, rare earth elements, U, Nb, Ta
Volcanic rock-hosted deposits
[1]Komatiite-hosted Ni and Cu (PGE)

[1]Hypothetical resources.

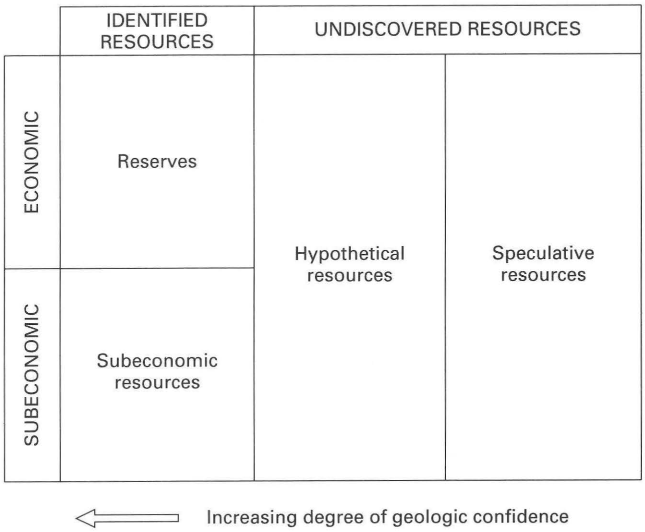


Figure 14. Simplified classification of categories of mineral resources (modified from U.S. Bureau of Mines and U.S. Geological Survey, 1980).

MINERAL DEPOSITS AND OCCURRENCES IN THE WABIGOON AND WAWA-SHEBANDOWAN SUBPROVINCES

Greenstone-dominated terranes in the Superior province are host to much of the metal production in Canada. Deposits of volcanogenic massive sulfide produce Cu and Zn and byproducts of Ag, Au, Pb and other base metals. Gold is produced principally from lode deposits found near major shear zones. Modest amounts of iron are produced presently from oxide iron-formations, although, large amounts of iron have been historically produced. Nickel is produced from ultramafic intrusions related to komatiites. Prospecting for platinum-group elements, Cu, Ni, Ti, and V has been carried out in many gabbroic intrusions; platinum-group elements are produced from one deposit.

Major deposits of volcanogenic massive sulfide in the Superior province are found in several greenstone-granite-dominated subprovinces, the Abitibi, Uchi, and Wabigoon (fig. 15). These syngenetic deposits are related to former bimodal volcanic centers. The metavolcanic rocks in the northern part of the study area are part of the Wabigoon subprovince, which in Canada contains several massive sulfide deposits (Mattabi, Sturgeon Lake, and Lyon Lake and Creek zone) near Sturgeon Lake (fig. 15). Massive sulfide deposits are generally found within rhyolitic pyroclastic rocks deposited in a shallow-water (<500 m) marine environment which generally overlie a thick sequence of mafic metavolcanic rocks (Morton and Franklin, 1987; Franklin, 1990). These bimodal volcanic sequences generally resemble those in modern island arcs. In the Manitowage area, the Geco mine, which contains approximately 70 million metric tons of ore, lies within a small amphibolite-grade greenstone segment of the Wawa-Shebandowan subprovince (Franklin and others, 1981; Williams and others, 1990) (fig. 15). The deposit is immediately overlain by metasedimentary rocks containing oxide and sulfide-rich iron-formation, which, in turn, are overlain by mafic metavolcanic rocks. Footwall rocks, even though strongly recrystallized during regional metamorphism, show Mg and Fe enrichment and Na-Ca-K depletion typical of most Archean massive sulfide deposits (Friesen and others, 1982). The Winston Lake deposit, near Schreiber, is similar to the Geco deposit in terms of the character of the hydrothermal alteration and strong amphibolite-grade metamorphic overprint (fig. 15). This deposit is contained in calc-alkaline felsic volcaniclastic and flow rocks and is overlain by a mixed mafic and felsic fine-grained tuff. About 40 percent of the upper surface area of the ore body is in intrusive contact with a thickly layered gabbro sill (Severin and others, 1990). A summary of production and reserves from massive sulfide deposits in the Wabigoon and Wawa-Shebandowan subprovinces is shown in table 2.

Most of the gold deposits in the Superior province (fig. 15) are immediately adjacent to major, generally east-trending, transcurrent fault zones or in high-strain zones adjacent to large felsic intrusives in greenstone-granite terranes. Most current models favor an epigenetic origin for Archean gold deposits (Colvine and others, 1988; Groves and others, 1989).

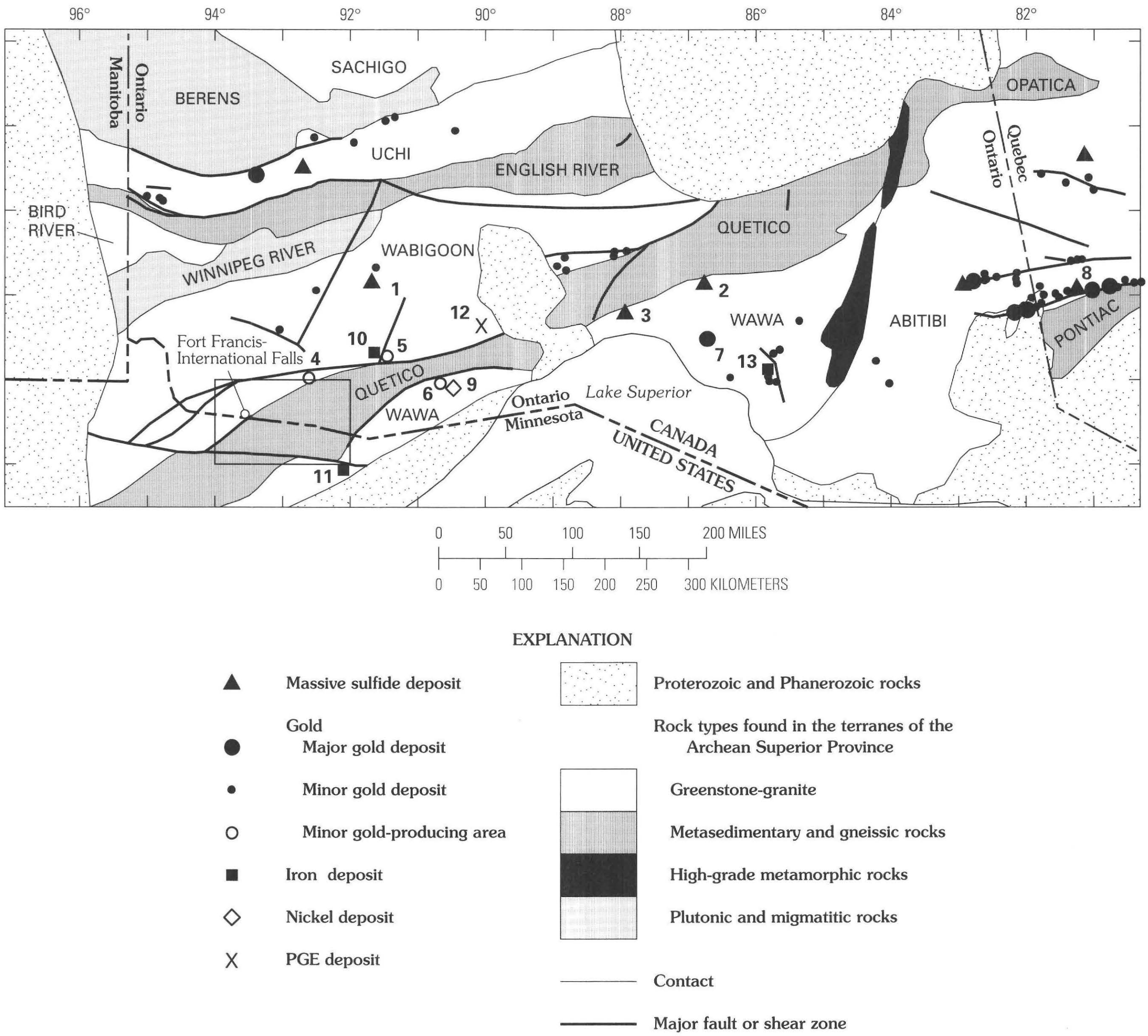


Figure 15. Sketch map showing distribution of volcanogenic massive sulfide, gold, iron, nickel, and the platinum-group element deposits in the Archean Superior province. Subprovinces, terranes, and faults (fig. 3) adapted from Card and others (1987). Deposits referred to in text by type. Massive sulfide deposits: 1, Sturgeon Lake area (Mattabi, Sturgeon Lake, and Lyon Lake and Creek; 2, Geco mine; 3, Winston Lake. Gold deposits: 4, Mine Centre; 5, Atikoken; 6, Shebandowan; 7, Hemlo; 8, Bosquet. Nickel deposit: 9, Shebandowan mine. Iron deposits: 10, Steep Rock mine; 11, Vermilion district. Platinum-group element (PGE) deposit: 12, Lac des Illes. International Falls 1°×2° quadrangle shown by box.

Table 2. Production from the principal volcanogenic massive sulfide deposits in the Wabigoon and the Wawa-Shebandowan subprovinces, Canada.

[Only reserves as of 1987 are reported from the Winston Lake deposit (Severin and others, 1990). Other data from Franklin and Thorpe (1982), Williams and others (1990), and Morton and others (1990). Leaders (---) indicate no data available]

Deposit name	Tons[1]	Cu, %	Zn, %	Ag, g/t	Au, g/t
Wabigoon subprovince					
Mattabi	11.4	0.74	8.28	113	0.38
Sturgeon Lake	2.07	2.55	9.17	179	.093
Lyon Lake and Creek zone	2.88	1.26	8.67	155	.34
Wawa-Shebandowan subprovince					
Geco mine	42.6	1.9	3.8	58	---
Winston Lake	3.10	1.0	15.6	34	1.0

[1]Metric tons × 10^6.

The distribution of major gold camps along or near these major faults implies a genetic link between movement along them, the final stages of greenstone-belt evolution, and gold deposits (Colvine and others, 1988). The largest districts or deposits appear to be have been formed during early episodes of high-angle reverse motion along these dominantly transpressive zones (Sibson and others, 1988; Sibson, 1989). Most deposits appear to have been emplaced in the zone of brittle-ductile deformation (at approximately 10-km depth) after Late Archean peak deformation and metamorphism, which occurred between 2,700 and 2,680 Ma (Card and others, 1989), although movement along the zones may have continued into the Proterozoic. The characteristics of Archean lode-gold deposits are summarized in Appendix 2.

The location of large gold deposits (gold resource >3,200 kg) by each subprovince of the Superior province was tabulated by Card and others (1989). The Abitibi and Uchi subprovinces combined account for more than 96 percent of the past production and gold resources (production+reserves) in the province. The amount of gold production does not correlate with any lithologic or geochemical characteristics or the age of the major rock units within the subprovinces. However, production is greatest in subprovinces such as the Abitibi and Uchi that show the greatest degree of preservation of volcanosedimentary rocks, as reflected by extremely low metamorphic grade and a high ratio of volcanic to plutonic rocks (Card and others, 1989). The Wabigoon subprovince ranks third in gold production when compared with other subprovinces (table 3). Production data from the Hemlo deposit, located in the eastern part of the Wawa-Shebandown subprovince, was not included in the summary by Card and others (1989). The western part of the Wawa-Shebandowan subprovince contains no deposits with more than 3,200 kg gold production and therefore was not included in the total.

Total known production from the gold deposits nearest the study area—those in the Wabigoon subprovince near Mine Centre (670 kg of gold and 19 kg of silver) and the Atikoken area (250 kg of gold and 45 kg of silver) (Schnieders and Dutka, 1985), amounts to less than 0.1 percent of the total gold resources in the Superior province. Most of the gold produced in the Shebandowan area of the Wawa-Shebandowan subprovince was from a single mine, the Ardeen (975 kg of gold and 5,500 kg of silver).

Gold deposits in both the Mine Centre and Shebandowan areas occur along subprovince boundaries, where the greenstone-granite-dominated subprovinces, the Wabigoon and the Wawa-Shebandowan, are adjacent to the metasedimentary rock-gneiss dominated Quetico subprovince (fig. 15). In the Mine Centre area, the boundary is in part a major transpressive shear zone, the Rainy Lake-Seine River fault.

A number of occurrences and deposits near Atikoken, Ontario, east of the study area, lie near the regional-scale Quetico fault system, of which the Rainy Lake-Seine River fault is a part (Schnieders and Dutka, 1985). In that area, deposits that are not located near the trace of the main Quetico fault are found along northeast-trending topographic lineaments and shear zones, which are probably secondary structures caused by dextral movement along the Quetico fault. Wilkinson (1980, 1982) described three major host rock environments in the Atikoken area (fig. 15) that contain quartz vein gold deposits. Metavolcanic rocks contain about 50 percent of the known occurrences and deposits in quartz-carbonate vein systems. Many small occurrences and several deposits (approximately 40 percent of all deposits) are localized in small shear zones within the deformed granitoid rocks of the Marmion batholith, near Atikoken. A few occurrences (about 10 percent) are found in shear zones in the variably altered contact zone between the Marmion batholith and its metavolcanic host rocks.

In the Shebandowan area (fig. 15), where no regional shear system related to gold mineralization has been described, gold deposits are localized in small shear zones. Stott and Schneiders (1983) concluded that these shears may be related to the D_2 north- and northwest-directed compressional event, which may have included a component of left-lateral simple shear. The adjacent metasedimentary rocks of the Quetico subprovince were also affected by the same compressional event that accompanied regional metamorphism. In the greenstone terrane this simple shear produced small northwest- and northeast-trending shear zones and en echelon dilational veins. These structures are located principally near the contacts of metavolcanic rocks with porphyritic feldspathic intrusions, where there was a marked ductility contrast between the two rock types. The large gold deposit near Hemlo, Ontario, is also in rocks of the Wawa-Shebandowan subprovince near the northeastern shore of Lake Superior (Burk and others, 1986; Kuhns and others, 1986; Valiant and Bradbrook, 1986)(fig. 15). The deposit contains approximately 653×10^3 kg of gold, based on

Table 3. Gold resources by greenstone-granite subprovince in the Superior province, Canada.

[Data modified from Card and others (1989). Only deposits with more than 3,200 kg of gold resources are tabulated except for local deposit. Production in kg × 10^6. Leaders (---) indicate no data]

Subprovince	Number (percent)	Resources (percent)	Resources (percent)	Large deposits[2]
Abitibi	86 (72)	3.74 (84)	4.97 (85)	16 (80)
Uchi	16 (13)	.53 (12)	.63 (11)	3 (15)
Wabigoon	10 (8)	.12 (3)	.16 (3)	1 (5)
Sachigo	5 (4)	.01 (1)	.04 (1)	---
Other	3 (3)	.02 (1)	.05 (1)	---
Local[1]	---	.002	---	---

[1]Total production from the Mine Centre, Atikokan, and Shebandowan areas.
[2]Number of the 20 largest deposit.

production and reserve figures given by Smyk and others (1990). In contrast to other Canadian gold deposits of Archean age, the Hemlo deposit (1) contains relatively high concentrations of Mo and Ba (as barite), (2) lacks significant quantities of carbonate alteration, (3) is dominated by potassic (white mica and microcline) alteration, (4) contains some aluminosilicate minerals as part of the alteration halo, (5) contains sulfide mineralization that is disseminated rather than confined to quartz veins and their margins, and (6) appears to be stratiform.

Several genetic models for the gold deposit at Hemlo have been proposed, but because the geologic history involves large amounts of deformation, genetic interpretations are difficult to substantiate. Burk and others (1986) propose that the gold-bearing hydrothermal solutions were structurally controlled and emplaced in a shear zone prior to the culmination of the regional amphibolite-grade metamorphic event. They do favor, however, a syngenetic origin for the barite-rich horizon. Kuhns (1986), Kuhns and others (1986), and Walford and others (1986) suggest that the mineralization may be related to a porphyry-copper or molybdenum system on the basis of similarities in the geochemistry and alteration mineralogy, mainly, a pretectonic, premetamorphic origin. Valiant and Bradbrook (1986) emphasized the similarities between the Hemlo deposit and the Bosquet deposit, near Val D'Or, Quebec, (Valiant and others, 1982) and proposed that they are syngenetic, stratiform deposits formed during seafloor hot-spring activity.

Iron has most recently been produced in the Wabigoon subprovince from the Steep Rock mine, near Atikoken (Jolliffe, 1966; Shlanka, 1972) (fig. 15) and production is summarized in table 4. This deposit contains a mixture of siderite and pyrite iron-formation, underlain by a thin, metamorphosed conglomerate and stromatolitic limestone, and overlain by an ultramafic metatuff at the base of an overlying bimodal volcanic cycle. The metasedimentary rocks that contain this deposit appear to have been deposited in a relatively shallow, shelflike environment; therefore they differ from the more common Algoma-type iron-formations, which are generally interbedded with deep water, bimodal volcanic assemblages, or volcanogenic graywacke and pelite sequences. The siderite and pyrite iron-formation protore was oxidized to a direct-shipping mixture of hematite and goethite probably during subaerial weathering that occurred along a paleo-erosion surface (Gross, 1965).

In the Wawa-Shebandowan subprovince, iron has been produced from the Vermilion district in Minnesota and the Algoma Properties mine near Wawa, Ontario (Gross, 1965) (fig. 15). The iron deposits in the Vermilion district were direct-shipping hematite ore that occurred in replacement bodies within a single stratigraphic unit of chert-iron oxide iron-formation interbedded with a sequence of metamorphosed pillow basalts (Sims, 1972b). Production from the Vermilion district is summarized in table 4. The Algoman Properties mine in Ontario produced iron from siderite-rich iron-formation.

Nickel has been produced from the Shebandowan mine in the Wawa-Shebandowan subprovince, which is the largest Archean Ni-Cu deposit in the Canadian Shield (fig. 15). Ore is produced from a thin, continuous zone of pyrite-pyrrhotite-pentlandite-chalcopyrite-cemented breccia, which contains fragments of both the host peridotitic intrusion and the adjacent metabasaltic wallrocks. The origin of the deposit is not well understood. However, the ore zone is at the top of the ultramafic intrusion and clearly developed later than the intrusion (Morton, 1979), precluding an origin by the gravitational settling of an immiscible-sulfide liquid from the peridotitic liquid. The Cu/Cu+Ni ratio of the ore is similar to that of immiscible liquids derived from a gabbroic melt (Franklin and Thorpe, 1982).

A major platinum-group element (PGE) occurrence has been recently investigated in the 30 km^2 igneous complex at Lac des Illes, in the Wabigoon subprovince (fig. 15) (Sutcliff and others, 1989). Production of platinum-group elements

Table 4. Summary of production from the largest iron and nickel deposits or districts in the Wabigoon and Wawa-Shebandowan subprovinces, Minnesota and Ontario.

[Tons = metric tons × 10^6]

Deposit or district	Tons (date)	Grade, in percent
Nickel deposits		
Shebandowan mine, Ontario[1]	6.2 (to 1981)	1.5 Ni, 0.8 Cu(?)
Iron deposits		
Vermilion district, Minnesota[2]	89.3 (1884-1967)	60 Fe
Steep Rock mine, Ontario	60 [3](1944-1979)	[4]52 Fe

[1]Franklin and Thorpe (1982).
[2]Alm and Trethewey (1970).
[3]Wilks and Nisbet (1988).
[4]Gross (1965).

began at the Lac des Illes mine in late 1993. Initial reports indicate that the deposit contains as much as 20.4×10^6 metric tons of disseminated chalcopyrite, pyrrhotite, pentlandite, and pyrite with an average grade of 6.34 g/t combined PGE and 0.2 percent Cu+Ni. Ore reserves for the two ore zones currently being mined (Roby and C zones) are 7.4×10^6 metric tons containing 6.2 g/t platinum-group elements and 0.5 g/t gold (Skillings Mining Review, 1993). The palladium to platinum ratio averages about 15-to-1. Six other ore zones are known. At full production in 1994, it is expected to be the largest palladium deposit in North America, producing 3 metric tons of palladium and 0.25 metric tons platinum, annually. The complex consists of several coalescing, cyclically layered, mafic to ultramafic intrusions that were emplaced into 3.0 to 2.7 Ga gneissic tonalite (Davis and Jackson, 1988; Davis and Sutcliffe, 1985), at about the same time as the emplacement of nearby late granitoid rocks (typically 2.7 to 2.69 Ga) (Davis and Edwards, 1986).

MINERAL DEPOSITS AND OCCURRENCES WITHIN THE INTERNATIONAL FALLS 1°× 2° QUADRANGLE

Inferred marginal and subeconomic resources have been identified for Au, Ag, Zn, Cu, Ni, Ti, V, and Fe in the International Falls 1°×2° quadrangle, principally on the basis of the results of exploration in the nearby Fort Frances-Mine Centre area. The results of that exploration are summarized in this section. Published data indicating subeconomic reserves, as defined by extensive sampling and drilling, are available only for two prospects, one containing Cu and the other Ti, in the Grassy Portage gabbroic intrusion (Poulsen, 1984).

Production of nonferrous metallic minerals in northern Minnesota consists of only gold from the small mining operation on Little America Island in Rainy Lake. The amount of production is not known because records are unavailable for the Little America mine, which was discovered in 1893 (Winchell and Grant, 1895).

GOLD

Canadian gold production in the area between Fort Frances and Kenora (150 km northwest of Fort Frances) began as early as 1885. Most of the production has been from the Kenora area, where data from Ferguson and others (1971) indicate a minimum production of 4,998 kg of gold and 737 kg of silver. Metal production from the adjacent Fort Frances-Mine Centre area in Ontario also includes small amounts of Cu and Au. Precious-metal production has been principally from the Mine Centre area, whereas prospects for Ti, V, Cu, Ni, and Zn are numerous throughout the Rainy Lake area. Production figures and published assay data, largely from Poulsen (1984) and Beard and Garratt (1976), were summarized for the International Falls 1°×2° quadrangle by Klein (1989).

Gold was produced from a number of small mines in the Mine Centre area from 1893 to 1902 (fig. 16), the total production is estimated at about 653 kg (table 5). The three largest producers, the Olive, Foley, and Golden Star mines produced more than 98 percent of the total (fig. 16). Most of the gold has been produced from relatively narrow quartz veins (0.6 to 2 m) containing minor amounts of pyrite and base metal sulfide minerals. Minor amounts of carbonate minerals and, locally, tourmaline and scheelite may also be present in and adjacent to the veins.

Poulsen (1983) related the formation of fractures that controlled the emplacement of the gold-bearing veins to transcurrent movement along the nearby Quetico and Rainy Lake-Seine River faults or related subsidiary faults. Veins in this area are typically emplaced in subvertical, tensional fractures resulting from the dominantly dextral transcurrent movement. The small amount of gold production in this area relative to other areas in the Superior province (for example the Abitibi subprovince) may be the direct result of the dominant transpressional regime, where hydrothermal fluid migration along the faults may have been largely unimpeded and gold was not precipitated (Poulsen and Robert, 1988).

The correspondence of precious metal deposits with shear zones in the International Falls quadrangle is shown in figure 16. More than 90 percent of the known precious-metal deposits lie within 0.5 km of a shear zone. As is typical of Archean lode-gold deposits, mineralization may occur in nearly any host rock; in the Mine Centre area, however, coarse-grained felsic intrusive rocks host much of the mineralization. Poulsen (1984) observed that rocks in this area that were metamorphosed above greenschist grade were not

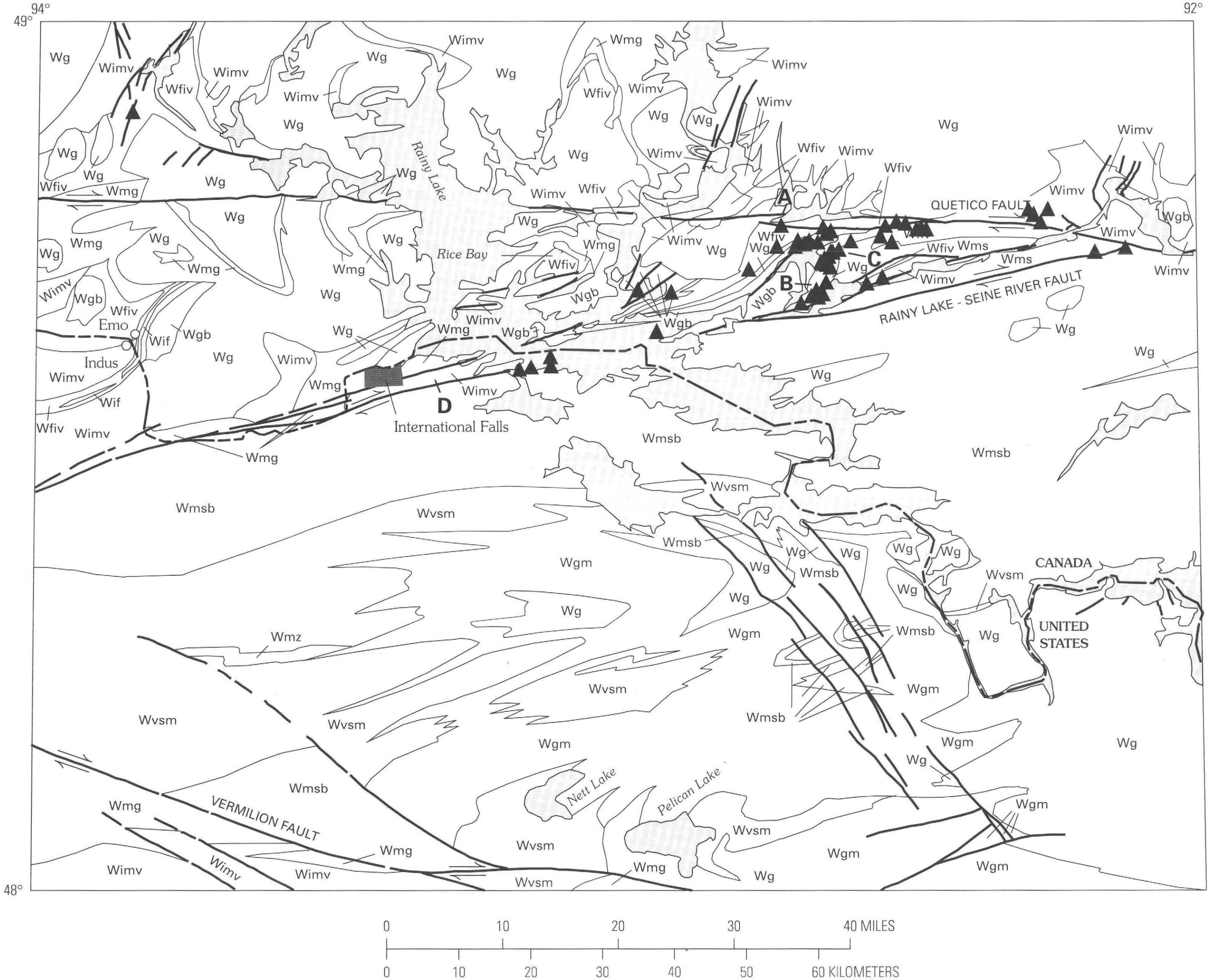


Figure 16. Distribution of gold deposits and prospects (solid triangles) in the International Falls 1°× 2° quadrangle. Locations discussed in text: A, Olive mine; B, Foley mine; C, Golden Star mine; and D, diamond drill hole RR-1. See figure 3 for explanation of geology.

Table 5. Summary of gold production in the Fort Frances–Rainy Lake area, Ontario, from deposits of greater than 30 kg.

[Data from Poulsen (1984)]

Name	Au, in kg
Golden Star mine	334
Foley mine	164
Olive mine	111
R.C. Cone mine	31

favorable hosts for gold deposits, although they contained numerous base metal volcanogenic massive sulfides and gabbro-hosted mineralization. This lack of gold mineralization may be due to the tendency of rocks under metamorphic conditions above greenschist grade to behave ductily and to develop few tensional open space depositional sites.

Anomalous gold-bearing zones are found in strongly ductily deformed rocks in the study area. Several intervals less than 0.5 m thick in drill hole RR-1, drilled by the Minnesota Department of Natural Resources east of International Falls (fig. 16), and nearby rock exposures contain anomalous gold values (as much as 3 ppm) in quartz veins emplaced in highly deformed mafic, ultramafic, and felsic metavolcanic rocks that contain minor amounts of metagraywacke and thin magnetic iron-formation (Sellner and others, 1985). Results of recent exploration in this area were unavailable for this assessment.

COPPER AND ZINC

Copper and zinc were produced from several small stratiform massive sulfide lenses enclosed by a chlorite-rich mafic metavolcanic host rock within a bimodal volcanic sequence at the Port Arthur mine in Ontario (fig. 17). The ore zone is directly overlain by chert, which is succeeded by quartz-phyric felsic tuff. The production was small, amounting to approximately 11.8 metric tons of copper at a grade of 3 percent Cu (Poulsen, 1984). A significant amount of exploration at the Wind Bay prospect (fig. 18) has indicated that two 8 m-thick, low-grade, sulfide-rich zones (containing approximately 1.3 percent Zn and 0.15 percent Cu) are present in stratigraphic setting similar to that of the Port Arthur mine. At the Gagne Lake prospect (fig. 17), a 20 cm-thick, zinc- and lead-rich, massive sulfide lense occurs in metamorphosed rhyolitic volcaniclastic rocks. These host rocks show extensive magnesium enrichment, which is typical of many Archean volcanogenic massive sulfide deposits, as indicated by the development of chlorite and cordierite. The mineralized zone is overlain by fine-grained metasedimentary rocks and chert (Poulsen, 1984). Drilling at the Pidgeon property (fig. 17) has intersected similar base metal mineralization (0.53 percent Zn and 1.76 percent Pb) in a 2-m-thick zone in felsic metavolcanic rocks. Exploration drilling near Indus, west of International Falls, has intersected several thin layers of massive sulfide with low-level enrichments in base metals (Listerud, 1976).

All of the massive sulfide occurrences, as known from their present state of exploration, are subeconomic. However, most of the occurrences have characteristics similar to economic base metal massive sulfide deposits elsewhere in the Superior province.

NI-CU AND TI-V IN GABBRO

Several Ni-Cu prospects are found in the basal parts of the two steeply dipping, layered gabbroic intrusions, the Grassy Portage Bay and the Seine Bay-Bad Vermilion intrusions (Poulsen, 1984) in the Rainy Lake area of Ontario (fig. 18). Poulsen (1984) indicated that the basal melagabbro zone of the Grassy Portage Bay intrusion contains at least 300,000 metric tons of 1.89 percent copper in magmatic sulfide concentrations. Titanium and vanadium mineralization in magnetite, ilmenite, and rutile occurs both in the Seine Bay-Bad Vermilion and Grassy Portage Bay intrusions but is restricted to the more fractionated central parts. Approximately 2 million metric tons of magnetite-ilmenite ore at greater than 45 percent combined FeO and TiO_2 and approximately 0.1 percent vanadium has been outlined in the Grassy Portage Bay intrusion as the result of extensive exploration (Rose, 1969).

The Dobie intrusion (fig. 18), near Emo along the Rainy River, is a nearly flat-lying, layered gabbroic intrusion (Fletcher and Irvine, 1954). Magmatic Ni-Cu sulfide minerals are primarily associated with a norite phase. Sulfide-rich samples with concentrations of as much as 2.5 percent nickel and 0.3 percent copper were reported from test pits (Fletcher and Irvine, 1954). Average values calculated from the assay results presented by Fletcher and Irvine (1954) for the most continuous mineralization in drill hole D-1 indicate 0.39 percent copper and 0.44 percent nickel over an interval of 26 m.

Recently, analyses of several samples from a sulfide-rich, lower part of the Grassy Portage Bay intrusion reported by Blackburn and others (1988), contained anomalous precious- and platinum group-metal values (460 ppb of gold; 150 ppb of platinum; 240 ppb of palladium). Several similar samples from the Dobie intrusion contain less than 1 ppb of platinum and palladium.

IRON-FORMATION

Several relatively continuous layers of magnetic iron-formation, generally within mafic metavolcanic units, are delineated by the prospect symbols present in the quadrangle (fig. 3). The iron-formation commonly is enclosed by biotitic metasedimentary rocks within regionally extensive metabasalts (Poulsen, 1984). These rocks represent a sub-economic iron resource (fig. 19) because they are thin (generally less than 2 m thick), lensoidal, and not tectonically thickened.

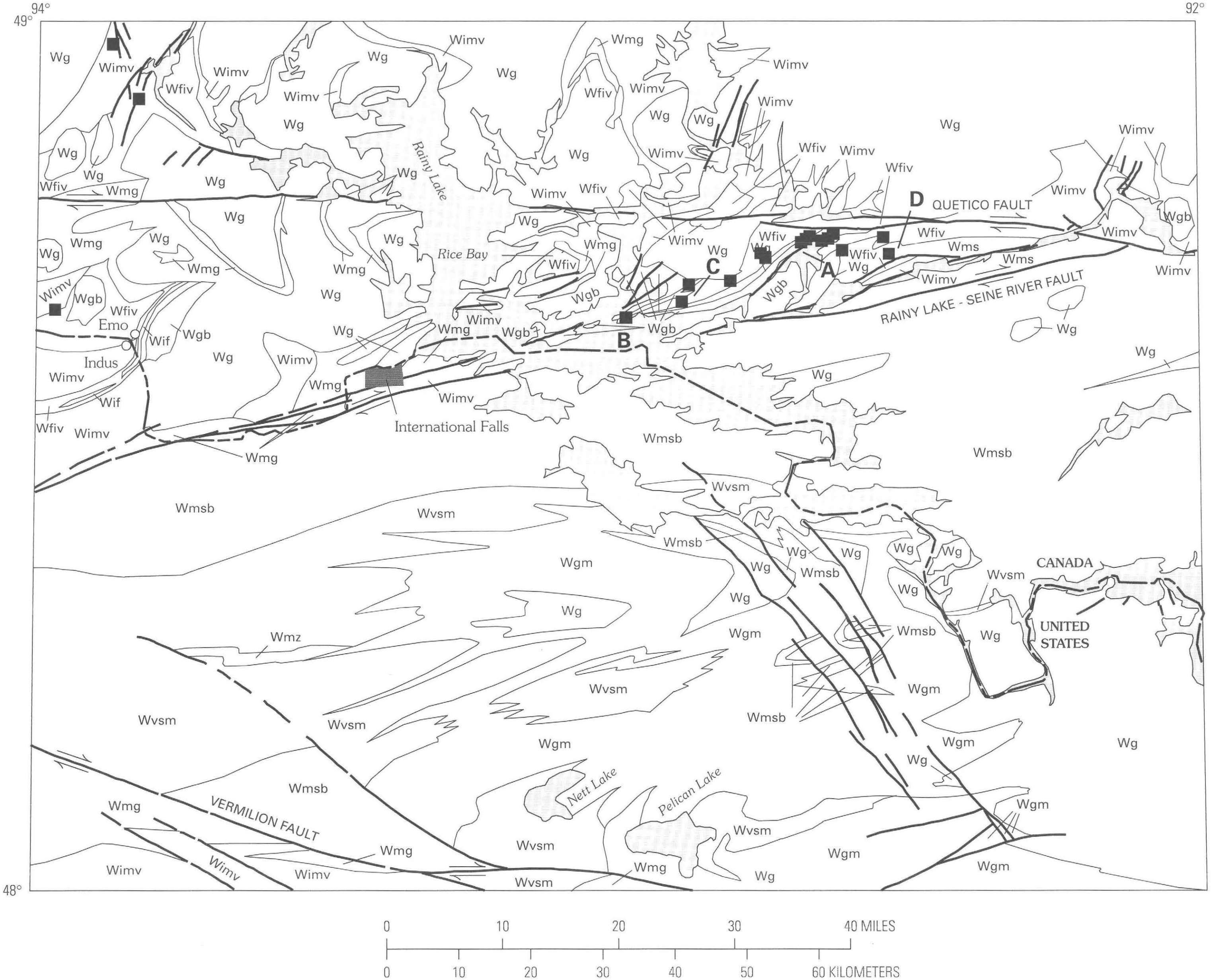


Figure 17. Distribution of volcanogenic massive sulfide deposits (solid square) in the International Falls 1°× 2° quadrangle. Locations in the Fort Frances-Mine Centre area discussed in text: A, Port Arthur mine; B, Wind Bay prospect; C, Gagne Lake prospect; and D, Pidgeon property. See figure 3 for explanation of geology.

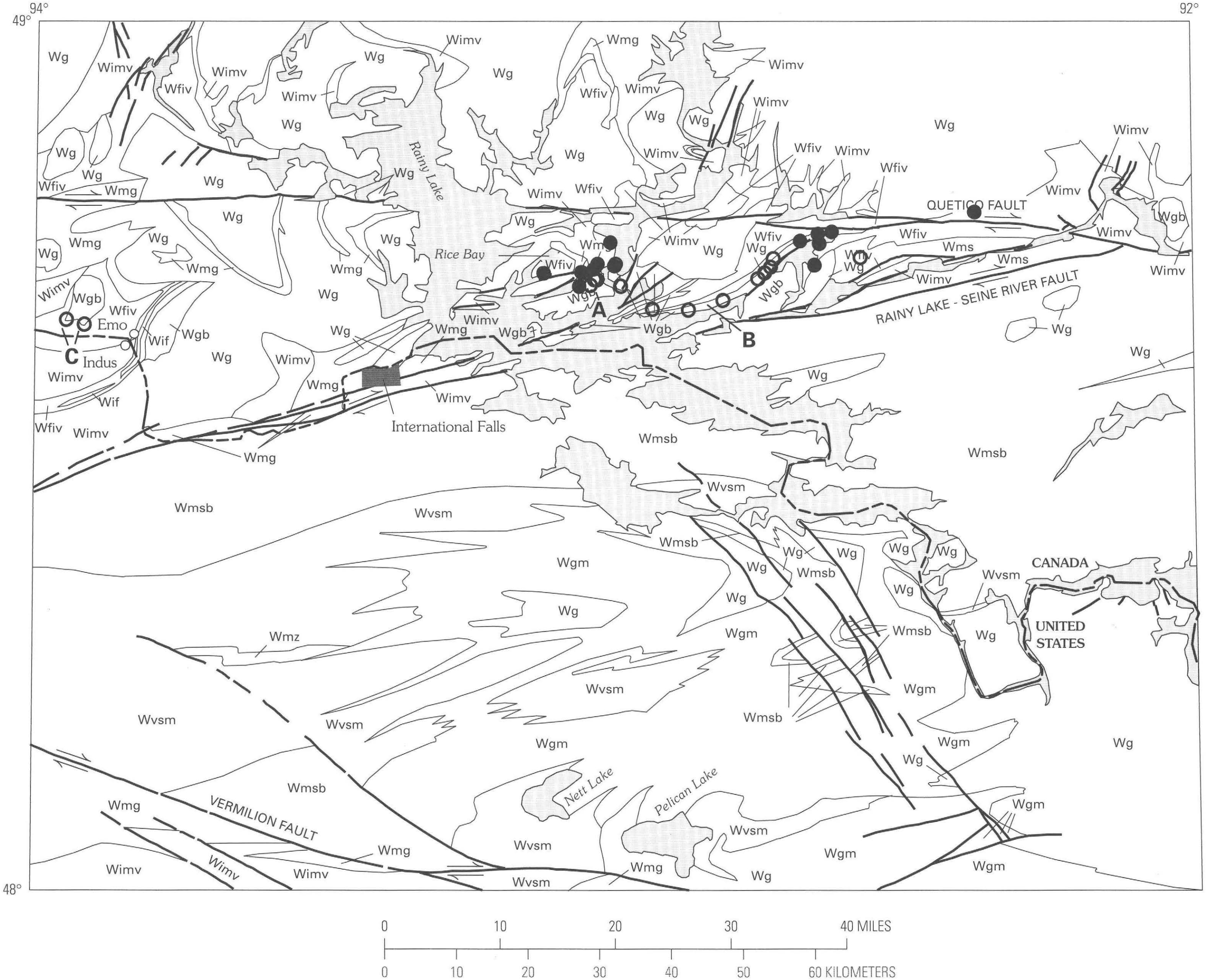


Figure 18. Distribution of gabbro-hosted Ni-Cu (open circle), and Ti-V (solid circle) deposits in the International Falls 1°×2° quadrangle. Locations discussed in text: A, Grassy Portage Bay intrusion; B, Seine Bay-Bad Vermilion intrusion; and C, Dobie intrusion. See figure 3 for explanation of geology.

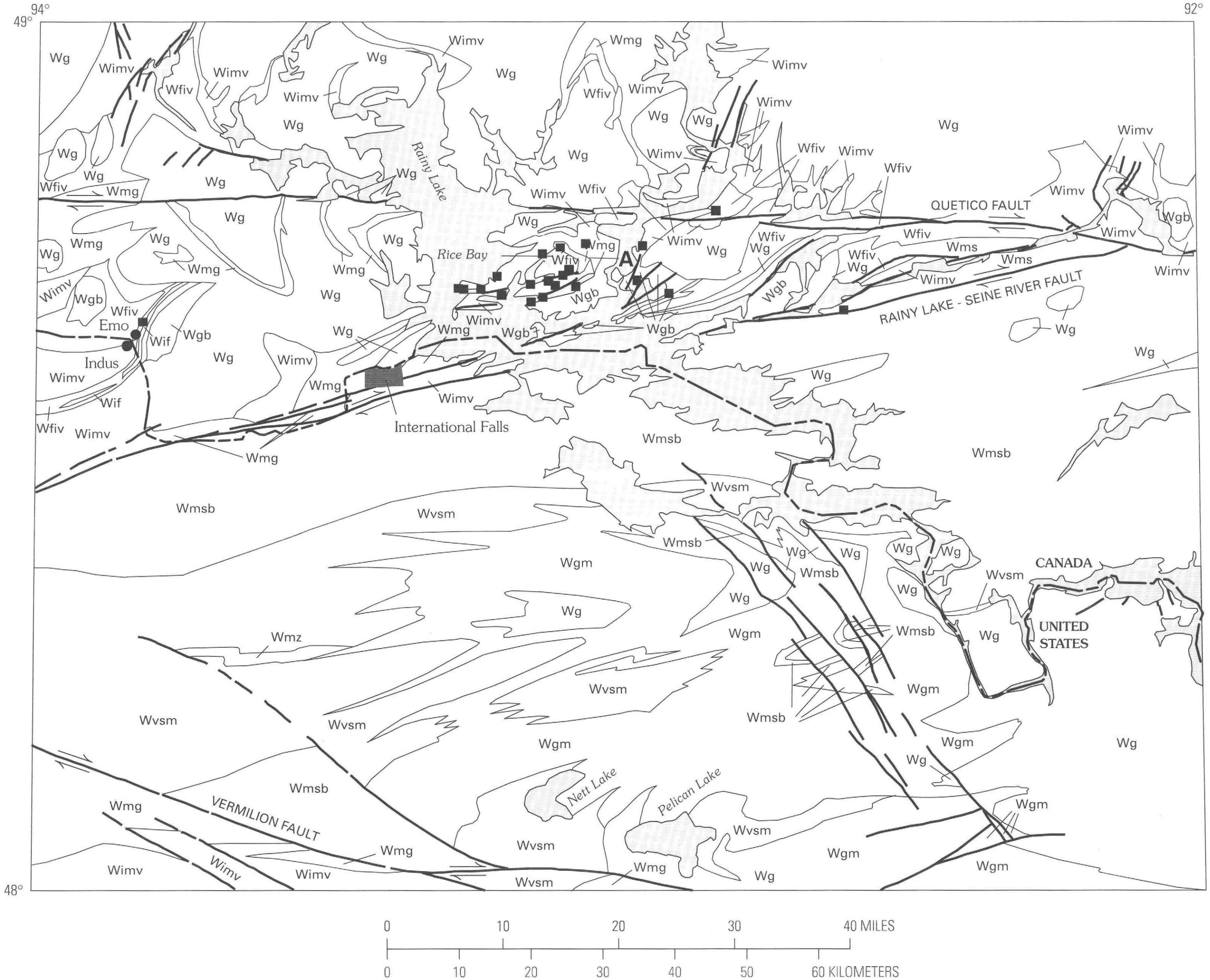


Figure 19. Distribution of iron prospects (solid squares) in the International Falls 1°× 2° quadrangle. Pocket Pond prospect (A) discussed in text. See figure 3 for explanation of geology.

Subeconomic concentrations of other metals, such as Zn, Cu, and Au are found locally in iron-formation or adjacent minor pyritic or pyrrhotitic massive sulfide or graphitic zones, such as that Pocket Pond occurrence (fig. 19) (Poulsen, 1984).

MAGNETIC ANOMALIES AND MINERAL OCCURRENCES

Magnetic maps and the mineral occurrence data of Klein (1989) were analyzed to determine the relation between magnetic response and mineral deposits. Known or potential deposits of sedimentary iron-formation are indicated by positive magnetic anomalies of high amplitude. Deposits of ilmenite-magnetite or titaniferous magnetite may be suspected under any of the high-amplitude anomalies produced by gabbroic rocks. Absence of positive anomalies over known gabbro also constitutes an ore guide because some gold-bearing quartz vein deposits occur in fractures in nonmagnetic gabbros. Gold-bearing quartz veins in shear zones and cleavage-parallel dilatant zones occur mainly on the flanks of magnetic anomalies (hence, near geologic contacts), but numerous deposits are on magnetic highs and in the troughs of magnetic lows.

MINERAL RESOURCE ASSESSMENT

ASSESSMENT CRITERIA

Once the deposit models were selected on the basis of analogy and projection, permissive domains or tracts that might contain the selected deposit types within the International Falls 1°×2° quadrangle were defined on the basis of the diagnostic criteria derived from deposit models. Recognition criteria are the geologic, geophysical, or geochemical features that suggest a particular mineral deposit may be present in a given area. Recognition criteria are divided into the two types listed below.

1. Diagnostic-features present in most, or all, of the deposits that are thought to be essential for the formation of the deposit. The presence of these features is a favorable indication that a particular kind of deposit may be present in a given area. Conversely, the absence of diagnostic criteria, or negative criteria, indicates that there is little likelihood for the occurrence of a particular type of deposit.

2. Permissive-features that are present in some deposits and that, although not required for ore formation, may indicate the presence of a mineral deposit.

The definition of potential metal-bearing domains was based largely upon two types of diagnostic criteria: 1, the presence of favorable host rocks in the case of syngenetic and magmatic deposits and 2, the presence of favorable structures in the case of epigenetic gold deposits.

Other diagnostic criteria, such as electrical conductors or magnetic anomalies, geochemical anomalies, coarse-grained felsic metavolcanic rocks, or chert layers, indicate a greater potential for massive sulfide deposits in a given area. Likewise, extensive chlorite-carbonate alteration; As, Sb, Mo, and base metal anomalies; and multiple episodes of veining are considered to increase the favorability for epigenetic gold deposits. Few permissive criteria were defined and the level of information was not consistent, therefore the presence of permissive criteria was not used to derive the resource assessment; but only to present supplemental information on the character of each tract.

These deposit types were delineated on the basis of the presence of favorable host rocks, favorable structural environment, small amounts of production, or the occurrence of significant prospects in the Canadian part of the study area and from the Little America mine in Minnesota.

Five deposit types were evaluated as hypothetical resources: volcanogenic massive sulfide deposits, gabbro-hosted Ni-Cu and Ti-V deposits, Algoma-type iron-formation, shear-zone-hosted lode-gold deposits, and gold deposits hosted by chemical metasedimentary rocks.

The locations and resource potential of the tracts defined on the basis of the diagnostic criteria for four of the five deposit types are shown on plates 1-4. Some speculative deposits types are present in equivalent geologic environments but tracts were not defined because no analogs exist in immediately adjacent parts of the Superior province or we lack sufficient geologic, geochemical, or geophysical information to evaluated them. Some of these speculative deposit types are listed in table 1. These include diamonds in kimberlites, chromite in layered ultramafic rocks, komatiite-hosted Ni deposits, Cu-Mo porphyry deposits, alkalic ultramafic Cu and U deposits, and carbonatite-hosted rare earth element, U, Nb, and Ta deposits. Ag-Co-As mineralization may be present in the quadrangle, as suggested by the surficial geochemical data from this study, but its presence has not been substantiated by other techniques. Therefore, this mineralization is considered only a speculative resource.

After each of the tracts was geographically defined, an objective score was assigned based on the sum of the point values for each of the diagnostic criteria. Each tract where one diagnostic criterion was met was assigned a value of 1. A tract with the known absence of a criterion was assigned a minus 1 for that criterion. A score of zero was assigned if the information was not sufficient to establish the presence or absence of a given criterion. The summed score allows the tracts to be ranked on the basis of the relative favorability to other tracts in the study area. Subjective interpretation of these scores was used to establish the probability rank of each tract for a given deposit type. The frequency distribution of the tract sums presented with the tabled scores for each deposit type was tabulated as a qualitative check on the distribution of probability classes for each deposit type.

The assignment of resource potential in this study was accompanied by a qualitative expression of the certainty which indicates the level of confidence we place on the estimate of resource potential. This value is related directly to such characteristics as the degree of exposure of the bedrock or the amount of exploration that has taken place in a given area. We have adopted the convention suggested by Goudarzi's (1984) four levels of certainty ranging from A, the lowest level of confidence, to D, the highest. The relationship between the level of certainty and the resource potential is illustrated in Appendix 1.

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

Based on the diagnostic criteria for volcanogenic massive sulfide deposits presented in table 6, 16 tracts in the study area were ranked on the basis of their resource potential for massive sulfide deposits. The scores and confidence ratings for each of the tracts are shown in table 7 and the resource potential for each tract is shown on plate 1. Tracts I through VII and XI contain metavolcanic rocks in the Wabigoon subprovince and some positive diagnostic criteria (table 1). The exploration drilling and outcrop sampling of several electrical conductors in these metavolcanic rocks near Indus (Tracts I, II, III) have found only pyrite and pyrrhotite-rich massive sulfide lenses containing low base and precious-metal concentrations. Soil geochemistry from this study in the same area also indicates only low-level anomalies. Even though these tracts (I, II, III) contain appropriate host rocks, they are rated as having moderate potential to contain base metal massive sulfides relative to other tracts because of the overall character of the volcanic rocks, the lack of base metal concentrations, and the low-level soil geochemical anomalies.

Table 6. Diagnostic and permissive criteria for volcanogenic massive sulfide deposits.

Diagnostic criteria
1. Presence of metavolcanic rocks; geophysical indicators are irregular aeromagnetic patterns and relative gravity highs
2. Proximity to felsic volcanic centers characterized by coarse felsic volcaniclastic breccias and fragmental rocks
3. Evidence for hydrothermal fluids associated with massive sulfide mineralization a. Exhalite such as volcanogenic chert, sulfide-rich horizons, or Algoma-type iron-formation b. Hydrothermal alteration such as Mg, Fe, and K enrichment and Na depletion c. Base-metal enrichment (Zn, Cu, +Sb+Se+In+Sb+B) d. Presence of barren massive sulfide horizons
4. Presence of base-metal massive sulfide mineralization as indicated by bedded deposits, stringer zones, or electrical conductors
5. Site-specific characteristics (continuation of known favorable horizons containing other diagnostic criteria; presence of "gull wing" or heavy rare earth element-enriched rhyolites)
Permissive criteria
1. Presence of graphitic metasedimentary rocks

The probability that a deposit is present in a given area is proportional to the size of that area. The extremely small amounts of metavolcanic rocks exposed in the moderately favorable tracts within the U.S. part of the International Falls quadrangle make it highly unlikely that a mineable base metal massive sulfide deposit is present. This conclusion is well supported by a comparison of the relatively small geographic area of the study area with that of the entire Wabigoon subprovince, which contains only three known deposits, one of moderate size (Mattabi) and two small (Sturgeon Lake and Lyon Lake) (fig. 15).

Low potential for massive sulfides is indicated for the schistose, mixed metavolcanic and metasedimentary rocks in Tract IV; and although the tract contains favorable host rocks, it does not contain other diagnostic criteria. The mafic metavolcanic rocks in Tract VIII, because of they lack indications of felsic volcanism, are also assigned a low potential.

Tracts IX, XII, XIII, and XVI, containing rocks of the Wabigoon subprovince, are all considered to be unfavorable for the occurrence of massive sulfide deposits because of their lithologic character, namely, abundant granitic intrusions (IX), presence of iron-formation (XVI), and existence of clastic metasedimentary rocks (XII, III).

The entire Quetico subprovince (Tract XV) is also considered to lack any potential for massive sulfide deposits because of the predominance of graywacke which is unfavorable for volcanogenic massive sulfide mineralization, and the presence of granitic rocks derived from graywacke by partial melting. This conclusion is supported by the lack of metal production from rocks of this subprovince that are better exposed in parts of southern Ontario.

No exploration has taken place in the metavolcanic rocks of the Wawa-Shebandowan subprovince (Tract XIV) in the International Falls quadrangle. The protoliths for these variably metamorphosed, generally medium-grade rocks (Jirsa and Boerboom, 1990) are principally mafic metavolcanic rocks and a minor component of felsic metavolcanic rocks. The degree of deformation is moderate to high, and several northwest-trending fault segments are present, possibly related to movement along the Vermilion fault. The character of the metavolcanic rocks is probably mostly mafic resulting in the assignment of low potential for this tract. Exploration immediately south of the study area has been concentrated on an interbedded bimodal mafic to felsic metavolcanic unit that is not present in the study area (Jirsa and Boerboom, 1990). However, the subprovince does contain one large massive sulfide deposit, the Geco deposit, near Shebandowan, Ontario, and a relatively small one at Winston Lake (fig. 15). Thus, deposits of this type could be present in other parts of the Wawa-Shebandowan subprovince south of the study area.

Table 7. Resource potential for volcanogenic massive sulfide deposits in the U.S. part of the International Falls 1°×2° quadrangle.

[Diagnostic criteria 1-5 outlined in table 6; values discussed in text. Confidence levels from Goudarzi (1984)]

Tract No.	Diagnostic criteria[1] 1	2	3	4	5	Sum	Confidence level
I	1	1	1[c,d]	0	0	3	C
II	1	0	1[c]	0	0	2	C
III	1	0	1[a,c]	0	0	2	C
IV	1	0	0	0	0	1	B
V	1	0	1[a,c]	0	0	2	B,C
VI	1	0	1[a,c]	0	0	2	B
VII	1	1	1[a]	0	1	4	C
VIII	1	-1	0	0	0	0	C
IX	-1	0	0	0	0	-1	D
X	1	0	1[a,c]	0	0	2	C
XI	1	0	1[a-d]	1	0	3	D
XII	-1	0	0	0	0	-1	D
XIII	-1	0	0	0	0	-1	D
XIV	1	0	0	0	0	1	B
XV	-1	0	0	0	0	-1	D
XVI	-1	0	0	0	0	-1	D

[1]Frequency distribution of tract scores and resource potential:

Class	No.	Resource potential
-1	5	none
0	1	low
1	1	low
2	5	moderate
3	2	moderate
4	1	moderate

[a]Cherts; [b]Mg or Fe enrichment; [c]base-metal anomalies; [d]massive sulfide present.

GABBRO-HOSTED NI-CU AND TI-V DEPOSITS

Appropriate host rocks, as defined in the diagnostic criteria (table 8), have not been identified in the U.S. part of the International Falls quadrangle for gabbro-hosted Ni-Cu and Ti-V deposits. Small deposits in the Grassy Portage Bay and Seine Bay-Bad Vermilion Lake intrusions in the Mine Centre area and the Dobie intrusion near Emo, Ontario, are typical of those found elsewhere in greenstone terranes. But there is a low probability that such deposits are present in the U.S. part of the International Falls 1°×2° quadrangle in rocks of the Wabigoon subprovince or the Wawa-Shebandowan subprovince.

ALGOMA-TYPE IRON-FORMATION

The resource potential for the seven tracts defined on the basis of the diagnostic criteria for Algoma-type iron-formation (table 9) is summarized in table 10 and shown on plate 2. A thin unit of magnetic iron-formation can be traced for more than 10 km by aeromagnetic data (Chandler and Horton, 1988) in the Wabigoon terrane in the northwest corner of the study area (Tract III). The unit was encountered by diamond drilling westward along strike in the adjacent Roseau 1°×2° quadrangle (Day and others, 1990a). Because of its limited thickness (probably less than 10 m) and lack of structural thickening, it is not likely to be exploited. However, it is assigned a high potential for the presence of a small tonnage deposit on the basis of its appropriate composition and its geophysical continuity.

Tracts IV and V, near International Falls, contain small lenses of silicate-rich magnetic iron-formation as interpreted from geologic mapping (Day, 1990b) and aeromagnetic data (Case and others, 1990). Because of their unfavorable silicate-rich mineralogy, these tracts containing iron-formation were assigned a moderate resource potential. Any iron

Table 8. Diagnostic criteria for gabbro-hosted Ni-Cu, Ti-V, and PGE deposits.

Diagnostic criteria
1. Presence of layered gabbro intrusions and associated pyroxenite, dunite, peridotite, anorthosite, and norite
2. Anomalously high concentrations of Ni, Cu, PGE, Co, Ti, V; presence of Ni- and (or) Cu-sulfide minerals

mineralization in these tracts is likely to be low grade, low tonnage, and of little economic importance.

Tracts I and VII, containing mostly metavolcanic rocks of the Wabigoon and Wawa-Shebandowan suprovinces, respectively, were assigned a low potential because of the lack of magnetite-rich rocks, indicated by the aeromagnetic and lithologic character. Metasedimentary rocks in the Quetico subprovince, Tract VI, lack known iron-formation and in the study area lack the characteristic magnetic anomalies caused by iron-formation, even though the host rock is permissive. Tract VI has therefore has been assigned a low mineral resource potential.

The plutonic rocks of the Wabigoon and Quetico subprovinces (Tract II), consisting of felsic, intermediate, and some mafic intrusions, have no resource potential for iron-formation because they are not appropriate host rock.

LODE GOLD DEPOSITS

The diagnostic criteria defined for lode gold deposits (table 11) were used to evaluate eight tracts, whose resource potential is summarized in table 12 and shown on plate 3. Tracts I and V are located along major transpressive shear zones in metavolcanic rocks in the Wawa-Shebandowan and Wabigoon subprovinces, and in metasedimentary rocks and amphibolite of the Quetico subprovince. These tracts are considered to have moderate potential to host epigenetic gold deposits. The two tracts outlined include approximately 2 km of the adjoining metasedimentary rocks of the Quetico subprovince along its boundaries with the Wawa-Shebandowan and Wabigoon subprovinces. Gold has not been produced from rocks in the Quetico subprovince, but deformation related to the transverse shear zones can be seen, on the average, about 2 km from the mapped major shears and may have produced structures favorable for the localization of gold mineralization.

Tracts II and III, in the intensely deformed rocks along the Rainy Lake-Seine River fault zone near International Falls, are assigned a high potential for the occurrence of epigenetic gold mineralization. This rating is based on the coincidence of the structurally favorable shear zone, small past production, bedrock gold anomalies both in outcrop and in the Minnesota Department of Natural Resources diamond drill hole RR-1, and metal anomalies in the relatively thin overburden (Clark and others, 1990). However, these deposits are likely to be small (producing less than 300 kg of gold) because the overall structural framework is similar to that which controlled the numerous small-scale gold deposits in the Mine Centre area, Ontario. The small size of the known deposits may be due to the dominance of lateral movement over vertical movement (Sibson, 1989) and the lack of the development of subsidiary structures.

Volcanic rocks in the Wabigoon subprovince near Indus contain some low-level gold and base metal anomalies in several exploration drill holes. A small mineralized shear zone was reported in drill hole MR 86-1, although it was not detected in the airborne magnetic survey. Because anomalous metal values and at least one minor mineralized structure are present, Tract IV is thought to have moderate potential for the occurrence of lode-gold deposits.

Tract V, along the Vermilion and Silver Lake faults near the southern boundary of the study area, contains highly deformed metavolcanic and metasedimentary rocks

Table 9. Diagnostic criteria for Algoma-type iron-formation.

Diagnostic criteria
1. Presence of permissive iron-rich strata
2. Presence of volcanosedimentary rocks
3. Presence of magnetite-rich strata with high aeromagnetic anomalies (>1000 gammas)

Table 10. Resource potential for Algoma-type iron-formation in the U.S. part International Falls 1°×2° quadrangle.

Tract No.	Diagnostic criteria[1] 1	2	3	Sum
I	0	1	-1	0
II	-1	-1	-1	-3
III	1	1	1	3
IV	-1	1	1	1
V	1	1	0	2
VI	0	0	0	0
VII	0	1	-1	0

[1]Frequency distribution of tract scores and resource potential:

Class	No.	Resource potential
-3	1	none
-2	0	none
-1	0	none
0	3	low
1	1	moderate
2	1	moderate
3	1	high

(Boerboom and others, 1989) as interpreted from drill core. In several locations, hydrothermal alteration minerals such as calcite, adularia, and quartz occur in veins. Calcite and adularia generally occur in tensional veins emplaced in brittle fractures, whereas both deformed and undeformed quartz veins are present in several drill cores. Anomalous gold values were not reported from this area, but one drill core contains elevated concentrations of arsenic (>1 ppm). A moderate resource potential for lode-gold mineralization has been assigned on the basis of the occurrence of the hydrothermal minerals within the highly deformed rocks along this transpressive fault system.

Metasedimentary rocks in the Quetico subprovince, exclusive of those near the shear systems, are included in Tract VI. These rocks, because of lack of past production and evidence of appropriate structural preparation, are assigned a low potential for shear-zone hosted gold deposits. However, the presence of relatively coarse gold in several overburden drill holes near Littlefork, in the west-central part of the study area (pl. 1), suggests a source in the metasedimentary rocks of the Quetico subprovince (Martin and others, 1988). To date no source has been identified. Tract VII, located along a northwest-trending splay of the Vermilion fault in metasedimentary rocks and amphibolite of the Quetico subprovince, also has low potential for gold deposits. However, the presence of a fracture system of the same age as systems that may be productive elsewhere, suggests that this tract is more favorable for gold deposits than less sheared rocks in the Quetico subprovince.

Metavolcanic rocks of the Wawa-Shebandowan subprovince in Tract VIII do not contain any known structures of the type thought to control gold mineralization.

Table 11. Diagnostic and permissive criteria for lode gold deposits.

Diagnostic criteria
1. Presence of anomalous Au and Ag abundances
2. Proximity to shear zones (<2 km) and dilatant zones
3. Evidence of appropriate hydrothermal alteration
a. Vein and (or) ribbon quartz
b. Carbonate alteration minerals
c. Potassic alteration (sericite)
d. Anomalous boron (exclusive of high abundances typical of sedimentary rocks and massive sulfide deposits)
e. Anomalous concentrations of As, Se, W, Hg, Sb, Te, Mo, Bi, Zn, and (or) Cu
f. Disseminated or vein-filling arsenopyrite or pyrite
Permissive criteria
1. Presence of chemically favorable host rock such as iron-formation and iron-rich tholeiitic basalt
2. Presence of fuchsite or scheelite

Table 12. Resource potential for lode gold deposits in the U.S. part of the International Falls 1°×2° quadrangle.

Tract No.	Diagnostic criteria[1] 1	2	3	Sum
I	0	1	1	2
II	1	1	1	3
III	1	1	1	3
IV	1	0	1	2
V	0	1	1	2
VI	1	0	0	1
VII	1	0	0	1
VIII	0	0	0	0

[1]Frequency distribution of tract scores and resource potential:

Class	No.	Resource potential
1	2	low
2	3	moderate
3	2	high

Because no geochemical or mineralogical information is available for the rocks in this tract, we were unable to evaluate its gold potential.

CHEMICAL SEDIMENT-HOSTED GOLD DEPOSITS

Low-level enrichment of gold is widespread in many volcanogenic cherts and iron-formation. However, most gold deposits that occur in chemical sedimentary rocks have been interpreted to be epigenetic rather than syngenetic. Nevertheless, we believe that deposits may exist in this environment, and accordingly, we have evaluated the lithologic units in the study area. The diagnostic criteria defined for this deposit type are given in table 13, and the resource-potential scores for ranking the eight defined tracts are summarized in table 14. The resource potential for the tracts is shown on plate 4.

The metavolcanic rocks in Tracts I, V, and VII of both the Wabigoon and Wawa-Shebandowan subprovinces characteristically contain layers of metamorphosed chemical sedimentary rocks. However, unless the chemical metasedimentary rocks are magnetic, they cannot be detected through the glacial sediments with the geophysical methods that were available for this study. Several layers and lenses of iron-formation were mapped on the basis of their magnetic signature, but gold analyses were not available to characterize them. We have assigned a moderate potential with a high degree of uncertainty to Tracts I, V, and VII.

The few layers of iron-formation known to occur in the clastic metasedimentary rocks of Tract III were included in Tract V. Because clastic metasedimentary rocks rarely contain volcanogenic chert layers and the tracts containing

Table 13. Diagnostic criteria for chemical metasedimentary rock-hosted gold deposits.

Diagnostic criteria
1. Presence of chemical metasedimentary rocks, especially if iron, sulfur, or carbonate rich
2. Precious-metal enrichment or enrichment of associated elements such as As or Te

Table 14. Resource-potential for chemical metasedimentary rock-hosted gold deposits in the U.S. part of the International Falls 1°×2° quadrangle.

	Diagnostic criteria[1]		
Tract No.	1	2	Sum
I	1	0	1
II	-1[a]	0	-1
III	0	0	0
IV	-1[b]	0	-1
V	1	0	1
VI	-1[c]	0	-1
VII	1	0	1
VIII	-1[d]	0	-1

[1]Frequency distribution of tract scores and resource potential:

Class	No.	Resource-potential
-1	4	none
0	1	low
1	4	moderate

[a]Metagraywacke; [b]felsic intrusion; [c]metaconglomerates; [d]metagraywacke and granitoids.

magnetic iron-formation in all areas were delineated in Tract V, the remainder of these Tract III rocks are assigned a low potential for the occurrence of gold in chemical metasedimentary rocks.

Tracts that contain mostly metagraywacke (II, VIII), metaconglomerates (VI), and felsic intrusions (IV) have no potential to contain this type of gold deposit.

QUETICO SUBPROVINCE

Several different single- or multi-element metal geochemical anomalies are apparent in soil samples in the northern part of the area. Some anomalies correlate with the Rainy Lake-Seine River fault or the volcanic terrane north of the fault and may reflect the presence of gold or base metal deposits. However, other anomalies detected in our study by soil sampling and in sampling of basal till, during reconnaissance glacial drift drilling by the Minnesota Department of Natural Resources (Martin and others, 1988, 1989), cannot be correlated with any known geologic or geophysical features in the Quetico subprovince. The anomalies could indicate the presence of gold mineralization, perhaps removed only a few kilometers from its source, as suggested in our assessment of lode-gold potential. Alternatively, the anomalies could reflect Ag-Co-As mineralization localized in northwest-trending fractures inferred to be of Proterozoic age (fig. 13). Lacking additional supporting evidence, the relation of the anomalies to mineralization is speculative.

The Canadian segment of the Quetico subprovince, although well exposed, has produced virtually no metallic resources. However, the metasedimentary belts have received relatively little attention during gold exploration. Pegmatite-hosted deposits containing rare earth element, Nb-Ta, Li, U, and Th occur at some places in the belt. However, we did not include the pegmatite-hosted deposits in our evaluation of the area. Recently, some exploration for Ni, Cu, and PGE in syntectonic mafic and ultramafic bodies in the Quetico subprovince has taken place in Canada, but the results were not available this assessment.

REFERENCES CITED

Alm, M.R., and Trethewey, W.D., 1970, Mining directory of Minnesota: University of Minnesota Bulletin, 250 p.

Alminas, H.V., 1984, Interpretative geochemical map of the Iron River 1°×2° quadrangle, Michigan and Wisconsin: U.S. Geological Survey Miscellaneous Investigations Series Map I–1360–N.

Andrews, A.J., Masliwec, A., Morris, W.A., Owsiacki, L., and York, D., 1986, The silver deposits of Cobalt and Gowganda, Ontario Part II, An experiment in age determinations employing radiometric and paleomagnetic measurements: Canadian Journal of Earth Sciences, v. 23, p. 1507–1518.

Arth, J.G., and Hanson, G.N., 1975, Geochemistry and the origin of the early Precambrian crust of northeastern Minnesota: Geochimica et Cosmochimica Acta, v. 39, p. 325–362.

Ashwal, L.D., Morrison, D.A., Phinney, W.C., and Wood, J., 1983, Origin of Archean anorthosites—Evidence from the Bad Vermilion Lake anorthosite complex, Ontario: Contributions to Mineralogy and Petrology, v. 82, p. 259–273.

Ayres, L.D., Thurston, P.C., Card, K.D., and Weber, W., 1985, Archean supracrustal sequences; An introduction and perspective, *in* Ayres, L.D. and others, eds., Evolution of Archean supracrustal sequences: Geological Association of Canada Special Paper 28, p. 1–7.

Bauer, R.L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: Geology, v. 13, p. 657–660.

———1986, Multiple folding and pluton emplacement in Archean migmatites of the southern Vermilion Granitic Complex, northeastern Minnesota: Canadian Journal of Science, v. 23, p. 1753–1764.

Beard, R.C., and Garratt, G.L., 1976, Gold deposits of the Kenora-Fort Frances area, Districts of Kenora and Rainy River: Ontario Division of Mines Mineral Deposits Circular 16, 46 p.

Bhattacharyya, B.K., Sweeney, R.E., and Godson, R.H., 1979, Integration of aeromagnetic data acquired at different times with varying elevation and line spacing: Geophysics, v. 44, no. 4, p. 742–757.

Blackburn, C.E., Hailstone, M.R., Parker, J., and Storey, C.C., 1988, Kenora resident geologist's area-1987, *in* Kustra, C.R., ed., Report of Activities 1987, Resident Geologists: Ontario Geological Survey Miscellaneous Paper 138, p. 3–40.

Boerboom, T.J., Jirsa, M.A., Southwick, D.L., Meints, J.P., and Campbell, F.K., 1989, Scientific core drilling in parts of Koochiching, Itasca, and Beltrami Counties, north-central Minnesota, 1987-1989—Summary of lithologic, geochemical, and geophysical results: Minnesota Geological Survey Information Circular 26, 159 p.

Boyle, R.W., 1968, The geochemistry of silver and its deposits: Geological Survey of Canada Bulletin 160, 264 p.

Bracken, R.E., 1991, Description of magnetic tapes containing gridded aeromagnetic anomaly data from north-central Minnesota: USGS-EROS Data Center, Sioux Falls, South Dakota, Data release serial no. D91–0597.

Bracken, R.E., and Godson, R.H., 1987, Aeromagnetic map of the International Falls 1°×2° quadrangle, Minnesota and Ontario: U.S. Geological Survey Open-File Report 87–620, scale 1:250,000.

Bracken, R.E., and Petrafeso, F., 1991, Description of magnetic tapes containing north-central Minnesota aeromagnetic flight line data: USGS-EROS Data Center, Sioux Falls, South Dakota, Data release serial no. D91-0439.

Briggs, I.C., 1974, Machine contouring using minimum curvature: Geophysics, v. 39, no. 1, p. 39–48.

Burk, R., Hodgson, C.J., and Quartermain, R.A., 1986, The geological setting of the Teck-Corona Au-Mo-Ba deposit, Hemlo, Ontario, Canada, *in* Macdonald, A.J., ed., Proceedings of Gold '86, an International Symposium on the Geology of Gold, Toronto, 1986: p. 311–326.

Card, K.D., 1990, A review of the Superior Province of the Canadian Shield: Precambrian Research, v. 48, p. 99–156.

Card, K.D., Poulsen, K.H., and Robert, F., 1989, The Archean Superior Province of the Canadian Shield and its lode gold deposits, *in* Keays, R.R., and others, eds., The geology of gold deposits, The perspective in 1988: Economic Geology Monograph 6, p. 19–36.

Case, J.E., Day, W.C., Chuchel, B.A., and Bracken, R.E., 1992, Interpretation of the magnetic anomaly map of the International Falls quadrangle, Minnesota and Ontario: U.S. Geological Survey Open-File Report 92–373, 97 p.

Chambers, J.M., Cleveland, W.S., Kleiner, B., and Tukey, P.A., 1983, Graphical methods for data analysis: Pacific Grove, Calif., Wadsworth and Brooks/Cole Publishing, 395 p.

Chandler, V.W., 1983, Aeromagnetic map of Minnesota, St. Louis County: Minnesota Geological Survey Aeromagnetic Map Series Map A, 2 maps, scale 1:250,000.

Chandler, V.W., and Horton, R.J., 1988, Complete Bouguer gravity anomaly map of the International Falls 1°×2° quadrangle, Minnesota and Ontario: U.S. Geological Survey Open-File Report 88–265.

Chandler, V.W., Jirsa, M.A., and Ikola, R.J., 1985, Simple Bouguer gravity map of Minnesota, Hibbing sheet: Minnesota Geological Survey Miscellaneous Map Series Map M–56, scale 1:250,000.

Chandler, V.W., Mills, S.J., and Ferderer, R.J., 1987, Simple Bouguer gravity map of Minnesota, International Falls sheet: Minnesota Geological Survey Miscellaneous Map Series Map M–62, scale 1:250,000.

Chao, T.T., 1984, Use of partial dissolution techniques in geochemical exploration: Journal of Geochemical Exploration, v. 20, p. 101–135.

Clark, J.R., Meier, A.L., and Riddle, G., 1990, Enzyme leaching of surficial geochemical samples for detecting hydromorphic trace-element anomalies associated with precious-metal mineralized bedrock buried beneath glacial overburden in northern Minnesota, *in* Gold '90: Society of Mining Engineers, Chapt. 19, p. 189–207.

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, A.J., Lavigne, M.J., Macdonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.S., and Troop, D.G., 1984, An integrated model of the origin of Archean lode gold deposits: Ontario Geological Survey Open File Report 5524, 99 p.

Colvine, A.C., Fyon, J.A., Heather, K.B., Marmont, S., Smith, P.M., and Troop, G.G., 1988, Archean lode gold deposits in Ontario: Ontario Geological Survey Miscellaneous Paper 139, 136 p.

Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Davis, D.W., and Edwards, G.R., 1986, Crustal evolution of Archean rocks in the Kakagi Lake area, Wabigoon subprovince, Ontario, as interpreted from high-precision U-Pb geochronology: Canadian Journal of Earth Science, v. 23, p. 182–192.

Davis, D.W., and Jackson, M.C., 1988, Geochronology of the Lumby Lake greenstone belt—A 3 Ga complex within the Wabigoon subprovince, northwest Ontario: Geological Society of America Bulletin, v. 100, p. 818–824.

Davis, D.W., Poulsen, K.H., and Kamo, S.L., 1989, New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada: Journal of Geology, v. 97, p. 379–398.

Davis, D.W., and Sutcliffe, R.H., 1985, U–Pb zircon ages from the Nipigon Plate and northern Lake Superior: Geological Society of America Bulletin, v. 96, p. 1572–1579.

Day, W.C., 1987, The nature of the Wabigoon-Quetico subprovincial boundary in northern Minnesota: Abstracts with Programs, 21st Annual Meeting, North-Central Section, Geological Society of America, v. 19, no. 4, p. 195.

———1990a, Petrology of the Rainy Lake area, USA–Implications for petrotectonic setting of the Archean southern Wabigoon subprovince of the Canadian Shield: Contributions to Mineralogy and Petrology, v. 105, p. 303–321.

———1990b, Bedrock geologic map of the Rainy Lake area, northern Minnesota: U.S. Geological Survey Miscellaneous Investigations Series Map I–1927, 1 sheet, scale 1:50,000.

Day, W.C., Klein, T.L., Horton, R.J., Clark, J.R., Carlson, R.R., and Smith, B.D., 1992, Geology, geophysics, soil geochemistry, and mineral resource assessment for the Red Lake Indian Reservation, northern Minnesota: U.S. Geological Survey Administrative Report BIA–2–93I, 10 plates, 220 p.

Day, W.C., Klein, T.L., and Schulz, K.J., 1990a, Preliminary bedrock geologic map of the Roseau $1° \times 2°$ quadrangle, Minnesota, USA, and Ontario Canada: U.S. Geological Survey Open-File Report 90–0544B, scale 1:250,000.

Day, W.C., Southwick, D.L., Schulz, K.J., and Klein, T.L., 1990b, Bedrock geologic map of the International Falls $1° \times 2°$ degree sheet, Minnesota, USA and Ontario, Canada: U.S. Geological Survey Miscellaneous Investigations Series Map I–1965B, scale 1:250,000.

Day, W.C., and Weiblen, P.W., 1986, Origin of late Archean granite—geochemical evidence from the Vermilion Granitic Complex of northern Minnesota: Contributions to Mineralogy and Petrology, v. 94, p. 283–296.

Defense Mapping Agency, 1974, World Relative Gravity Reference Network, North America, Part 2: St. Louis, Missouri, Aerospace Center, DMAAC Reference Publication 25, with supplement updating gravity values to the International Gravity Standardization Net 1971, 1635 p.

Eckstrand, O.R., ed., 1984, Canadian mineral deposit types—A geologic synopsis: Geological Survey of Canada Economic Geology Report 36, 86 p.

Eng, M.T., 1980, Surficial geology, Koochiching County, Minnesota, Minnesota peat inventory project: Minnesota Department of Natural Resources, Division of Minerals, map.

Ferguson, S.A., Groen, H.A., and Haynes, R., 1971, Gold deposits of Ontario: Ontario Division of Mines Mineral Resources Circular 13, 315 p.

Fletcher, G.L., and Irvine, T.N., 1954, Geology of the Emo area: Ontario Department of Mines Annual Report, v. 63, part 5, 36 p.

Franklin, J.M., 1990, Volcanic-associated massive sulphide deposits, *in* Ho, S.E., and others, compilers, Gold and base-metal mineralization in the Abitibi subprovince, Canada, with emphasis on the Quebec segment: University of Western Australia Publication 24, p. 211–242.

Franklin, J.M., Kissin, S.A., Smyk, M.C., and Scott, S.D., 1986, Silver deposits associated with the Proterozoic rocks of the Thunder Bay district, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 1576–1591.

Franklin, J.M., Lydon, J.W., and Sangster, D.F., 1981, Massive sulfide deposits, *in* Skinner, B.J., ed., Economic Geology Seventy-Fifth Anniversary Volume: p. 485-627.

Franklin, J.M., and Thorpe, R.I., 1982, Comparative metallogeny of the Superior, Slave and Churchill Provinces, *in* R.W. Hutchinson and others, eds., H.S. Robinson memorial volume, Precambrian sulfide deposits: Geological Association of Canada Special Paper 25, p. 3–90.

Friesen, R.G., Pierce, G.A., and Weeks R.M., 1982, Geology of the Geco base metal deposit, *in* Hutchinson, R.W., and others, eds., Precambrian sulphide deposits, H.S. Robinson memorial volume: Geological Association of Canada Special Paper 25, p. 343–363.

Geological Survey of Canada, 1981, Lake of the Woods: Energy, Mines and Resources of Canada, Geophysics Division, Manuscript Map 48090 for Gravity Map of Canada 1980, scale 1:1,000,000.

Godson, R.H., and Webring, M.W., 1982, Contour—A modification of G.I. Evendon's general purpose computer contouring program: U.S. Geological Survey Open-File Report 82–797, 73 p.

Goldich, S.S., Lidiak, E.G., Hedge, C.E., and Walthall, F.G., 1966, Geochronology of the midcontinent region, United States, Part 2, northern area: Journal of Geophysical Research, v. 71, p. 5389–5408.

Goldich, S.S., and Peterman, Z.E., 1980, Geology and geochemistry of the Rainy Lake area: Precambrian Research, v. 11, p. 307–327.

Goudarzi, G.H., 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84–787, 51 p.

Gross, G.A., 1965, Geology of iron deposits in Canada: Geological Survey of Canada Economic Geology Report 22, 181 p.

Groves, D.I., Barley, M.E., and Ho, S.E., 1989, Nature, genesis, and tectonic setting of mesothermal gold mineralization in the Yilgarn Block, Western Australia, *in* Keays, R.R., and others, eds., The geology of gold deposits, the perspective in 1988: Economic Geology Monograph 6, p. 71–85.

Hodgson, C.J., 1989, The structure of shear-related, vein-type gold deposits—A review: Ore Geology Reviews, v. 4, p. 231–273.

Hodgson, C.J., and MacGeehan, P.J., 1980, A review of the geological characteristics of "gold only" deposits in the Superior Province of the Canadian shield, *in* Hodder, R.W., and W. Petruk, eds., Geology of Canadian gold deposits: The Canadian Institute of Mining and Metallurgy Special Volume 24, p. 211–229.

Horton, R.J., 1987, Gravity survey data of the International Falls CUSMAP area: U.S. Geological Survey Open-File Report 87–327, 52 p.

Horton, R.J., and Kucks, R.P., 1988, Gravity survey data for the International Falls and Roseau $1° \times 2°$ quadrangles and surrounding area, Minnesota and Ontario: U.S. Geological Survey Open-File Report 88–513, 27 p.

Horton, R.J., Meyer, G.N., and Bajc, A.J., 1989, Reconnaissance Quaternary geology map of the International Falls $1° \times 2°$ quadrangle: U.S. Geological Survey Open-File Report 89–654, scale 1:250,000.

Hudleston, P.J., 1976, Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 13, p. 579–592.

Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota: Canadian Journal of Earth Sciences, v. 25, p. 1060–1068.

Hutchinson, R.W., and Burlington, J.L., 1984, Some broad characteristics of greenstone belt gold lodes, *in* Foster, R.P., ed., Gold '82: Geological Society of Zimbabwe Special Publication 1, p. 339–372.

International Association of Geodesy, 1967, Systeme geodesique de reference 1967: International Geodesy Special Publication 3, 115 p.

Jirsa, M. A., and Boerboom, T.J., 1990, Bedrock geologic map of parts of Koochiching, Itasca, and Beltrami Counties, north-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M–67, scale 1:250,000.

Johnson, W.A., 1915, Rainy River District, Ontario, Surficial geology and soils: Geological Survey of Canada Memoir 82, 123 p.

Jolliffe, A.W., 1966, Stratigraphy of the Steeprock Group, Steep Rock Lake, Ontario, *in* Goodwin, A.M., ed., Precambrian Symposium on the relationship of mineralization to precambrian stratigraphy in certain mining areas of Ontario and Quebec: Geological Association of Canada Special Paper 3, p. 68–75.

Kerrich, R., 1983, Geochemistry of gold deposits in the Abitibi greenstone belt: Canadian Institute of Mining and Metallurgy Special Volume 27, 75 p.

Klein, T.L., 1988, Tabulated geochemistry of bedrock samples from exploration drilling in the Roseau and the western part of the International Falls 1°×2° quadrangles, northern Minnesota: U.S. Geological Survey Open-File Report 88–525, 91 p.

———1989, Mineral occurrence and drill-hole location map of the International Falls 1°×2° quadrangle, Minnesota and Ontario: U.S. Geological Survey Miscellaneous Field Studies Map MF–2082, scale 1:250,000.

———1991, Lithologic descriptions of bedrock core from the Roseau 1°×2° quadrangle, northern Minnesota: U.S. Geological Survey Open-File Report 91-35, 10 p.

Klein, T.L., Brown, F., Jackson, J.C., Taggart, J.E., Ardith, J., Bartel, J., Stewart, K., Palmer, C., Wandless, G., Crock, J., Wilson, S., Brown, Z., Skeen, C., Crandell, W., Moore, R., Rait, N., Smith, H., Bauer, R., Steineck, R., and Day, W., 1987, Geochemical data from the International Falls and Roseau, Minnesota CUSMAP projects: U.S. Geological Survey Open-File Report 87–366, 98 p.

Klein, T.L., and Day, W.C., 1989, Tabular summary of lithologic logs and geologic characteristics from diamond drill holes in the western International Falls and the Roseau 1°×2° quadrangles, northern Minnesota: U.S. Geological Survey Open-File Report 89–346, 42 p.

Kuhns, R.J., 1986, Alteration styles and trace element dispersion associated with the Golden Giant deposit, *in* Macdonald, A.J., ed., Proceedings of Gold '86, An international symposium on the geology of gold, Toronto, 1986: Hemlo, Ontario, Canada, p. 340–354.

Kuhns, R.J., Kennedy, P., Cooper, P., Brown, P., Mackie, R., Kusins, R., and Friesen, R., 1986, Geology and mineralization associated with the Golden Giant deposit, Hemlo, Ontario, Canada, *in* Macdonald, A.J., ed., Proceedings of Gold '86, An international symposium on the geology of gold, Toronto, 1986: p. 327–339.

Lawson, A.C., 1913, The Archean geology of Rainy Lake re-studied: Canadian Geological Survey Memoir 40, 115 p.

Listerud, W.H., 1976, Sulfides in the Birchdale-Indus area, Koochiching County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals, Minerals Exploration Section, Report 26, p. 21.

Lydon, J.W., 1984a, Volcanogenic massive sulphide deposits Part 1, A descriptive model, *in* Roberts, R.G. and Sheahan, P.A., eds., Ore deposit models: Geoscience Canada Reprint Series 3, p. 145–153.

———1984b, Volcanogenic massive sulphide deposits Part 2, genetic models, *in* Roberts, R.G. and Sheahan, P.A., eds., Ore deposit models, Geoscience Canada Reprint Series 3, p. 155–181.

Macdonald, A.J., 1983, The iron formation-gold association evidence from Geraldton area, *in* Colvine, A.C., ed., The geology of gold in Ontario: Ontario Geological Survey Miscellaneous Paper 110, p. 75–83.

Martin, D.P., Meyer, G.N., Cartwright, D.F., Lawler, T.L., Pastika, T., Jirsa, M.A., Boerboom, T.J., and Streitz, A.R., 1989, Regional geochemical survey of glacial drift samples over Archean terrane in the Effie area, northern Minnesota: Minnesota Department of Natural Resources, Division of Minerals, Report 263, 382 p.

Martin, D.P., Meyer, G.N., Lawler, T.L., Chandler, V.W., and Malmquist, K.L., 1988, Regional survey of buried glacial drift geochemistry over Archean terrane in northern, Minnesota: Minnesota Department of Natural Resources, Minerals Division, Report 252, Part I, 74 p., Part II, 386 p.

McGinnis, L., Durfee, G., and Ikola, R.J., 1973, Simple Bouguer gravity map of Minnesota, Roseau Sheet: Minnesota Geological Survey Miscellaneous Map Series Map M–12, scale 1:250,000.

Miller, J.K., 1984, Model for clastic indicator trains in till, *in* Prospecting in areas of glaciated terrain 1984: London, Institute of Mining and Metallurgy, p. 69–77.

Morelli, Carlo, ed., 1974, The international gravity standardization net, 1971: International Association of Geodesy Special Publication 4, 194 p.

Morton, P., 1979, Volcanic stratigraphy in the Shebandowan Ni-Cu mine area, Ontario: Geological Survey of Canada Paper 79–1b, p. 39–43.

Morton, R.L., and Franklin, J.M., 1987, Two-fold classification of Archean volcanic-associated massive sulfide deposits: Economic Geology, v. 82, p. 1057–1063.

Morton, R.L., Hudak, G.J., Walker, J.S., and Franklin, J.M., 1990, Physical volcanology and hydrothermal alteration of the Sturgeon Lake caldera complex, *in* Franklin, J.M., and others, eds., Mineral deposits in the western Superior Province (Field Trip 9), 8th IAGOD Symposium field trip guidebook: Geological Survey of Canada Open File Report 2164, p. 74–94.

Ojakangas, R.W., 1972, Rainy Lake area, *in* Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 163–171.

Ojakangas, R.W., Meineke, D.G., and Listerud, W.H., 1977, Geology, sulfide mineralization and geochemistry of the Birchdale-Indus area, Koochiching County, northwestern Minnsnesota: Minnesota Geological Survey Report of Investigations 17, 78 p.

Ojakangas, R.W., and Olson, J.M., 1982, Sedimentation and petrology of Archean feldspathic quartzite and conglomerate (Seine Series equivalent), Rainy Lake, Minnesota, 28th Annual Institute on Lake Superior Geology, International Falls, Minnesota: Minnesota Geological Survey, p. 36–37.

Percival, J.A., Stern, R.A., and Digel, M.R., 1985, Regional geological synthesis of western Superior Province, Ontario, *in* Current Research, Part A: Geology of Canada, Geological Survey of Canada Paper 85-1A, p. 385–397.

Peterman, Z.E., and Day, W.C., 1989, Early Proterozoic activity on Archean faults in the western Superior province—evidence from pseudotachylite: Geology, v. 17, p. 1089–1092.

Philips, G.N., and Groves, D.I., 1984, Fluid access and fluid-wall-rock reactions in the genesis of the Archean gold-quartz-vein deposit at the Hunt mine, Kambalda, Western Australia, *in* Foster, R.P., ed., Gold '82—The geology, geochemistry, and genesis of gold deposits: Geological Society of Zimbabwe Special Publication 1, p. 389–416.

Plouff, Donald, 1977, Preliminary documentation for a FORTRAN program to compute gravity terrain corrections based on topography digitized on a geographic grid: U.S. Geological Survey Open-File Report 77-535, 43 p.

Poulsen, K.H., 1983, Structural setting of vein-type gold mineralization in the Mine Centre-Fort Frances area: Implications for the Wabigoon subprovince, *in* A.C. Colvine, ed., The geology of gold in Ontario: Ontario Geological Survey Miscellaneous Paper 110, p. 174–180.

———1984, The geological setting of mineralization in the Mine Centre-Fort Frances area, District of Rainy River: Ontario Geological Survey Open-File Report 5512, 126 p.

Poulsen, K.H., Borradaile, G.J., and Kehlenbeck, M.M., 1980, An inverted Archean succession at Rainy Lake, Ontario: Canadian Journal of Earth Sciences, v. 17, p. 1358–1369.

Poulsen, K.H., and Robert, F., 1988, A comparison of structural style and endowment of three Archean gold districts, Superior Province, Canada, Bicentennial Gold '88: Geological Society of Australia Abstracts 23, p. 36–38.

Riddle, G.D., Meier, A.L., Motooka, J.M., Erlich, O., Clark, J.R., Saunders, J.A., Fey, D.L., and Sparks, T., 1992, Analytical results and sample locality maps of soil samples from the International Falls and Roseau 1° × 2° quadrangles, Minnesota/Ontario: U.S. Geological Survey Open-File Report 92–721.

Roberts, R.G., 1987, Archean lode gold deposits: Geoscience Canada, v. 14, p. 37–52.

Rose, E.R., 1969, Geology of titanium and titaniferous deposits of Canada: Geological Survey of Canada Economic Geology Report 25, 171 p.

Sangster, D.F., 1972, Precambrian volcanogenic massive sulphide deposits in Canada—A review: Geological Survey of Canada Paper 72–22, 44 p.

Schlanka, R., 1972, Geology of the Steep Rock Lake area, district of Rainy River: Ontario Department of Mines and Northern Affairs Geological Report 93, p. 1–84.

Schnieders, B.R. and Dutka, R.J., 1985, Property visits and reports of the Atikoken economic geologist, 1979–1983: Atikoken Geological Survey, Ontario Geological Survey Open-File Report 5539.

Schulz, K.J., 1980, The magmatic evolution of the Vermilion greenstone belt, northeastern Minnesota: Precambrian Research, v. 11, p. 215–245.

Scott, S.D., 1978, Structural control of the Kuroko deposits of the Hokuroku district, Japan: Mining Geology, v. 28, p. 301–311.

Sellner, J.M., Lawler, T.A., Dahlberg, E.H., Frey, B.A., and McKenna, M.P., 1985, 1984-1985 geodrilling report: Minnesota Department of Natural Resources Division of Minerals Report 242, 75 p.

Severin, P.W.A., Balint, F., and Sim, R., 1990, Geological setting of the Winston Lake massive sulphide deposit, *in* Franklin, J.M., and others, eds., Mineral deposits in the western Superior Province (Field Trip 9), 8th IAGOD Symposium field trip guidebook: Geological Survey of Canada Open File Report 2164, p. 58–73.

Shawe, D.R., 1981, U.S. Geological Survey workshop on nonfuel mineral-resource appraisal of Wilderness and CUSMAP areas: U.S. Geological Survey Circular 845, 18 p.

Shirey, S.B., 1984, The origin of Archean crust in the Rainy Lake area, Ontario: State University of New York at Stony Brook, Ph.D. dissertation, 330 p.

Shirey, S.B., and Hanson, G.N., 1984, Mantle-derived Archean monzodiorites and trachyandesites: Nature, v. 310, p. 222–224.

Sibson, R.H., 1989, Structure and mechanics of faults zones in relation to fault-hosted mineralization, Adelaide, Australian Mineral Foundation, Course Book, 64 p.

Sibson, R.H., Robert, F., and Poulsen, K.H., 1988, High angle reverse faults, fluid pressure cycling, and mesothermal gold-quartz deposits: Geology, v. 16, p. 551–555.

Sims, P.K., 1972a, Mineral deposits in Lower Precambrian rocks, northern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 172–176.

———1972b, Vermilion district and adjacent areas, *in*, Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 49–62.

———1976, Early Precambrian tectonic-igneous evolution in the Vermilion district, northeastern Minnesota: Geological Society of America Bulletin, v. 87, p. 376–389.

Sims, P.K., and Viswanathan, S., 1972, Giants range batholith, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 120–139.

Sinclair, A.J., 1976, Applications of probability graphs in mineral exploration: Association of Exploration Geochemists Special Volume 4, 95 p.

Skillings Mining Review, 1993, North American palladium now starting up its Lac des Illes mine after lengthy delay: Skillings Mining Review, September 11, 1993, p. 4–6.

Smyk, M.C., Schnieders, B.R., and Muir, T.L., 1990, Field guide to the Hemlo area, *in* Franklin, J.M., and others, eds., Mineral deposits in the western Superior Province (Field Trip 9), 8th IAGOD Symposium field trip guidebook: Geological Survey of Canada Open-File Report 2164, p. 26–38.

Southwick, D.L., 1972, Vermilion granite-migmatite massif, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 108–119.

———1978, The Vermilion Granitic Complex, northern Minnesota, *in* Smith, I.E.M., and Williams, J.G., eds., Proceedins of the 1978 Archean Geochemistry Conference: p. 265–276.

Southwick, D.L., and Day, W.C., 1983, Geology and petrology of Proterozoic mafic dikes, north-central Minnesota: Canadian Journal of Earth Sciences, v. 20, no. 4, p. 22–638.

Southwick, D.L., and Ojakangas, R.W., 1979, Geologic map of Minnesota, International Falls sheet: Minnesota Geological Survey, scale 1:250,000.

Stanley, C.R., 1987, Probplot: Association of Exploration Geochemists Special Volume 14, disk.

Stott, G.M., and Schnieders, B.R., 1983, Gold mineralization in the Shebandowan belt and its relation to regional deformation patterns, *in* Colvine, A.C., ed., Geology of gold in Ontario: Ontario Geological Survey Miscellaneous Paper 110, p. 181–193.

Sutcliffe, R.H., Sweeney, J.M., and Edgar, A.D., 1989, The Lac des Illes Complex, Ontario: Petrology and platinum-group-elements mineralization in an Archean mafic intrusion: Canadian Journal of Earth Science v. 26, p. 1408–1427.

U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of resource/reserve classification for minerals: U.S. Geological Survey Circular 831, 5 p.

Valiant, R.I., and Bradbrook, C.J., 1986, Relationship between stratigraphy, faults and gold deposits, Page-Williams mine, Hemlo, Ontario, Canada, *in* Macdonald, A.J., ed., Proceedings of Gold '86, and International Symposium on the Geology of Gold, Toronto, 1986: Gold '86, Toronto, p. 362 –378.

Valiant, R.I., Mongeau, C. and Doucet, R., 1982, The Bousquet pyritic gold deposit, Bousquet Region, Quebec, Descriptive geology and preliminary interpretations on genesis, *in* Hodder, R.J., and Petruk, W., eds., Geology of Canadian gold deposits: Canadian Institute of Mining and Metallurgy Special Volume 24, p. 41–45.

Walford, P., Stephens, J., Skrecky, G., and Barnett, R., 1986, The geology of the 'A' zone, Page-Williams mine, Hemlo, Ontario, Canada, *in* Macdonald, A.J., ed., Proceedings of Gold '86, and International Symposium on the Geology of Gold, Toronto, 1986: Gold '86, Toronto, p. 362–378.

Webring, M.W., 1981, Minc—A gridding program based on minimum curvature: U.S. Geological Survey Open-File Report 81–1224, 41 p.

Wilkinson, S.J., 1980, Gold deposits of the Atikokan area, District of Rainy River and Kenora: Ontario Geological Survey Open-File Report 5307, 125 p.

———1982, Gold deposits of the Atikoken area: Ontario Geological Survey Mineral Deposits Circular 24, 54 p.

Wilks, M.E., and Nisbet, E.G., 1988, Stratigraphy of the Steep Rock Group, northwest Ontario—A major Archaean unconformity and Archaean stromatolites: Canadian Journal of Earth Science, v. 25, p. 370–391.

Williams, H.R., Breaks, F.W., Schnieders, B.R., Smyk, M.C., Charlton, S.G., and Lockwood, H.C., 1990, Field guide to the Manitowage Area, *in* Franklin, J.M., and others, eds., Mineral deposits in the western Superior Province (Field Trip 9), 8th IAGOD Symposium field trip guidebook: Geological Survey of Canada Open-File Report 2164, p. 7–24.

Winchell, H.V., and Grant, U.S., 1895, Preliminary report on the Rainy Lake gold region: Minnesota Geological Survey and Natural History Survey 23rd Annual Report, p. 36–105.

Wood, J., 1980, Epiclastic sedimentation and stratigraphy in the North Spirit Lake and Rainy Lake areas: Precambrian Research, v. 12, p. 227–255.

Wright, H.E., 1972, Physiography of Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume in honor of George M. Schwartz: Minnesota Geological Survey, p. 561–578.

Zoltai, S.C., 1961, Glacial history of part of northwest Ontario: Proceedings of the Geological Association of Canada, v 13, p. 61–83.

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APPENDICES

APPENDIX 1

Relationship between levels of resource potential and certainty (modified from Goudarzi, 1984).

Definitions of Mineral Resource Potential

LOW mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is unlikely. This broad category embraces areas with dispersed but insignificantly mineralized rock as well as areas with few or no indications of having been mineralized.

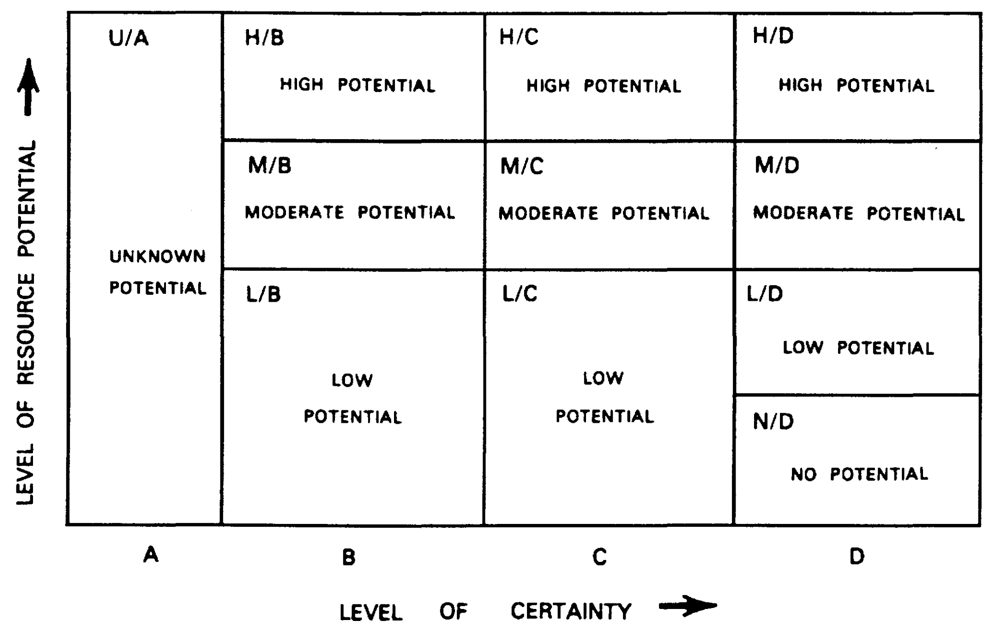
MODERATE mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a reasonable likelihood of resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

HIGH mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data support mineral-deposit models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential to an area requires some positive knowledge that mineral-forming processes have been active in at least part of the area.

UNKNOWN mineral resource potential is assigned to areas where information is inadequate to assign low, moderate, or high levels of resource potential.

NO mineral resource potential is a category reserved for a specific type of resource in a well-defined area.

Levels of Certainty



A. Available information is not adequate for determination of the level of mineral resource potential.
B. Available information suggests the level of mineral resource potential.
C. Available information gives a good indication of the level of mineral resource potential.
D. Available information clearly defines the level of mineral resource potential.

Abstracted with minor modifications from:

Taylor, R. B., and Steven, T. A., 1983, Definition of mineral resource potential: Economic Geology, v. 78, no. 6, p. 1268–1270.

Taylor, R. B., Stoneman, R. J., and Marsh, S. P., 1984, An assessment of the mineral resource potential of the San Isabel National Forest, south-central Colorado: U.S. Geological Survey Bulletin 1638, p. 40–42.

Goudarzi, G. H., compiler, 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84–0787, p. 7, 8.

APPENDIX 2

Models for deposit types that may occur in the International Falls 1°×2° quadrangle, Minnesota and Canada. These models are based largely on those presented in Eckstrand (1984), supplemented with information from Cox and Singer (1986) and more recent genetic studies

ARCHEAN LODE GOLD DEPOSITS

HOST OR MINERALIZED ROCKS

Dominantly metamorphosed, highly altered, tholeiitic basalts, komatiites or their volcaniclastic equivalents; also graywacke and conglomerate or intrusive rocks. Intrusive host rocks commonly consist of (1) tonalite-granodiorite-quartz monzonite stocks, plugs, and dikes; (2) Syenitic intrusions and surrounding metavolcanic and metasedimentary rocks; (3) Subvolcanic mafic intrusions. Deposits that contain both disseminated and fracture-controlled mineralization and may be "porphyry gold" deposits (Franklin and Thorpe, 1982).

COMMODITIES

Au (Ag)

DEPOSIT FORM, SIZE, AND DISTRIBUTION OF ORE MINERALS

Persistent or discontinuous veins and irregular bodies of gold-bearing quartz are found along fractures and faults, or as replacement deposits in altered and (or) highly deformed rock. Gold is associated with disseminated sulfide minerals that are controlled by minor fractures, are in small irregular patches in quartz, or in the wallrock immediately adjacent to the vein. Crack-seal vein textures are common. Veins are generally less than 10 m thick and have strike lengths of less than 100 m. Some mineralized districts (for example, the Kirkland Lake district, Ont.) may have a strike length of as much as 5 km, and a width of 500 m, and vertical continuity of at least 2 km.

ORE MINERALS

Principal:

Native gold, or gold in pyrite, arsenopyrite, and galena; Au-Ag tellurides.

Associated:

Pyrite, arsenopyrite, and pyrrhotite; minor amounts of galena, sphalerite, chalcopyrite, molybdenite, stibnite, and scheelite (common in deposits associated with quartz-phyric felsic rocks).

ALTERATION

Quartz veins surrounded by silicification, carbonate (Ca-, Mg-, or Fe-) haloes, chlorite, minor sericite, tourmaline (especially where associated with epizonal felsic intrusions), and albite. Broad zones of silicification rather than discrete quartz veins are typical of replacement deposits. Fuchsite is present in some deposits where mafic and ultramafic rocks are hosts.

ASSOCIATED ROCKS

Volcaniclastic rocks, graywacke, and conglomerate of predominantly greenstone belt provenance; less commonly iron-formation and other chemical sedimentary rocks, felsic porphyritic intrusive bodies, and mafic or ultramafic intrusive rocks.

Less commonly alkalic volcanic rocks and locally derived sedimentary rocks; ultramafic volcanic and intrusive rocks, mafic volcanic rocks and graywacke.

AGE, HOST ROCKS

Archean, although there are Mesozoic analogs, such as, Carolin and Bralorne, B.C., and Motherlode, Calif.

AGE, ORE

Archean. Usually not significantly younger than the last period of deformation and pluton emplacement although they are not necessarily coeval with the spatially associated intrusions.

GEOLOGIC SETTING

Most are found in Archean greenstone belts or their associated intrusions along highly deformed, steeply dipping shear zones. Most of these major structural discontinuities are near the contact between major sedimentary and volcanic rock sequences, subparallel to stratigraphy, continuous, or anastomosing over distances of greater than 30 km, and are as much as 2 km wide.

Discrete veins as much as tens of meters wide occur in deformation zones in greenschist metamorphic domains where brittle or brittle-ductile fracturing is dominant. However, disseminated mineralization in broad zones (as wide as hundreds of meters) is present in higher-grade metamorphic domains or in rocks that have a high phyllosilicate content, where ductile deformation does not favor the propagation of brittle fractures.

A high degree of structural complexity is caused by local contrasts in structural properties of host rocks. The development of conjugate shears during continuing transpressive deformation produces variable and complex vein geometries.

Deposits may be spatially associated with plutonic bodies because of their structural properties rather than because of a direct genetic relationship to magmatism.

GENETIC MODEL

Four origins for the gold-bearing hydrothermal fluids have been suggested. They may be derived from the following:

1. Devolatilization of underlying greenstones, where the metamorphic conditions change from greenschist to amphibolite grade and are focused along major deeply penetrating fractures (Kerrich,1983; Philips and Groves, 1984).
2. Degassing of the lower crust or upper mantle along deeply penetrating structures (Colvine and others, 1984).
3. Magmatic fluids.
4. Circulation of seawater by shallow convective hot spring systems (Hutchinson and Burlington, 1984).

Sources 1, 2, and 3 appear capable of generating fluids that are chemically similar to those that formed most shear zone deposits. Gold and associated elements were likely scavenged from large volumes of rocks underlying greenstone belt rocks, which were adjacent to deeply penetrating structures.

Gold is commonly deposited in dilatant fractures, faults, and shear zones in response to local physical or chemical variations (pH, pCO_2, temperature, or the activity of sulfur). Associated hydrothermal alteration commonly includes carbonatization (the CO_2 probably derived from a deep crustal or upper mantle source). Alteration is often extensive and pervasive, indicating a long-lived hydrothermal system.

A genetic relationship may exist between gold mineralization and some alkalic and subalkaline intrusions (Kirkland Lake and McIntyre). For other deposits, intrusions may simply serve as structurally and chemically favorable traps, or as a heat source for the hydrothermal systems.

ORE CONTROLS AND EXPLORATION GUIDES

1. Archean age.
2. Major shear zones are generally present within 5 km of the deposits.
3. Presence of thin komatiitic or high-Mg basalt units.
4. Molasse-type sedimentary rocks indicating fault-related basin fill.
5. Presence of silicified, carbonatized, K-enriched, pyritized zones; fuchsite may be a guide in some cases.
6. The presence of small intrusions near major structural breaks is a broadguide (Val d'Or, Kirkland Lake)

EXAMPLES

Metavolcanic and metasedimentary rock hosted deposits include Con and Giant Yellowknife mines, Northwest Territories, Canada; Dome and Pamour mines at Timmins, Campbell mine at Red Lake, and Kerr Addison mine, Ont., Canada; Norseman, Australia.

Calc-alkaline intrusive rock hosted deposits include Lamaque and Perron, Camflo, Barnat, McIntyre, Hollinger, and Renabie, Canada; Porphyry, and Charter Towers, Australia.

Syenitic intrusive rock hosted deposits include the Kirkland Lake camp and Young-Davidson, Canada.

Subvolcanic mafic intrusion host deposits such as Howey-Hasaga, Canada; Kalgoorlie Golden Mile, Australia.

GRADE AND TONNAGE

Metavolcanic and metasedimentary rock hosted deposits contain as much as 40 million metric tons averaging 8.6 g Au/t. Long-term producers of this type range from 1 to 6 million metric tons at grades of 7 g Au/t. Most of the significant mines in intrusive host rocks produced 1 to 5 million metric tons grading 7 to 17 g Au/t; the Hollinger, the largest Canadian deposit of this types has produced more than 60 million metric tons at 10 g/t. The Kirkland Lake camp has produced at least 46 million metric tons grading 15.4 g Au/t.

REFERENCES

Adapted from models of R.I. Thorpe, and J.M. Franklin, in Eckstrand (1984) and Hodgson and MacGeehan, (1980), Hodgson (1989), and Roberts (1987).

CHEMICAL SEDIMENT-HOSTED GOLD DEPOSITS

HOST OR MINERALIZED ROCKS

Carbonate-oxide iron formation.

COMMODITIES

Au (Ag, Cu)

DEPOSIT FORM, SIZE, AND DISTRIBUTION OF ORE MINERALS

Stratiform, disseminated uniformly in the host units, or irregularly or systematically distributed in structurally controlled minor quartz or quartz-carbonate veins. Commonly thickened and structurally controlled in fold hinges.

ORE MINERALS

Principal:

Native gold, Au in pyrite, Au tellurides in some deposits.

Associated:

Pyrite, arsenopyrite, pyrrhotite, magnetite, hematite.

ALTERATION

Silicification and carbonatization.

ASSOCIATED ROCKS

Mafic volcanic rocks, metasedimentary rocks including graywacke and arkose.

AGE, HOST ROCKS

Archean.

AGE, ORE

Similar to the host rocks or younger.

GEOLOGIC SETTING

In Archean greenstone belts near a major transition from volcanic to sedimentary rocks.

GENETIC MODEL

The gold may be syngenetically precipitated in chemical sediments from nearby submarine hydrothermal vents or epigentically deposited in chemically and structurally favorable sites in iron-formation.

ORE CONTROLS AND EXPLORATION GUIDES

In greenstone belts, particularly in carbonate-oxide, sulfide, or sulfide-silicate (±arsenides) rich iron-formation, which may or may not be accompanied by chert.

EXAMPLES

Geraldton and Pickle Crow districts, Ontario; Agnico-Eagle, Quebec; Lupin, Contwoyto Lake, Northwest Territories, Canada; Hill 60, Mt. Morgans, Copperhead, Western Australia; Vubachikwe, Zimbabwe.

GRADE AND TONNAGE

Grades commonly range from 6 to 17 g Au/t and size ranges from 1 to 5 million metric tons.

REFERENCES

Adapted from models by J.M. Franklin and R.I. Thorpe in Eckstrand (1984) and Macdonald (1983).

VOLCANOGENIC MASSIVE SULFIDE

(COPPER- AND ZINC-RICH)

COMMODITIES

Cu, Zn, Pb, Ag, Au, Cd, Sn, Bi, Se

FORM, SIZE, AND DISTRIBUTION OF ORE MINERALS

Typically, these deposits are pyrite-rich lenses of sulfide minerals and concordant tabular massive sulfide bodies, which may be underlain by variable thicknesses (tens to hundreds of meters) of discordant stringer sulfide ore and hydrothermally altered volcanic rocks roughly in the shape of an inverted cone. Lensoidal massive sulfide bodies may be brecciated or surrounded by a clastic apron of brecciated massive sulfide, whereas tabular concordant bodies are typically finely layered or laminated. Grain size in the massive ore, which is generally fine grained in unmetamorphosed deposits, may increase with increasing thermal metamorphism. Concentric zoning of ore and alteration minerals is commonly centered around the central stringer zone or pipe and above and outside the contact between the pipe and massive ore zones.

These deposits show the following pattern from the center outward:

chalcopyrite + pyrrhotite ±magnetite -> pyrite -> sphalerite.

Many Cu-Zn deposits have a Mg enrichment zone (generally as chlorite or talc) coinciding with the core of the stringer sulfide ore, which in turn grades outward to a more potassic alteration assemblage. Some deposits also show Fe enrichment, and most are heavily silicified in the central alteration pipe. An extensive zone of Na depletion and K enrichment usually surrounds the central alteration zone.

ORE MINERALS

Principal:

Sphalerite, chalcopyrite, galena.

Associated:

Pyrite, pyrrhotite, bornite, magnetite, sulphosalt minerals, native silver, cassiterite, tetrahedrite.

ALTERATION MINERALS

Hydrothermal silicate alteration products include quartz, chlorite, smectite, talc, epidote, andalusite, chloritoid, sericite, and iron, calcium, and magnesium carbonates. In deposits that are metamorphosed beyond the stability of chlorite, alteration minerals include cordierite, anthophyllite, biotite, kyanite, garnet, staurolite, and gahnite.

HOST OR MINERALIZED ROCKS

Deposits are commonly located in or adjacent to the uppermost, most highly fractionated part of tholeiitic or calc-alkaline volcanic cycles in clusters around felsic volcanic edifices. The footwall rocks are nearly always dominantly mafic volcanic rocks or sedimentary rocks derived from them.

ASSOCIATED ROCKS

Host rocks commonly include rhyolite domes and flows and their feeder dikes; felsic explosion breccias; volcanic-derived sedimentary rocks, including debris flows and graywacke; chemical sedimentary rocks including sulfidic chert, iron oxide, manganese oxide, and carbonaceous mudstones and shales. Many Cu-Zn deposits overlie shallow-level porphyritic, trondjhemitic or quartz dioritic sills that are similar in age and composition to the host volcanic rocks. The underlying and, to some extent the overlying rocks of those deposits with a recognized stringer ore zone are characterized by varying degrees of hydrothermal Mg, K, Si, Ca, and Na enrichment. The mineralized interval may grade laterally into or be overlain by thinly bedded chemical sedimentary rocks (hematitic, manganiferous, or pyritic chert) and silicified tuffaceous rocks or be overlain by clastic rocks, including mudstone and graphitic shale.

AGE, HOST ROCKS

From >3.4 to 2.65 Ga.

AGE, ORE

Same as the enclosing rocks.

GEOLOGIC SETTING

Widely varied tectonic environments. Deposits tend to occur in clusters (32 km average diameter in the Abitibi subprovince) and are typically related to only a few volcanic centers in a given volcanic belt (Lydon, 1984a). Most are found in a single, relatively thin stratigraphic unit in a thick accumulation of cyclic mafic to felsic volcanic rocks in the productive volcanic centers. Most volcanism is submarine, predominantly mafic in composition and often related to spreading centers, and back-arc basins. Linear fractures may control the location of hydrothermal vents in a given deposit cluster (Scott, 1978; Sangster, 1972). Paleowater depth ranges from shallow to as much as 500 m.

GENETIC MODEL

Pyrite and base metal sulfides are deposited on the seafloor from solutions discharged from high-temperature (usually>250°C), fracture-controlled, submarine hydrothermal vents or as fracture fillings in pipe-shaped zones in the shallow subsurface. The composition of the host rocks and temperature of the hydrothermal fluid control the composition of the ore deposit and the accompanying alteration mineral assemblage. After deposition, gravity transport from the vent area may occur.

ORE CONTROLS AND EXPLORATION CRITERIA

1. In successions of submarine volcanic rocks with multiple cycles that were deposited at relatively shallow-water depth.
2. Coarse volcanic pyroclastic rocks or flows and abundant subvolcanic felsic sills indicate the proximity of felsic volcanic centers.
3. Deposits tend to occur in clusters with diameters of about 30 km.
4. Hydrothermal alteration of host rocks such as
   a. Intense magnesium enrichment of the immediately subjacent footwall rocks.
   b. Silicification below the ore zone.
   c. Widespread carbonatization and Na depletion surrounding the vent in footwall rocks.
   d. Possible Na enrichment in hanging wallrocks overlying the vent area.
   e. Laterally extensive chemical sedimentary rocks, such as ferruginous or sulfidic cherts or tuffs indicating hydrothermal origin.

EXAMPLES

Kidd Creek, and Matabi mines, Ontario; Millenbach and Horne mines, Quebec; Flin Flon mine, Manitoba; York Harbour and Betts Cove mines, Newfoundland; Norwegian Caledonide deposits; deposits in the Cyprus ophiolite belt.

TYPICAL GRADE, TONNAGE

Average grade and tonnage of 142 Canadian deposits is 5.30 million metric tons containing 1.82 percent Cu, 4.3 percent Zn, 0.09 percent Pb, 36 g Ag/t and 0.81 g Au/t (Franklin, 1990). Average grade and tonnage of 38 deposits of the Norwegian Caledonides is 3.46 million metric tons containing 1.41 percent Cu, 1.53 percent Zn, 0.05 percent Pb (precious metal data not available) (Lydon, 1984a).

REFERENCES

Based on models by J.M. Franklin, J.W. Lydon, D.F. Strong, and J.M. Sangster in Eckstrand (1984); Lydon (1984a, b), Franklin and others (1981), and Franklin (1990).

ALGOMA-TYPE IRON-FORMATION

HOST OR MINERALIZED ROCKS

Iron oxide, silicate, carbonate, and sulfide minerals are commonly interlayered with thin (0.5-3 cm thick), alternating layers of silica (chert and quartz). These iron-rich layers are interbedded with clastic sedimentary and volcanic rocks. Four facies of iron-formation (oxide, silicate, carbonate, sulfide) are recognized on the basis of the composition of the iron minerals.

COMMODITIES

Fe (Mn)

DEPOSIT FORM, SIZE, DISTRIBUTION OF ORE MINERALS

Ore-bearing layers in sedimentary sequences are commonly as thick as 100 m thick and several kilometers long, whereas layers in volcanic rocks are generally no more than tens of meters thick and more restricted in lateral extent. Structural thickening of the iron-formation by folding and faulting may increase its economic value. Ore mineralogy is directly related to the sedimentary depositional facies.

ORE MINERALS

Principal

Magnetite, hematite, siderite, pyrite, and pyrrhotite.

Associated

Chert, quartz, iron-silicates, iron-carbonates, chlorite, amphiboles, biotite, feldspar, garnet, and chalcopyrite.

ASSOCIATED ROCKS

Interlayered with felsic, mafic, and ultramafic volcanic rocks, graywacke, shale, aigrette, chert, and their metamorphic equivalents.

AGE, HOST ROCKS

Predominantly Archean, but ranges to the Holocene.

AGE, ORE

Same as the enclosing rocks.

GEOLOGIC SETTING

Iron-formation is most abundant in Archean greenstone belts where it is associated with widely ranging compositions of submarine volcanic rocks and laterally equivalent graywacke and shale that surround the volcanic centers. Deposits of all ages may be controlled by deep fault systems and rift zones. Some oxide, carbonate, and sulfide facies have base metal sulfide (especially Cu and Co) or gold mineralization associated with them.

GENETIC MODEL

Iron is probably precipitated in colloidal form by fluctuating Eh and pH conditions or by iron-stripping bacteria. Carbonate facies iron-formation may be formed by direct chemical precipitation. Diagenetic changes and thermal metamorphism alter the primary precipitates to the observed mineral assemblages. The controls on the deposition of the accompanying silica, probably also as a colloid is not known. The major constituents, iron and silica, are derived from volcanic and hydrothermal vents along volcanic belts, deep faults, or rift systems. Fe-carbonates, sulfides, or magnetite may be oxidized to hematite during subsequent weathering or hydrothermal alteration.

ORE CONTROLS AND EXPLORATION GUIDES

1. Distribution of iron-formation can be determined from magnetic surveys.
2. Oxide facies is the most economically favorable facies.
3. Thick primary beds (30-100 m) and repetition of beds by folding or faulting are economically favorable.
4. Metamorphism increases grain size and improves metallurgical recovery.
5. Weathering or hydrothermal alteration may upgrade the original Fe content by oxidation to hematite.

EXAMPLES

Helen mine at Wawa, Steep Rock mine, Sherman mine at Temagami, Ontario; Woodstock, New Brunswick; Kudrem UK, India.

GRADE AND TONNAGE

As much as billions of metric tons, with grades ranging from 15 to 45 percent Fe, averaging 25 percent Fe.

REFERENCES

Adapted from model by G.A. Gross in Eckstrand (1984).

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