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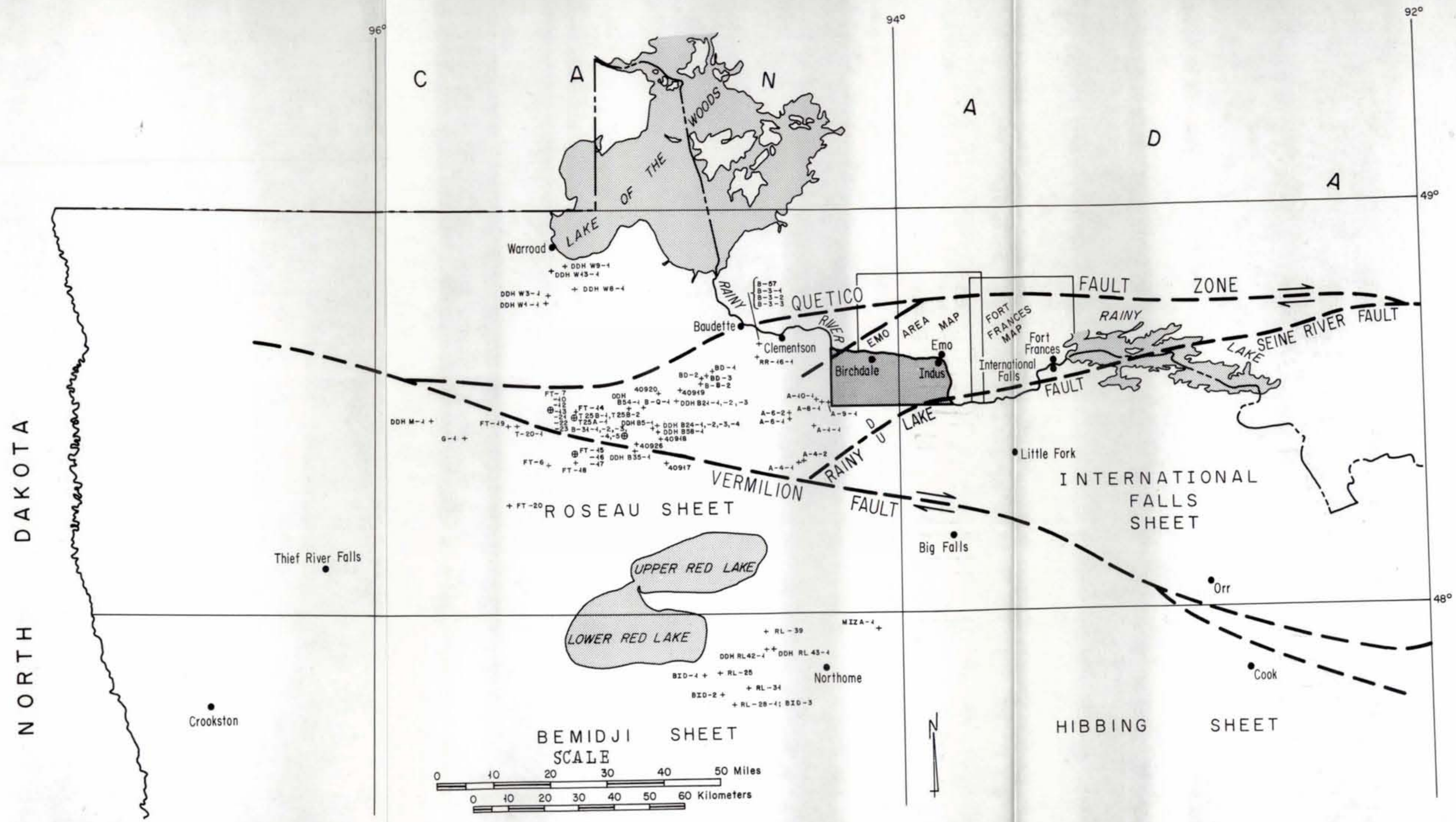

Figure 1 - Location map. Area of this report is shaded. Small crosses and numbers signify sulfide exploration drill holes.

MINNESOTA GEOLOGICAL SURVEY

MATT S. WALTON, *Director*

GEOLOGY, SULFIDE MINERALIZATION AND GEOCHEMISTRY OF THE BIRCHDALE - INDUS AREA KOOCHICHING COUNTY, NORTHWESTERN MINNESOTA

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Report of Investigations 17

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GEOLOGY,
SULFIDE MINERALIZATION
AND GEOCHEMISTRY OF
THE BIRCHDALE - INDUS
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Department of Natural Resources Contract 07568.

CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGY, SULFIDE MINERALIZATION AND GEOCHEMISTRY OF THE BIRCHDALE-INDUS AREA, KOOCHICHING COUNTY, MINNESOTA

by

RICHARD W. OJAKANGAS, DAVID G. MEINEKE,

and WILLIAM H. LISTERUD

ABSTRACT

The rocks of the Birchdale-Indus area, in northern Minnesota, are part of a poorly-exposed volcanic-sedimentary sequence within the southwest extension of the Wabigoon Volcanic Belt of Canada. The bedrock is Early Precambrian (or Archean) in age and includes mafic to intermediate lavas and subvolcanic intrusive rocks; felsic dikes, agglomerate, tuff, and volcaniclastic rocks; iron-formation and associated metasediments; and granitic rocks of Algoman age. All rock types are cut by northwest-trending Middle Precambrian mafic dikes. The area is largely covered by Pleistocene glacial deposits.

The volcanic-sedimentary sequence has been isoclinally folded and has steeply-dipping northeast-trending bedding and foliation. A doubly-plunging anticline and a syncline have been mapped within the area, and a second generation of folding on more northerly trending axes is suggested by some structural observations. Three sets of faults and fractures have been delineated. All the Lower Precambrian rocks were metamorphosed to amphibolite grade during the Algoman event.

Synthesis of the geology of the Birchdale-Indus area with that of the better exposed Emo area in adjacent Ontario (Fletcher and Irvine, 1954) provides a firm basis for interpretation of the development of the volcanic accumulation. Mafic and intermediate volcanic and intrusive rocks apparently constitute a lower stratigraphic unit. An explosive felsic volcanic center, marked by abundant agglomerate, developed upon the older, mafic platform in the vicinity of Birchdale, Indus, and Emo. Felsic tuff, volcaniclastic rocks, and iron-formation were deposited outward from this center.

The Birchdale-Indus area and areas to the west and south have been actively explored for base metal sulfide deposits during the past decade. Thick zones of massive, submassive, and disseminated pyrite and/or pyrrhotite have been penetrated at several localities, but copper and zinc have not been found in economic quantities. Several of the iron-sulfide bodies that were penetrated are associated with oxide iron-formation. To assist in further exploration, geophysical and geochemical anomalies have been located by ground survey methods by the Minnesota Department of Natural Resources.

INTRODUCTION

The Birchdale-Indus area comprises about 200 square miles (more than 500 km^2) in northwestern Koochiching Couty, Minnesota, just south of the Rainy River and about midway between Rainy Lake and Lake of the Woods (fig. 1). It lies near the westernmost exposures of the Wabigoon Volcanic Belt of Canada (Stockwell, 1964; Goodwin, 1970), which extends for more than 450 miles (720 km) eastward from the International boundary to the Paleozoic cover of the Hudson Bay Lowland. Although this report is mainly concerned with the Birchdale-Indus area, it also presents some aspects of the geology to the north, west, and south, to provide a better perspective of the regional framework.

The Birchdale-Indus area was selected for detailed study because it contains the best exposed volcanic-sedimentary rocks in the northwestern third of the state and since 1967 has been explored intermittently for massive base-metal ore deposits. The Mattabi and Sturgeon Lake copper-zinc-silver-lead deposits of Ontario lie about 175 miles (280 km) to the northeast, and several other ore deposits also occur in the Wabigoon Belt in Canada (Mackasey and others, 1974).

Exploration in the region has as yet failed to disclose any ore bodies, but several drill holes have penetrated thick zones of disseminated and massive pyrite and pyrrhotite, with but traces of copper and zinc minerals. About 27 exploration holes have recently been drilled on state lands within the 200 square mile area (more than 500 km^2) of this report. An additional 45 holes or so have been drilled on state lands further west in the area covered by the Roseau 1:250,000 sheet, mostly within 50 miles (80 km) of Baudette in a southwesterly direction. Eight holes were drilled south of Red Lake, in the Bemidji map sheet. Numerous other holes have been drilled on private lands in the general region, but information from these sites is not readily available.

Outcrops are sparse in the area because of a thick cover of Pleistocene glacial deposits except within a few miles of the Rainy River. However, when outcrop data are integrated with the drill information and with the geologic maps and reports on the Emo area in adjacent Ontario (Fletcher and Irvine, 1954) and the Fort Frances area east of Emo (Davies, 1973), a reasonably accurate interpretation of the geology is possible. The general geology of adjacent areas to the east, south, and west is shown on the geologic maps of the International Falls (Southwick and Ojakangas, 1973) and Roseau (Sims and Ojakangas, 1973) 1:250,000 map sheets. Plate 1 is the detailed geologic map of the Birchdale-Indus area. Figure 2 is a generalized composite map of the Birchdale-Indus area and the Emo area, included here as an aid to understanding the larger geologic picture.

Geologic interpretations were enhanced by aeromagnetic maps (Meuschke and others, 1957) and a gravity map (McGinnis and others, 1973). During field work, preliminary topographic quadrangles were available for the portion of the area west of the 94° meridian and photoquadrangles were available for the entire area. Topographic maps for the entire area were published after the field work had been completed, and the geology was replotted on these (pl. 1); some outcrops may have been missed during the mapping, especially in the area east of the 94° meridian.

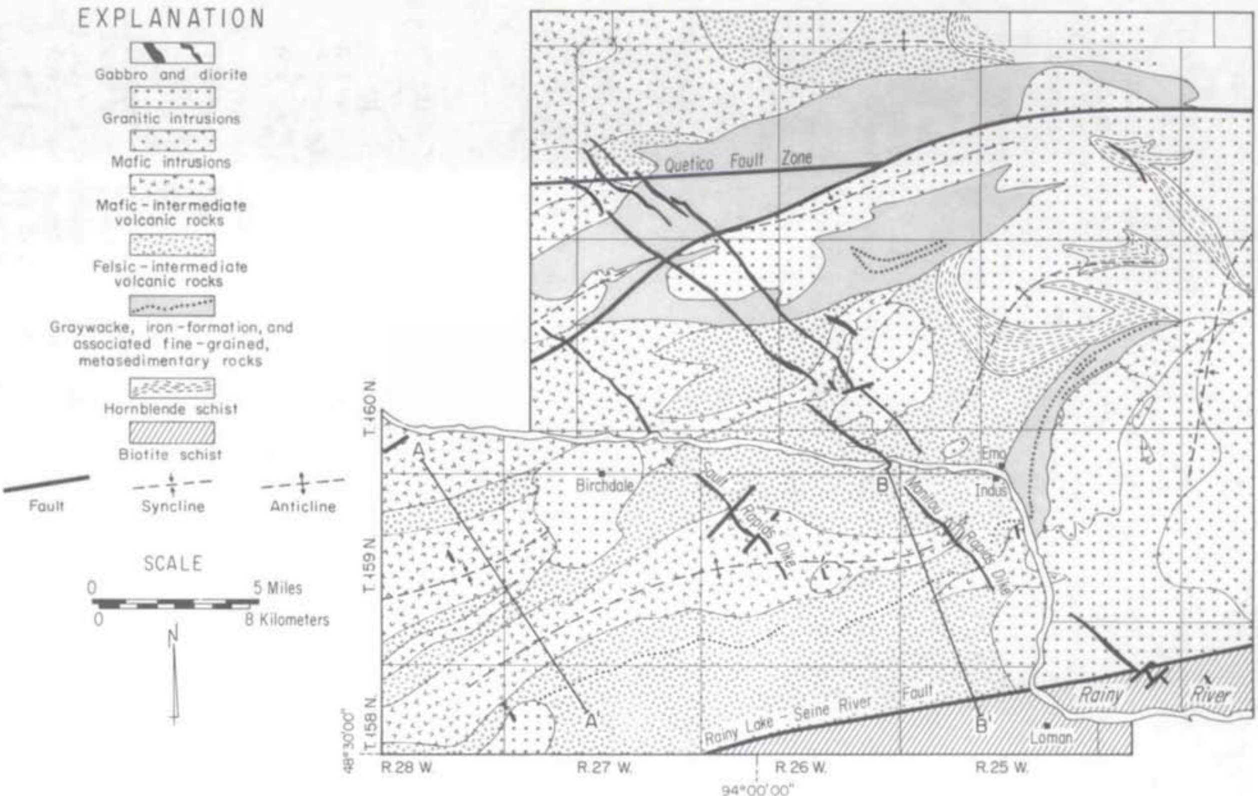

Figure 2 - Generalized geologic map of Birchdale-Indus and Emo areas. Emo map after Fletcher and Irvine (1954) and Davies (1973).

Most of the geologic field work was conducted during the summer of 1970, with some being accomplished during the summers of 1968, 1969, 1971, 1972, and 1973. Geochemical field work was done largely during the summers of 1972, 1973, and 1974.

Rock samples collected during the mapping and from selected drill cores available at the Minnesota Department of Natural Resources core-storage facility at Hibbing were thin sectioned and stained for potassium-feldspar. About 350 thin sections from the map area were studied, and an additional 50 from field samples and drill cores west of the map area were given more cursory examination. About 225 polished sections were studied, all from the Birchdale-Indus area. More than 1,100 soil and sediment samples were collected and prepared for geochemical studies; each was analyzed for copper, nickel, cobalt, zinc, and manganese, and a few were also analyzed for lead and silver.

The presence of northwest-trending mafic dikes is fortunate, for because of their somewhat greater resistance to weathering and erosion than the country rocks, they commonly stand as low ridges or hills. Inspection of the lower-lying edges of these exposures has yielded most of the data on the volcanic-sedimentary sequence. The two prominent dikes shown on Plate 1 will be hereafter referred to as the Sault Rapids dike to the west and the Manitou Rapids dike to the east.

The entire map area is low-lying with the highest ground near the Rainy River. Total relief is about 150 feet (45 m), but topographic highs are few; most of the area is very flat. The entire area is part of the lake bed of Glacial Lake Agassiz, and most of it is now either swamp or bog. Farming is well established on the higher ground near the Rainy River, but the main resource of much of the area is pulpwood, mainly second growth spruce, balsam, and aspen. Peat reserves are large (Emmons and Grout, 1933).

ACKNOWLEDGEMENTS

The geologic investigations were carried out by R. W. Ojakangas, and were completed under the auspices of the Minnesota Geological Survey, Matt Walton, Director. P. K. Sims, Director of the Survey during the time most of the geological field work was conducted (1968-1973), suggested the project and provided advice and encouragement. The Minnesota Department of Natural Resources provided support for the completion of the geologic field work and for making some thin sections. Ojakangas was assisted in the field for several weeks by Greg Ojakangas and was accompanied for short periods by William Listerud, Jeffrey Reid, M. P. McKenna, M. A. Gilgosch, and P. K. Sims.

Discussions with geologists of several exploration companies, especially Paul Schmidt of Exxon Company, U.S.A. and Val Spring of Texas Gulf Sulfur Company, were helpful. Numerous local residents and forestry personnel of the Minnesota Department of Natural Resources provided valuable information on the locations of outcrops; forester Ross Cass of the Minnesota Department of Natural Resources provided an all-terrain vehicle on one occasion. Morris Eng of the Minnesota Department of Natural Resources supplied several outcrop locations based on interpretations of aerial photographs.

Ontario Division of Mines geologists Leo King, J. C. Davies, and C. E. Blackburn kindly led field trips to nearby areas in Ontario. G. B. Morey of the Minnesota Geological Survey provided willing cooperation during the final stages of map and manuscript preparation.

Studies of the sulfide minerals and of the geochemistry and geophysics of the area were done by the Minnesota Department of Natural Resources (DNR), Elwood F. Rafn, Director. William H. Listerud, Geologist, was responsible for the sulfide studies and David G. Meineke, Minerals Exploration Supervisor, was in charge of the geophysical and geochemical projects. Albert W. Klaysmat performed the geochemical analyses in the DNR Atomic Absorption laboratory at Hibbing. Charles L. Matsch of the University of Minnesota, Duluth, supplied information on the Quaternary geology of the area and offered suggestions on the geochemical study. M A. Gilgosch, M. P. McKenna, and M. K. Vadis of the DNR also devoted considerable time to the project, assisted at various times in the field and laboratory by Craig K. Anderson, Steve Ingle, Larry J. Lehtinen, Joyce A. Thompson, and Patrick R. Wotruba.

To all of the above persons, we extend our sincere thanks and appreciation.

PREVIOUS GEOLOGIC WORK

The detailed geology of this part of Minnesota was virtually unknown until this investigation was undertaken. Although A. C. Lawson (1888) made initial observations along the Rainy River, few of these pertained to Minnesota. In Minnesota, locations of some bedrock outcrops were plotted intermittently over the years on county road maps retained in the files of the Minnesota Geological Survey. Subsequently these were plotted on an aeromagnetic and geologic map of northwestern Koochiching County (Meuschke and others, 1957) and were also utilized in the compilation of aeromagnetic and geological maps of northwestern and northeastern Minnesota (Bath and others, 1964; 1965); each map includes part of the area of this report. Thiel (1947) had compiled some bedrock information on Koochiching County, but the Birchdale-Indus area was not mentioned in his report. An early report by Allison (1932) on the geology and water resources of northwestern Minnesota described the general features of glacial deposits and a few rock types in areas to the west of this report area. C.L. Matsch (written comm., 1973) later described the glacial deposits of the area in detail.

Of particular benefit to this study was the published report and map of the Emo area in Ontario, just across the Rainy River (Fletcher and Irvine, 1954). Also of use were Ontario Department of Mines Map P. 309 (Rainy River Sheet), compiled by J.C. Davies (1965); Map 2115 (Kenora-Fort Frances Sheet), compiled by Davies and Pryslak (1967); and a report and map by Davies (1973) on the Fort Frances area.

The geology of the International Falls 1:250,000 map sheet (Southwick and Ojakangas, 1973), available in open files at the Minnesota Geological Survey, includes the general geology of the eastern half of the Birchdale-Indus area. Similarly, the Roseau 1:250,000 map sheet (Sims and Ojakangas, 1973), which includes the western half of the Birchdale-Indus area, also is available in open files at the Survey, but the geology is highly generalized. A preliminary map of the Birchdale-Indus area was placed in open files in 1973 (Ojakangas, 1973); Plate 1 of this report is a revision of that map.

Detailed aeromagnetic maps were also available for adjacent Ontario (ODM Map 1166G, 1961; Davies, 1973). A gravity map of the Roseau 1:250,000 map sheet (McGinnis and others, 1973) was also of value.

REGIONAL GEOLOGY

The rocks of northern Minnesota are Early Precambrian (Archean) in age and are situated in the southeastern part of the exposed Superior Province of the Canadian Shield. Continuations of the broad east-west-trending volcanic belts and gneiss belts mapped and defined in Canada (Stockwell, 1964; Goodwin, 1970) are present in Minnesota; specifically, these are the Wabigoon and Shebandowan-Wawa Volcanic Belts and the Quetico Gneiss Belt which lies between them (fig. 3).

There are only three areas in Minnesota where volcanic-sedimentary belt rocks are well exposed. In the Vermilion district, the southwest extension of the Shebandowan-Wawa Volcanic Belt is exposed over a length of 100 miles (161 km) and is as much as 12 miles (19 km) wide. Parts of it have been mapped in detail, and the overall structure and stratigraphy of the rocks are fairly well known (e.g., Gruner, 1941; Morey and others, 1970; Sims and others, 1970; Sims, 1976; Green, 1970; much information on the district is contained in several articles in the Geology of Minnesota volume, edited by Sims and Morey, 1972).

The second exposed volcanic-sedimentary association is in the Rainy Lake area, an extension of the Wabigoon Volcanic Belt. It was originally mapped by Lawson (1888 and 1913), and since that time the stratigraphy of the area has been controversial, largely in regard to the stratigraphic position of the Coutchiching series. Several geologists have worked on aspects of this problem, with the most recent study in Minnesota being that of Ojakangas (1972). Metavolcanic, metaplutonic, and metasedimentary rocks, tuffaceous biotite-chlorite schist, chlorite schist, chlorite-actinolite schist, pillowed greenstone, felsic metatuff, metafelsite and intermediate, mafic, and ultramafic metaplutonic rocks are all represented.

The third exposed volcanic-sedimentary accumulation is in the Birchdale-Indus area, the subject of this report. Like the Rainy Lake area, this area is an extension of the Wabigoon Volcanic Belt.

Granitic plutons intrusive into the country rocks are present in all three belts (Wabigoon, Quetico, and Shebandowan-Wawa) and, based on geophysical interpretations, constitute an appreciable part of the bedrock beneath the glacial cover of northern Minnesota (Sims, 1970; Sims and Ojakangas, 1973). Only three of the large plutons--the Giants Range composite batholith in the Shebandowan-Wawa Belt (Sims and Viswanathan, 1972; Sims and others, 1970); the Saganaga batholith at the east end of the Vermilion district, in the Shebandowan-Wawa Belt (Grout, 1929 and 1936; Hanson, 1972); and the Vermilion granite-migmatite massif, in the Quetico Gneiss Belt (Southwick, 1972) --are fairly well exposed and known.

The right-lateral Quetico fault (Davies, 1973; Mackasey and others, 1974), a major east-west structural feature in Ontario that crosses into Minnesota near Baudette (Davies, 1973, p. 23) 15 miles (24 km) west of the area of this report, is not exposed in Minnesota, but has been mapped on the basis of pronounced changes in structural trends evident on gravity and aeromagnetic maps (Sims and Ojakangas, 1973). About 12 miles (19 km) north of Indus, a lesser southwest-trending fault splays off the main Quetico fault and apparently enters Minnesota in the northwest corner of the Birchdale-Indus map area (Davies and Pryslak, 1967) (figs. 1 and 2).

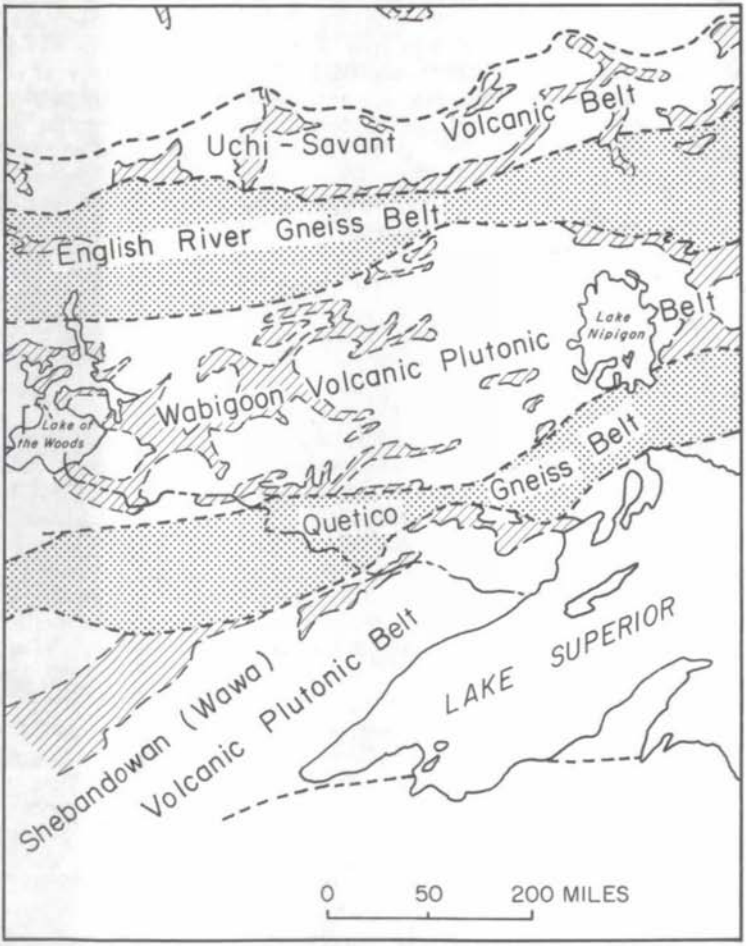

Figure 3 - Map of Minnesota and Canada showing major volcanic and gneiss belts (after Goodwin, 1974).

The Rainy Lake fault (Southwick and Ojakangas, 1973; Ojakangas, 1972) is a continuation of the Atikokan fault, east of Rainy Lake in Ontario; Davies (1973) has assigned the name Seine River fault to the segment in Ontario. This fault splays off the Quetico fault about 60 miles (97 km) east of International Falls and trends west-southwest across Rainy Lake, through International Falls, back into Ontario west of International Falls, and then re-enters Minnesota in the southeast part of the Birchdale-Indus map area. As the Rainy Lake-Seine River fault is parallel or subparallel to lithologic units, determination of lateral displacement along it is difficult. Based on a lesser metamorphic grade north of the fault in the Rainy Lake area, and lithologic changes across the fault, it is probable that the northern block has moved downward relative to the southern block (Ojakangas, 1972).

The Birchdale-Indus-Emo area, as well as the Fort Frances-International Falls area, is therefore located in a structural block that lies between two major faults, the Quetico and the Rainy Lake (figs. 1 and 2). To the south and southwest, both of these faults are interpreted to merge with the Vermilion fault, the largest known fault in Minnesota, and possibly are splays from it (Sims, 1970; 1972a). The Vermilion fault, which forms the boundary between the volcanic-sedimentary rocks of the Vermilion district in the Shebandowan-Wawa Volcanic Belt and the Vermilion massif of the Quetico Gneiss Belt, has a right-lateral, horizontal separation of 12 miles (19 km) and an estimated vertical displacement of one mile (1.6 km) in the Vermilion district (Sims, 1973a; 1973b); in northwestern Minnesota, the fault has an estimated 35 miles (55 km) of right-lateral separation, based on interpretations of displaced geophysical anomalies (Sims, 1976; Sims and Ojakangas, 1973).

Numerous northwest-trending undeformed mafic dikes, generally 150 to 200 feet (45 to 60 m) wide, cut the volcanic-sedimentary rocks and the granitic plutons of northern Minnesota and adjacent Ontario (e.g., Hanson and Malhotra, 1971; Sims and Mudrey, 1972; Davies and Pryslak, 1967). Several have been dated, and they have minimum K-Ar dates ranging from 1395 to 2240 m.y.; thus, these dikes are apparently Middle Precambrian in age. Only one dike in Minnesota from the swarm along the Minnesota-Ontario border has been dated; this dike, in the Rainy Lake area, has a K-Ar date of about 2100 m.y. (Hanson, 1968), which is a minimum age.

In summary, the rocks of the Birchdale-Indus area constitute a small part of an extensive volcanic-sedimentary sequence that apparently is representative of the Archean volcanic-sedimentary accumulations of the Superior Province of the Canadian Shield. Accordingly, it provides a unique opportunity for both mineral exploration and scientific inquiry into Early Precambrian crustal history.

GENERAL GEOLOGY AND PETROGRAPHY

Except for Middle Precambrian northwest-trending mafic dikes (pl. 1; fig. 2), the bedrock of the Birchdale-Indus area is Lower Precambrian. Pleistocene tills, various glaciofluvial sediments, and lake clays blanket the area. Peat is extensively developed on the old lake beds.

Most of the Lower Precambrian rocks compose a volcanic-sedimentary (greenstone) sequence, similar to those described from the Vermilion district (e.g., Morey and others, 1970) and in Canada (e.g., Goodwin, 1968). The sequence includes mafic to intermediate lavas, subjacent intrusive bodies and felsic dikes, flows (?), agglomerates, tuff, volcaniclastic rocks, iron-formation, and metasedimentary rocks. In adjacent Ontario, these rock types have been referred to Lawson's (1885; 1888; 1913) Keewatin and Coutchiching units (Fletcher and Irvine, 1954; Davies and Pryslak, 1967). The volcanic-sedimentary sequence has been intruded by several small granitic plutons, of which only the Birchdale pluton is well exposed in the area covered by this report. These plutons, presumably of Algoman age, vary in composition from granite to quartz diorite. Goldich and others (1961) obtained a K-Ar date of 2.4 b.y. on the Birchdale pluton.

The volcanic-sedimentary sequence has been isoclinally folded and has a pervasive regional foliation that varies from faint to extremely well developed. A regional amphibolite-grade metamorphism has resulted in extensive recrystallization of most rock units, although megascopic textures are generally well preserved. Near the granitic plutons, recrystallization is more intense than elsewhere. As a result of the deformation and metamorphism, much of the interpretation of protoliths was of necessity based on study of the less metamorphosed representatives of each rock type.

On Plate 1, two major volcanic rock units are shown--felsic-intermediate and mafic-intermediate. These are simply cartographic units that are based on presumed dominant lithologies, for the sparse outcrops and lack of distinctive aeromagnetic and gravity patterns for most of the rocks do not permit delineation of specific rock types. In reality, each unit includes rock types typical of the other unit. However, each rock type is described separately in the following pages. The rock units are described in order of probable age. Evidence for the stratigraphic relationships is presented in a later section of this report. Although all bedrock units have undergone metamorphism, for the sake of brevity, the prefix "meta" is omitted throughout the report. The units are as follows:

Pleistocene		Glacial drift; peat
		~~ unconformity ~~~
Middle Precambrian		Mafic dikes
		—— intrusive contact ——
Lower Precambrian		Granitic intrusions
		—— intrusive contact ——
	Not necessarily in order of age	Iron-formation and metasedimentary rocks
		Felsic-intermediate agglomerates, tuff, volcaniclastic rocks and dikes
		Mafic-intermediate volcanic and subvolcanic rocks and minor agglomerate and tuff
		Biotite schist

Biotite Schist

The biotite schist shown in the southeastern part of Plate 1 does not crop out within the area, but it is interpreted on the bases of regional geology and geophysics to be present south of the Rainy Lake-Seine River fault. The biotite schist unit has a generally subdued magnetic and gravity expression, but a few magnetic highs (Ontario Department of Mines, 1961; Meuschke and others, 1957), including one beneath the village of Loman in the southeast corner of the map, may represent layers of hornblende schist within the unit.

The nearest known outcrop of the biotite schist unit in Minnesota is on the Little Fork River, about 7 miles (11 km) east-southeast of the southeast corner of the map area; this garnetiferous biotite schist outcrop is visible only at low-water stage. Rock outcrops have also been reported in the swamp about 5 miles east-southeast of the southeast corner of the map, but these were not checked; if they exist, the rock is likely to be biotite schist.

In Ontario, one to two miles north of the southeast corner of the Birchdale-Indus map, there are exposures of a thinly bedded and intensely sheared and foliated unit of interbedded biotite and hornblende schist and siliceous tuff (Fletcher and Irvine, 1954), a continuation of the biotite schist unit of the Birchdale-Indus map area. Fletcher and Irvine suggested that this unit is Coutchiching, i.e., older than the metavolcanics of the region.

Excellent exposures of lower grade metamorphic rocks, which are probably similar to the protoliths of the biotite schist, can be seen on the Rainy River in the city of International Falls, 15 to 17 miles (24 to 27 km) east-northeast of the map area; these are intercalated, graded metagraywacke and fine-grained biotite schists that were originally graywacke and mudstone beds. However, these rocks are not exactly along strike from the biotite schist of this study, for they lie north of the Rainy Lake-Seine River fault. Just east of International Falls in the village of Ranier, similar rocks occur. Further east and to the south of International Falls, essentially complete recrystallization of this protolith to a garnet-biotite-plagioclase-quartz assemblage has occurred; excellent graded bedding and other sedimentary features in beds as much as 3 feet (1 m) thick have survived the recrystallization (Ojakangas, 1972).

Mafic-Intermediate Volcanic and Subvolcanic Rocks

Mafic to intermediate volcanic and subvolcanic rocks (greenstones) apparently underlie an appreciable part of the map area. Most occur in three broad northeast-trending units, which are designated as mafic-intermediate units on the map, the northwestern one being based on exposures in adjacent Ontario. Minor amounts of mafic-intermediate rocks also are present in the felsic-intermediate rock units, as mapped. Those cut at depth by drill holes cannot, of course, be shown on the map.

Recrystallization is commonly so thorough that the original mineralogies and textures are obliterated and the protoliths are obscure. In these cases, it is not possible to determine the composition of the plagioclase and hence it is not possible to classify the rocks as andesite or basalt. Some of the specimens now consist of 90 to 95 percent blue-green amphibole; this is suggestive of a basaltic rather than an andesitic protolith. Some samples with well preserved lathy plagioclase texture contain only minor to moderate amounts of amphibole, and are classified as andesites. "Greenstone" and "greenschist" are names easily applied to these rocks and in many cases would be the safest terms to use. However, most of these rocks appear to be mafic rather than intermediate in composition.

Fine-grained, dark-green pillowed lava is a common rock type in the area (fig. 4). The pillows are generally on the order of 0.5 to 2 feet (15 to 61 cm) long, locally 7 feet (2 m) long and 2 feet (0.6 m) wide, vary from highly stretched to relatively undeformed, and provide all the stratigraphic top information found in outcrops. A few exposures show amygdules near pillow boundaries, but these are rare. The recrystallized original glassy selvages are thin, commonly about half an inch (1 cm) thick. The rocks are generally quite massive but highly fractured; local schistose zones are uncommon. Similar rock was also penetrated in several drill cores including R-3-1, R-4-1, and RR-6-1 (tbl. A-1). In thin section, the felty texture of the plagioclase laths is locally well preserved; trachytic texture is rare.

Figure 4 - Pillowed mafic volcanic rock, west half Section 18, T.159N., R.7W.

Along the Manitou Rapids dike in Section 17, T.159N., R.25W., a set of dikes one to 3 feet (1 m) thick are cut by dikes associated with the Manitou Rapids dike; the older dikes are highly altered. Massive fine- to medium-grained mafic-intermediate volcanic rocks are also present at many localities and in drill cores. A fine-grained mafic-intermediate rock with highly altered plagioclase phenocrysts as much as 2 inches (5 cm) long occurs in the N½, Section 15 and in the SE¼, NE¼, Section 16, T.159N., R.26W. as several scattered outcrops. Some rocks which appeared in the field to be gabbros (as in Sections 9, 14, and 15, T.159N., R.26W.) proved upon microscopic examination to be rather fine-grained with large amphibole porphyroblasts.

Coarse-grained to medium-grained gabbroic, dioritic, and diabasic subvolcanic rocks are common in the map area, especially in the southwestern half of the central mafic-intermediate volcanic unit. Most exposures of these rocks are composed completely of this rock type, making actual dimensions of the subvolcanic bodies difficult to determine, but at one exposure near the center of Section 14, T.159N., R.28W. a dike or sill 150 feet (45 m) thick has intruded into pillowed lavas. Some exposures of rocks here called subvolcanic rocks could be parts of thick flows, but no field relationships observed in the area suggested this to be the case. A few of the mafic-intermediate subvolcanic rocks, as in the NW corner, NE¼, Section 1, T.158N., R.28W., display gneissic banding in outcrop. Drill holes in the area have intersected numerous mafic-intermediate subvolcanic rock bodies of varying dimensions. A zone of gabbro 225 feet (68 m) thick was penetrated in drill hole R-2-2 (the same body was cut in R-2-1 and S-43-1), and 500 feet (152 m) of diorite was penetrated in drill hole R-3-2.

Thin zones of probable mafic-intermediate tuff were noted locally in some pillowed lava sequences, but cataclasis and metamorphism of the pyroclastic units is too complete to allow positive determination of the protolith. Some of these are composed almost completely of fine-grained, blue-green amphibole and reddish garnets, as in some layers in drill hole R-3-3.

In an exposure in the center of the NE¼, Section 25, T.159N., R.28W., a 6-foot-thick (2 m) bed of volcaniclastic material in a pillowed unit contains bomb-like structures as much as 5 inches (13 cm) long, but again no original microscopic minerals or texture are preserved in the sampled, finer portion of the bed. Agglomerate with dark green clasts and a dark green matrix was observed at only a few localities.

Much of the dark-green mafic-intermediate tuff observed in the field crops out along the northern third of the Sault Rapids dike; other outcrops are found scattered throughout the map area. The well developed foliation and local shearing make recognition of bedding difficult but do allow delineation in the field from volcanic flows. Where tuff is interbedded with lighter colored felsic volcaniclastic rocks--a common association--the beds stand out well. Most beds are apparently thin and most are apparently fairly fine grained. Original lamination may be reflected by alternating laminae of epidote and amphibole and, in some samples, by variations in the grain size of amphibole in adjacent laminae. Brownish, primary (?) amphibole grains were noted in several samples.

Blue-green amphibole is the common metamorphic mineral in these rocks; epidote minerals of varying optical properies are very abundant as well, both in scattered grains and in veinlets. In some rocks, epidote is the dominant mineral. Chlorite is locally abundant. Disseminated opaques are locally fairly common. Carbonate and, to a lesser extent, quartz veins are common. Some samples, including some from drill cores, contain well developed garnet crystals as much as half an inch (1 cm) in diameter; in at least one sample, they are best developed in pillow rinds. The amphibole crystals are larger in the subvolcanic rocks, and are commonly poikilitic relative to many other constituents. Sphene seems to be more abundant in the subvolcanic than in the volcanic rocks, but this may simply be a function of its larger grain size.

Felsic-Intermediate Volcanic Rocks

This rock unit consists largely of clastic volcanogenic rocks of varying textures, and abundant but volumetrically minor felsic dikes. Some thin lava flows may be present, but poor exposure commonly prevents this determination.

The problem of ascertaining whether a given clastic rock wholly composed of volcanic detritus is a true pyroclastic rock (broken by volcanic explosion), a reworked pyroclastic (reworked prior to lithification), or an epiclastic rock (solidified or lithified volcanic rock broken by weathering and erosion) can be difficult even in unmetamorphosed and undeformed terrane (see Fisher, 1961; 1966). In the rock sequence of this area, apparently somewhat typical of Archean volcanic-sedimentary sequences, the problem is even greater. Most of these rocks consist of sand-sized particles, and therefore could be called tuff, reworked tuff, epiclastic volcanic sandstones, or "volcanic sandstone," a non-genetic term proposed by Fisher (1961). The term "sandstone" implies to most geologists considerable reworking and transportation, and as this does not seem to have been the case in this area, it was decided to group these rocks as felsic-intermediate volcaniclastic rocks; where sufficient genetic evidence is available a more specific term is applied.

Felsic Dikes

Light greenish-gray to gray porphyritic felsic dikes, all with abundant phenocrysts of plagioclase and most with less abundant but obvious phenocrysts of quartz, are common throughout the area, especially in the felsic-intermediate volcanic units. They are medium greenish-gray in color when fresh, and light greenish-gray to gray where weathered. These dikes are rarely more than a few feet to ten feet wide, but at one locality 2½ miles (4 km) due south of Manitou Rapids (NE¼, Section 13, T.159N., R.26W.), a minimum thickness of 225 feet (69 m) of massive porphyritic aphanitic felsic rock containing 10 percent K-feldspar is overlain by 125 feet (38 m) of pillowed and massive metabasalt, and this in turn is overlain by at least 110 feet (33 m) of massive porphyritic aphanitic felsic rock.

Although chemical analyses are not available for these dike rocks, most appear to be dacites or rhyodacites; the plagioclase phenocrysts are commonly albite or oligoclase. Some apparently have a rather potassium-rich matrix, based on staining; these are most abundant along the Manitou

Rapids dike and near the south edge of the Birchdale pluton. Some of the felsites near the pluton may possibly be coeval with the pluton. However the presence of thin-bedded rhyolitic tuff in drill hole R-5-2, 3¼ miles (5.2 km) southwest of and on strike with those near the pluton, and the presence of agglomerates containing abundant rhyolite clasts in drill hole R-2-1 suggest that older rhyolites are indeed present adjacent to the pluton. Fletcher and Irvine (1954) report rhyolite flows in southwestern Dobie Township, 2 to 3 miles (3 to 5 km) north of Long Sault Rapids, on strike with the northwesternmost felsic-intermediate belt shown on the Birchdale-Indus map; this belt contains some rhyolitic tuff in the vicinity of drill holes RR-12-1 and RR-12-2.

Some of the dike rocks accept only a slight potassium stain, suggesting possible rhyodacitic compositions; the presence of albitic phenocrysts supports this classification.

The plagioclase phenocrysts are generally highly sericitized and altered but have retained their original shapes despite the generally pervasive foliation that wraps around the crystals (fig. 5). Normal compositional zoning is common. The quartz phenocrysts, on the other hand, commonly have highly undulatory extinction or have been polygonized and stretched out into "eyes." Some quartz phenocrysts are as much as 8 mm in diameter. The phenocrysts vary in abundance from zero to about 50 percent of the rock, with 10 to 20 percent being a common figure. Small biotite phenocrysts occur in one sample near the south end of the Manitou Rapids dike. The groundmass of the felsic dikes generally consists of fine,

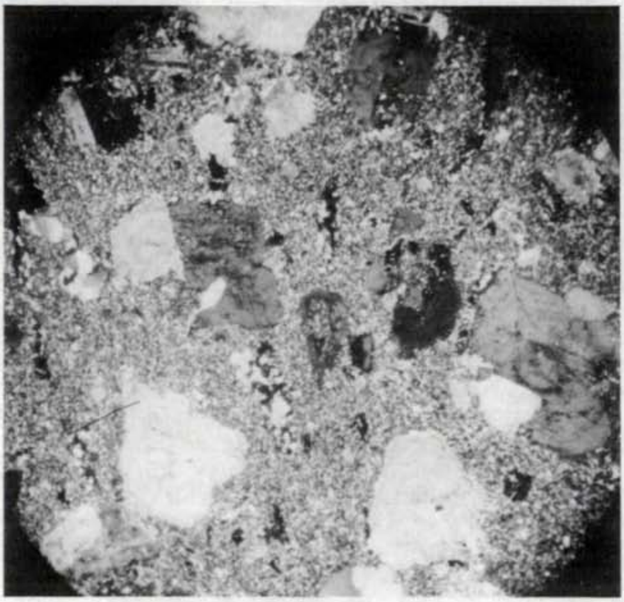

Figure 5 - Photomicrograph of typical foliated dacite with phenocrysts of plagioclase and quartz. Field of view 5 mm. in diameter.

equigranular, holocrystalline, allotriomorphic quartz and feldspar; trachytic texture is rare. Minor alteration products include biotite, muscovite, epidote, carbonate, chlorite, sphene, and blue-green amphibole. The amphibole is minor in these rocks, as compared to those rocks with mafic-intermediate compositions.

Felsic Agglomerate and Lapilli Tuff

Agglomerate and lapilli tuff, generally well-foliated and stretched, are widespread in both outcrops and drill cores (figs. 6 and 7). On weathered surfaces, light green to gray clasts stand out against a medium- to dark-green matrix; in fresh specimens, both clasts and matrix are green. The clasts are commonly about an inch or so in diameter. Larger clasts noted in the area are about 6 inches (15 cm) in diameter; these are exposed in the Manitou Rapids roadside park in Section 36, T.160N., R.26W. Fletcher and Irvine (1954) reported clasts twice this size to the north in the Emo area.

Agglomerate is best developed along the Manitou Rapids dike, and especially along the northern one-third of the dike. The most easily accessible examples are in the just-mentioned roadside park. Good examples are nearby, south of some fields and just east of an old gravel pit about in the center of the W½, Section 6, T.159N., R25W., where interbedded agglomerate, lapilli tuff, and tuff are associated with dacitic dikes.

Agglomerate and lapilli tuff are also present near the northern end of the Sault Rapids dike (Section 6, T.159N., R.26W.), east of the Birchdale pluton in E½ Section 2 and SE¼ Section 16, T. 159N., R.27W., and in drill holes RR-12-2, RR-6-2, R-3-1, R-3-3. R-2-1, R-2-1A, R-2-2 and, possibly, in R-4-2. Most of these outcrops and drill holes are in the central felsic-intermediate belt of the map. It is possible that some of these rocks were formed by weathering and erosion of solidified volcanic rocks, and accordingly would be epiclastic volcanic conglomerates, but the uniformity of clast compositions within each sample suggests a pyroclastic or a reworked pyroclastic origin.

The mineralogy of these rocks is similar to that of the felsic dikes described above. The main difference other than clastic texture is the varying internal texture in the volcanic fragments of different samples. Clasts in at least one agglomerate sample are very fine grained and darker than most, and may be devitrified glassy fragments. In some samples, the fragments are rhyolitic. Most of the metamorphic minerals (biotite, epidote, chlorite, amphibole, and carbonate) occur in the finer grained parts of these rocks between the large clasts.

Felsic Tuff and Volcaniclastic Rocks

All of the agglomerate-lapilli tuff units mentioned above are interbedded with beds of sand-, silt- and clay-sized particles which are here classified as tuff or reworked tuff because of the association with coarser pyroclastic rocks. A better recognition criterion would be the presence of glassy fragments with shardy or pumiceous textures, but the great age of these deposits, as well as the metamorphism and deformation, would have caused recrystallization of the glass and probably also destruction of original textures.

Figure 6 - Felsic-intermediate agglomerate and tuff (light) adjacent to Manitou Rapids dike (dark) in Manitou Rapids roadside park, Section 36, T.159N., R.26W.

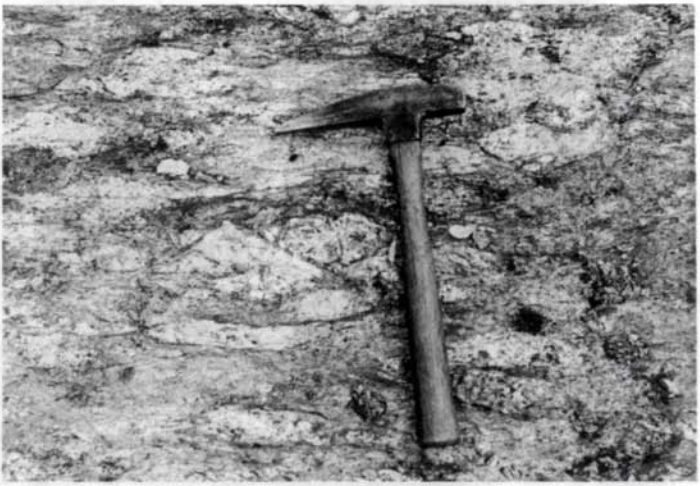

Figure 7 - Felsic-intermediate agglomerate, NW 1/4 Section 6, T.159N., R.25W. Note lighter-colored clasts in darker matrix.

Traces of possible shards (fig. 8a) remain in thin (1/4 to 1 inch (0.5 to 2.5 cm) tuff beds at a few localities along the Manitou Rapids dike and also in drill hole RR-6-1. Dark, fine-grained clasts with felsitic fabrics in some beds may indicate devitrified glasses. Possible fiamme (flattened and wispy pumiceous fragments), now recrystallized but still fine-grained, occur in drill hole R-3-1 (fig. 8b). Crystal tuff composed nearly completely of plagioclase was observed in a few samples from near the Manitou Rapids dike and also in drill hole R-5-2.

Figure 8a - Photomicrograph of possible shards from felsic-intermediate tuff exposed along Manitou Rapids dike in Section 6, T.159N., R.25W. Field of view 5 mm in diameter.

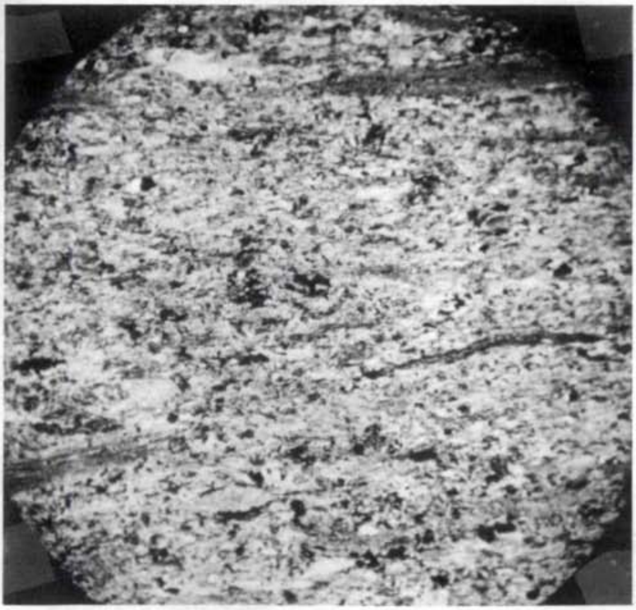

Figure 8b - Photomicrograph of possible fiamme from drill hole R-3-1. Field of view 5 mm in diameter.

In most occurrences, the felsic volcaniclastic rocks are either not clearly interbedded with agglomerate or they do not contain evidence of original glass; accordingly, their genesis is subject to interpretation, but various indirect lines of evidence, as follows, suggest either a direct pyroclastic origin or a slight reworking of pyroclastic materials:

(1) The primary components of these volcaniclastic rocks are plagioclase (commonly zoned), volcanic quartz (unit crystals, some with embayments or pyramids), and volcanic rock fragments (some with phenocrysts of plagioclase and quartz), as seen in Figures 9 and 10. All of these components are very similar to the components of the felsic dike rocks and the tuff. Most of the material appears to be dacitic, but staining for K-feldspar indicates the presence of some rhyodacitic and rhyolitic volcanic fragments. Brownish hornblende as free crystals and as phenocrysts in some volcanic rock fragments is an additional primary component in some beds (fig. 11), notably in outcrops in Section 10, T.159N., R.28W. and in drill hole R-5-2. Large volcanic quartz grains are lacking in some samples, but generally are present in at least minor amounts. Mafic volcanic rock fragments, which might be expected to be present in at least trace amounts if the clasts were the result of erosion or fragmentation of a lithified and solidified volcanic terrane, are conspicuously absent. Finally, the rocks are generally greenish rather than gray, an admittedly subjective criterion used here as an indicator of volcaniclastic rather than sedimentary rocks.

(2) In several thinly bedded exposures and drill cores, felsic laminae alternate with more mafic (probably intermediate) darker green beds and laminae (fig. 12). The original compositional differences are manifested after metamorphism by alternations of amphibole-rich, biotite-rich, epidote-rich, and feldspar-rich laminae visible in thin section (fig. 13). A few of the laminae lacking mafic minerals contain substantial K-feldspar.

(3) Where visible, bedding is characteristically thin and has planar top and bottom contacts (fig. 12). Locally, a series of well exposed beds may include some that are only a few inches thick and others that are as much as several feet thick. The thicker beds are generally coarser grained than the thinner ones. Grading of grain size is present in some drill core samples in beds less than an inch thick, but was not observed in outcrops within the map area. This general lack of both thick beds and grading and the complete lack of Bouma internal sedimentary intervals, channeling, and loading features, all common structures in graywackes of turbidite sequences, suggest that turbidity currents were not an important mechanism in the sedimentation of these layered rocks in the Birchdale-Indus area. Small-scale folds without an accompanying cleavage were observed in thin sections from drill hole R-5-2 and are interpreted to be the result of primary, soft-sediment deformational processes. Several drill cores classified by company geologists record features indicative of soft-sediment deformation.

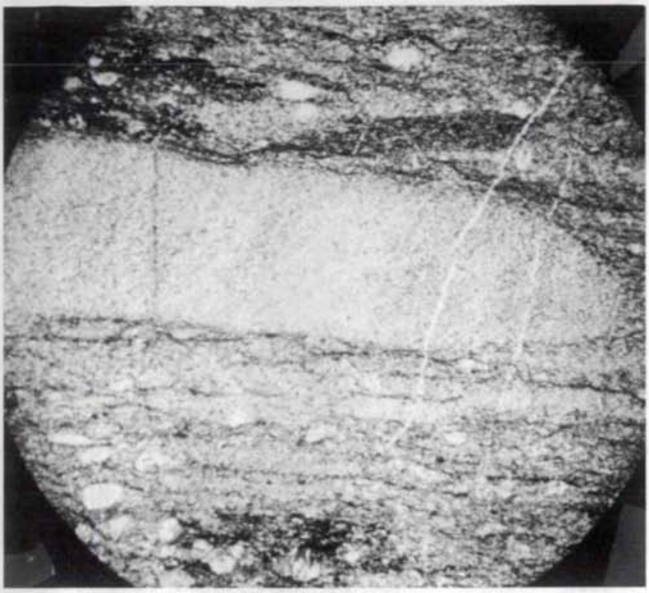

Figure 9a - Photomicrograph of felsic lapilli tuff from drill hole R-5-2. Note large fine-grained felsic volcanic rock fragments. Field of view 5 mm in diameter.

Figure 9b - Photomicrograph of volcaniclastic rock from N 1/2, Section 10, T.159N., R.28W. Note varying textures and colors of volcanic rock fragments. Field of view 5 mm in diameter.

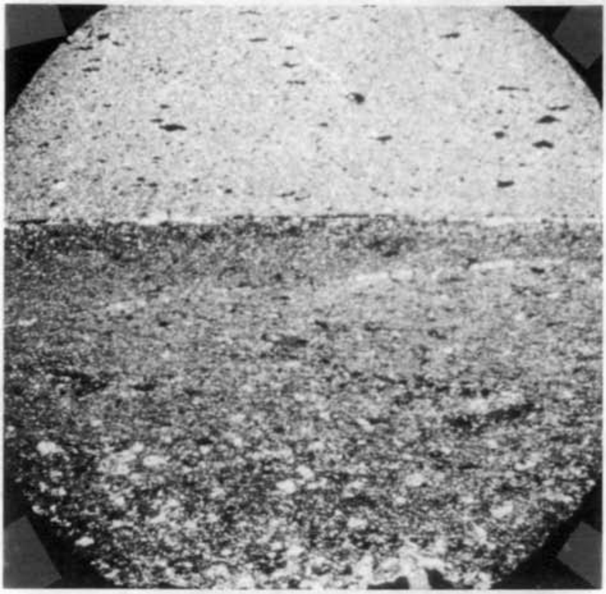

Figure 10a - Photomicrograph of fine-grained felsic tuff from drill hole R-5-2. Staining for K-feldspar indicates a rhyolitic composition. Note grading. Field of view 5 mm in diameter.

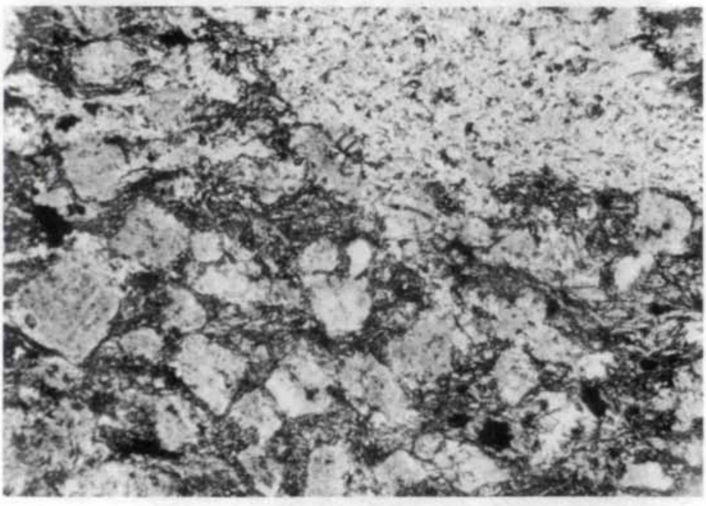

Figure 10b - Photomicrograph of plagioclase-rich felsic-intermediate tuff from drill hole R-3-3. Note large light-colored felsic volcanic rock fragment. Field of view 2 mm across.

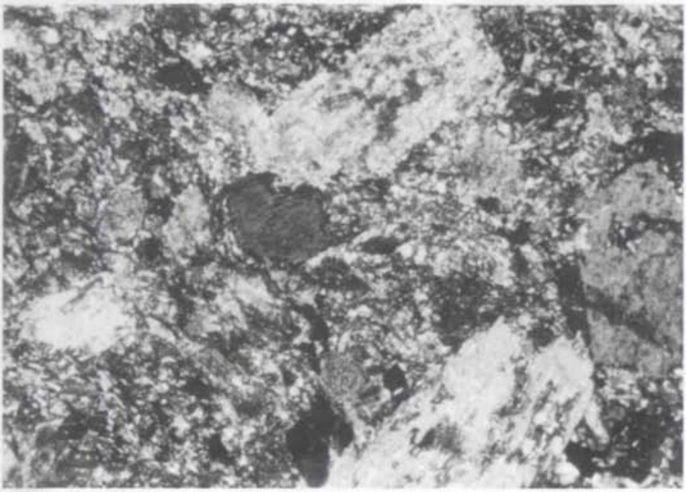

Figure 11a - Photomicrograph of hornblende-rich felsic-intermediate tuff from center Section 34, T.159N., R.28W. Most of the dark crystals are brownish hornblende. Remainder is felsic volcanic rock fragments and plagioclase. Field of view is 2 mm across.

Figure 11b - Photomicrograph of detrital brown hornblende grains (dark center) with metamorphic overgrowths of blue-green hornblende. From drill hole RR-12-2. Grain is 0.5 mm in diameter.

Figure 12 - Thin tuff beds from SE 1/4, NE 1/4, Section 21, T.159N., R.25W.

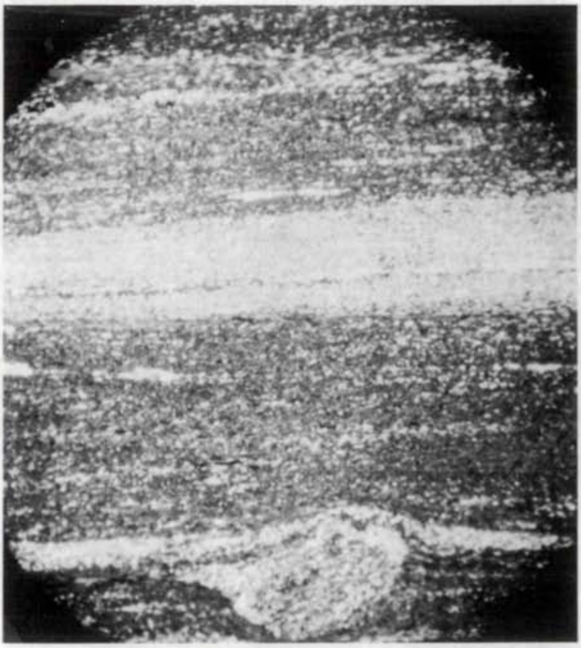

Figure 13 - Photomicrograph of thin compositionally-different laminae in intermediate tuff from drill hole BD-1. Amphibole-rich (broad medium-gray bands), biotite-rich (thin dark gray bands) and feldspar-quartz-rich alternations; one garnet crystal at left. Field of view is 5 mm across.

The metamorphic minerals present in the felsic volcaniclastic rocks include biotite, blue-green amphibole, chlorite, epidote, carbonate, and sphene. Evidently there were slight compositional variations in the original rocks, for some layers contain biotite, some contain amphibole, and some contain both. In no case, however, is amphibole as abundant as in the mafic-intermediate volcaniclastic rocks. Many rocks are so thoroughly recrystallized and cataclasized that the original texture is essentially destroyed; in these samples, the presence of biotite or the presence of only a modest amount of amphibole was used as evidence for classification as a felsic volcaniclastic rock.

Iron-Formation and Metasedimentary Rocks

In the Emo area, Fletcher and Irvine (1954) delineated three units of graywacke with minor basal conglomerate. Two of these units contain iron-formation (fig. 2), and one of these enters Minnesota in the northeast corner of Plate 1; the trend of this unit is clear from the magnetic anomaly associated with the iron-formation. In the Emo area, knowledge of the graywacke portion of this unit is based on a single outcrop about 5 miles (8 km) from the International boundary and the iron-formation is known only from drill holes. Outcrops in this unit are equally poor in Minnesota.

A small outcrop of hornblende-quartz-andesine schist is present on the bank of the Rainy River near the small point in the NE¼, SE¼, Section 3, T.159N., R.25W. A similar, but coarser, rock with large poikilitic hornblende and minor biotite was encountered in drill hole IH-13 (tbl. A-1). Where the magnetic anomaly crosses the Manitou Rapids dike in the SW¼, NE¼, SW¼, Section 16, T.159N., R.25W., a fine-grained biotite-quartz-plagioclase schist occurs near a single small exposure of iron-formation.

The iron-formation consists of highly contorted thin laminae of magnetite, chert, and felsic tuff. Alteration products include hematite, biotite, and minor amphibole, tourmaline, and microcrystalline iron silicate minerals. The lone exposure of iron-formation and the other three metasedimentary exposures are on the magnetic high that trends across the Birchdale-Indus map area from the northeast corner to the southwest corner (Bath and others, 1964; 1965; Meuschke and others, 1957). Within the Emo map area, this band of iron-formation has been traced by air and ground magnetometer work over a distance of 7 miles (11 km) (Fletcher and Irvine, 1954). The highest reported grade is 34.8 percent iron from a 35-foot (10 m) thick garnet-mica-magnetite zone in drill cores.

In Minnesota, the iron-formation can be traced as a magnetic anomaly for nearly 30 miles (48 km), mostly within the boundaries of the Birchdale-Indus map sheet. The anomaly is not continuous (Bath and others, 1964; 1965; Meuschke and others, 1957); this may be due to either (1) a lensoid nature of the iron-formation, (2) local oxidation of the magnetite, (3) intrusion of subvolcanic or plutonic rocks cutting across the zone (e.g., the small granitic pluton in the southwestern part of the map), or (4) facies changes from oxide to sulfide or carbonate iron-formation facies. A prospect pit in sulfide concentrations adjacent to the south side of the Manitou Rapids dike just to the northwest of the exposure of iron-formation is not directly on the anomaly, but sufficiently close to suggest a genetic relationship.

Holes drilled by the W.S. Moore company in 1952 (the KC series on Plate 1; tbl. A-1) encountered two 20-foot-thick (6 m) zones (indicated core footage) of what was described as magnetic iron-formation and graywacke slate. Sulfides occur with the magnetite in chert beds; oxidation has occurred in some sections. The highest reported iron content is 23 percent iron.

All three of the metasedimentary rock outcrops mentioned above could be more highly metamorphosed equivalents of the graywacke exposed in the Emo area. Mineralogically, they resemble the metagraywacke sampled for comparative purposes 11 miles (18 km) north of the International boundary on Highway 70; these beds, as much as a few feet thick, display excellent grading despite their recrystallization to an amphibole-biotite-quartz-plagioclase rock.

Unfortunately, there is only one additional outcrop on strike with the iron-formation and metasedimentary unit within the Birchdale-Indus map area, although the unit is presumed from aeromagnetic data to extend across the entire map area. This outcrop is in the center of the E½, Section 12, T.158N., R.28W., near the granitic pluton in the southwest part of the map area. It consists of a sequence of ungraded felsic tuff beds as much as 4 inches (10 cm) thick. However, there are four additional drill holes on or near the magnetic anomaly, drilled by the Exxon Corporation during exploration for massive sulfides (tbl. A-1). Drill hole R-1-1 consists of foliated chloritic schist with very poor bedding and a few beds of lapilli tuff and tuff; fine-grained disseminated magnetite is common. A single two-inch (5 cm) graded bed was noted in the 450 feet (137 m) of rock cut by the drill core. The rock in drill hole R-4-1, which penetrated 180 feet or 55 m (140 feet or 43 m true thickness) of massive sulfides, is brecciated felsic-intermediate volcaniclastic material lacking obvious bedding. The rock in drill hole R-4-2 is light-colored felsic volcaniclastic rock with indistinct bedding and one 30-foot-thick (9 m) zone of possible agglomerate; appreciable sulfide is present throughout 100 feet (30 m) of this section. Drill hole R-4-3 consists largely of thin-bedded, black (graphitic) argillaceous rock with felsic breccia and thinly bedded tuff at the base.

The characteristics of the rock penetrated in the drill holes and observed in outcrops are unlike those of a graywacke sequence, which commonly consists of well-graded prominent beds having abundant sedimentary structures. These characteristics generally survive high-grade metamorphism, and even near an intrusive pluton in the northern part of the Emo map area are well preserved. Therefore these rocks, although described here under the heading of metasedimentary rocks, perhaps should be grouped within one of the felsic-intermediate volcaniclastic rock units, which also contain the only definite metasedimentary rock in the area, the iron-formation. Undoubted graywackes do occur in the northern part of the Emo map sheet, and these have been interpreted by Fletcher and Irvine (1954) to be within the same stratigraphic unit as the graywacke under discussion here which contains the iron-formation. Graywacke may also be present across the International boundary just beyond the northeast corner of the Birchdale-Indus map sheet, but it appears that along strike in Minnesota, a volcaniclastic facies is dominant instead. If graywacke-type sedimentary rocks are associated with this iron-formation in Minnesota, they must be minor in abundance.

Other Rock Types

Two additional rock types, which are not exposed in the map area, are interpreted to be possibly present beneath glacial deposits and deserve some mention here.

Two major stocks and several smaller satellite bodies of mafic intrusive rock (post-volcanic and pre-mafic dike) occur just across the International boundary in the Emo area (Fletcher and Irvine, 1954). They consist of diabasic gabbro, medium-grained hypersthene gabbro, and norite. In the stock in Dobie Township, northwest of Emo, massive and disseminated pyrrhotite and pentlandite occur in the norite phase.

Two small, weakly positive magnetic anomalies occur in Minnesota, one about 2 miles (3 km) southwest of the Dobie intrusive and the second about 1½ miles (2.5 kilometers) further south (Meuschke and others, 1957). A shallow hole (M-1 on Table A-1) was drilled in the NE corner of Section 2, T. 159 N., R. 26 W. by the Minnesota Department of Natural Resources in conjunction with the Minnesota Highway Department, to determine the possible existence of similar mafic rocks, but it penetrated only porphyritic dacite. As the center of the anomaly is near the NE corner of Section 1, the hole may have missed the target. However, another shallow drill hole (IH-13 on Table A-1), near the junction of the magnetic anomaly of the Birchdale-Indus map area and the Rainy River, penetrated a 35-foot-thick (10 m) dike or sill of gabbroic rock, which may be related to the Emo rocks. It contains augite, orthopyroxene, biotite, plagioclase and 5 percent of perthitic K-feldspar.

Another DNR shallow drill hole, about 3 miles (5 km) south-southwest of Emo in the NW corner, SW¼, Section 16, T. 159 N., R. 25W. (IH-12 on Table A-1), penetrated a boulder which is similar to the Emo rocks; it consists of fresh labradorite, clinopyroxene, orthopyroxene, biotite, and opaques. Glacial striations in the area of the drill hole (fig. 14) point back towards the mafic pluton east of Emo, but a small mafic pluton could also be present in Minnesota between the drill hole and the village of Emo.

Another boulder in the same shallow drill hole (IH-12) consists of peridotite, a rock not seen in outcrop either in the Emo area or in the Birchdale-Indus area. It consists of labradorite, olivine (which is optically negative with a high 2V and is therefore high in iron), augite, and hypersthene. The boulder may well have been transported by glaciers from Canada, but as the till here is quite thin it is also possible that some peridotite exists in Minnesota northeast of the drill hole. One exposure of peridotite was described from the Rainy Lake area (Ojakangas, 1972, p. 166).

Granitic Intrusions

Two small granitic stocks are exposed within the map area; a third is exposed along the south edge of the map area (fig. 2; pl. 1; Sims and Ojakangas, 1973), and the western edge of a large fourth stock--exposed in the Emo area (Fletcher and Irvine, 1954; Davies and Pryslak, 1967)--is interpreted to be present along the east edge of the map sheet, although no rock is exposed here. Of these four stocks, only the Birchdale stock is well exposed; only one outcrop has been found on the southern body, and only two on the small stock between the Sault Rapids and Manitou Rapids dikes. All appear to be, in large part, discordant intrusions.

As the foliations in the stocks are generally parallel to the regional foliation in the country rocks, the stocks are considered as being either pretectonic or syntectonic relative to the regional deformation. This structural relationship also is characteristic of some plutonic rocks in the Emo area (Fletcher and Irvine, 1954, p. 18). Foliations in the eastern part of the Birchdale pluton are conformable with the margin of the intrusion and possibly represent primary structure imparted during emplacement.

The Birchdale pluton is pink where weathered and gray-pink to gray where fresh. Small dark inclusions of greenstone, oriented parallel to foliation, are common. The pluton is largely composed of quartz monzonite that has a slightly gneissic texture. One thin section shows 35 percent perthitic K-feldspar with grid twinning, 30 percent quartz, 25 percent oligoclase, and minor muscovite, biotite, chlorite, opaques, and calcite. Hornblende is visible in hand specimens in the southeastern one-third of the pluton. A study of 18 stained and slabbed specimens (R. Ringsred, oral comm., 1974) showed 12 quartz monzonites, 3 granites, 1 monzonite, 1 diorite, and 1 hybrid rock. K-Feldspar content is highest in the south (to 66 percent), plagioclase content is highest in the east-southeast (to 58 percent), and quartz content is highest in the northeast quarter (to 37 percent). Goldich and others (1961, p. 61) suggested that the "Birchdale gneiss" was originally a sediment, but all relationships observed in this study suggest that it had a magmatic origin.

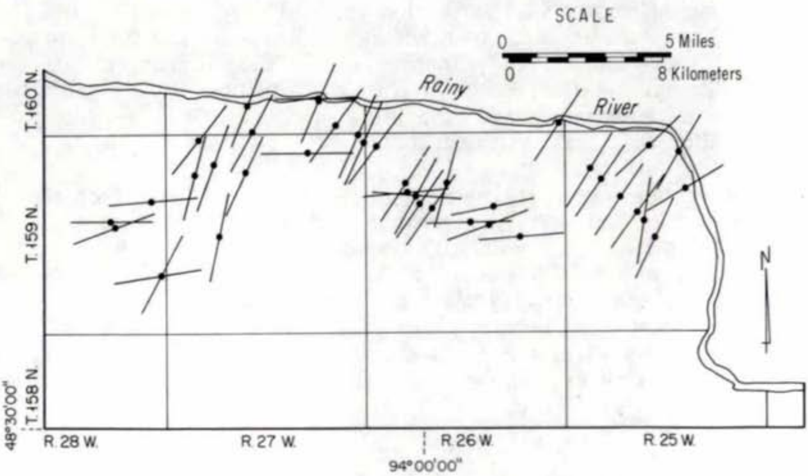

Figure 14 - Generalized map of Birchdale-Indus area showing locations of striated outcrops (dots) and trends of striations. Note two dominant trends.

Small diorite and andesite dikes cut both the pluton and the country rock in the southeast corner of the pluton, and probably are related to the pluton. Listerud (1974) mapped a small part of the pluton near the group of drill holes (SE ¼, Section 16) and noted that numerous simple granitic pegmatite veins cut the granite and the andesitic dikes. One small exposure contained black tourmaline crystals as much as 6 inches (15 cm) long and quartz and feldspar crystals as much as 18 inches (46 cm) across. This is the only complex pegmatite found in the Birchdale-Indus and Emo map areas. Only one other has been observed in the entire region, a 4-inch (10 cm) stringer of tourmaline-bearing pegmatite near Clementson, about 8 miles (13 km) west of the western boundary of the Birchdale-Indus map.

A small exposure of metadiorite (?) on the Rainy River near the northwestern corner of the Birchdale pluton may be either a metamorphosed part of the mafic-intermediate volcanic unit exposed in Ontario just across the river, or a hybrid phase of the pluton. It consists of quartz, plagioclase, hornblende, biotite, and apatite. Alteration products include blue-green amphibole, chlorite, and epidote.

The pluton in the southwestern part of the map area is a reddish, coarse-grained rock that was not studied petrographically.

The small pluton near the center of T.159N., R.26W., between the Sault Rapids and Manitou Rapids dikes, is a light pink quartz diorite consisting of plagioclase, hornblende, and less than 5 percent K-feldspar as scattered small grains. It is somewhat granulated and recrystallized. Its texture is suggestive of hypabyssal emplacement. It may extend farther to the south than shown on the map and could be responsible for the break in the magnetic anomaly, but this is strictly conjectural.

The plutonic rock shown on the eastern edge of the map area is described in Ontario as quartz monzonite with 25 percent quartz, 30 percent microcline, 25 percent andesine and 8 percent biotite (Fletcher and Irvine, 1954, p. 21). They describe the other granitic rocks in the Emo map area as granodiorite, hornblende granodiorite, and monzonite.

Mafic Dikes

Several northwest-trending, black to greenish-black, nearly vertical mafic dikes cut all the Lower Precambrian rocks in the area (pl. 1). The two well exposed dikes, the Manitou Rapids dike and the Sault Rapids dike, are also exposed intermittently in the Emo map area (fig. 2). A few other dikes are less well exposed in both map areas.

At most localities, the dikes are 150 to 200 feet (45 to 60 m) wide, but at one locality near its north end, the Sault Rapids dike is about 400 feet (120 m) wide. Thin dikes ranging in width from a few inches to a few feet commonly occur along the flanks of the main dikes and within the Manitou Rapids dike at the Rainy River. All dikes have sharp contacts and prominent chilled margins, and the thicker dikes have very coarse interiors. Minor pegmatitic segregations and internal flow boundaries are uncommon but locally present.

In addition to the two dikes named above, a third prominent dike is exposed in the Emo area, about 1½ miles (2.5 km) northeast of and parallel to the Manitou Rapids dike, but it is poorly exposed in Minnesota. Dikes and lineaments on strike with these three dikes occur far to the northwest on islands in Lake of the Woods, suggesting that the dikes have a strike length of more than 60 miles (95 km).

The rocks composing the dikes generally are highly altered but appear relatively fresh at certain localities. The plagioclase appears to be labradorite. Both orthopyroxenes and clinopyroxenes were observed; the clinopyroxenes generally are highly uralitized, with alteration products including actinolite, chlorite, and epidote. Brownish hornblende occurs in some samples and appears quite fresh; biotite was observed in one sample; and quartz occurs in all samples as a minor constituent. Opaques and accessory apatite also are present. Most minerals are interstitial to the plagioclase.

Similar mafic dikes elsewhere in northern Minnesota have been studied by Hanson (1968), Hanson and Malhotra (1971), and Sims and Mudrey (1972). Hanson (1968) dated one dike in the Rainy Lake area at 2100 m.y., which is a minimum age. Other dikes have minimum K-Ar dates ranging from 1395 to 2240 m.y.

Glacial Deposits

An isopach map of unconsolidated materials in the western half of the Birchdale-Indus map area has been prepared as part of the Roseau 1:250,000 map sheet by Mossler (1973). In much of the area these materials are less than 100 feet (30 m) thick, but thicknesses of nearly 200 feet (60 m) are present locally. To the west of the Birchdale-Indus map area (pl. 1), southwest of Baudette, thicknesses of the drift are commonly on the order of 200 feet (60 m) and locally are more than 300 feet (90 m). Far to the west, near the North Dakota border, more than 400 feet (120 m) of glacial materials cover the bedrock over large areas.

Matsch (written comm., 1973) has reconnoitered the Birchdale-Indus and adjacent areas in Minnesota and has reported drift deposits of two different ice lobes. The Rainy lobe advanced from the northeast and deposited till and outwash rich in Precambrian rock fragments of various types, especially granite. Later, the St. Louis sublobe advanced from the west and northwest and deposited materials rich in light-colored Paleozoic carbonate fragments as well as granite. Lake deposits are found stratigraphically between the products of these two advances, and deposits of Lake Agassiz occur above the carbonate-bearing units beneath the post-lake peat deposits.

Deep drainage ditches in the region have resulted in excellent exposures of peat and the underlying lake sediments. In this investigation, several feet of excellent varved clays with dropstones were found at locations east and west of the Birchdale-Indus map area. Gravel pits in the N½, Section 35, T.160N., R.27W., about 2 miles (3 km) northeast of Birchdale, display excellent glacial outwash deposits.

Measurements of glacial striations on 36 outcrops in the Birchdale-Indus area show evidence of two glacial advances (fig. 14); the dominant set (N=27) has an azimuthal trend of 215° and the other set (N=11) has a trend of 85°. The Emo map sheet shows a number of striations trending about 220° (Fletcher and Irvine, 1954), and Davies (1973) showed the existence of the same trend in the Fort Frances area. Elsewhere in the region, including the western part of the International Falls 1:250,000 map sheet and the eastern half of the Roseau 1:250,000 map sheet, 22 additional readings indicate the same azimuth of 85° and 44 additional readings indicate an azimuth of 205°. Altogether, nine outcrops contain both sets. Evidence as to which set is younger is contradictory on different outcrops, but the superposition of the limestone-bearing drift upon the granite-bearing drift indicates that the easterly-trending set is probably the younger.

Davies (1973) summarized studies of the glacial deposits of the Fort Frances area done by other workers. They record four glacial movements (presumably all Wisconsin in age); the first was from the northwest and deposited about 6 feet (2 m) of calcareous till. This highly oxidized till was covered by sandy till from the northeast. The third advance was from the west, spreading a calcareous till once again, and this was followed by lake deposits. The fourth advance was from the northeast, but it stopped 12 to 15 miles (19 to 24 km) north of the International boundary. The second and third of these advances are apparently the ones documented by sediments in the Birchdale-Indus area, but the contradictory evidence on juxtaposition of striae could be an indication that some of the striae date to the first of the four glacial advances.

Deep pre-glacial weathering is evident in two drill cores (40918 and 40920 of Table A-2) put down by the International Nickel Company; these are located about 30 miles west of the Birchdale-Indus map area, and the weathered zones are about 140 feet (43 m) and 90 feet (27 m) thick respectively (estimated true thicknesses). A hole (BID-1) drilled by Ridge Mining Company shows 100 feet (30 m) of weathering of the Precambrian rocks. Thick regoliths elsewhere in the state have commonly been ascribed to weathering during the Cretaceous period (e.g., Austin, 1970; Goldich, 1938), but Morey (1972) described a pre-Upper Cambrian regolith in eastern Minnesota.

METAMORPHISM

All the Archean rocks of the area have been regionally metamorphosed to amphibolite grade by the Algoman event. The metamorphic minerals developed in each rock type have been previously noted and will only be summarized here.

The felsic volcanic rocks generally show less obvious effects of the regional metamorphism than do the more mafic rocks; nevertheless, they do contain the same metamorphic minerals, but biotite is a more common constituent. The mafic-intermediate rocks are commonly more or less completely recrystallized to blue-green hornblende and lesser epidote, and in fact many are amphibolites. The amphibole is commonly pleochroic, ranging from a light bluish green or yellowish green to a deep bluish green, and only rarely are the colors pale. Although some amphibole is actinolite or even tremolite, most appears to be hornblende. Blue-green amphibole rims have been noted on primary brownish hornblende grains in several samples.

In the few specimens where plagioclase compositions were determinable optically, they proved to be oligoclase or andesine. Garnet is common, and several mafic rocks are now made up completely of blue-green hornblende and abundant garnet. Garnet-biotite rocks also occur. Epidote minerals vary greatly in birefringence colors and degree of crystallinity. Patchy chlorite is common, apparently a retrograde mineral formed at the expense of biotite and other minerals, but commonly the mineral it is replacing cannot be determined. Based on criteria presented by Albee (1962) iron-rich chlorite (without abnormal interference colors) is common, iron-magnesium chlorite (blue-violet interference colors) is abundant, and magnesium-iron chlorite (brown interference colors) is rare. Grayish-blue tourmaline was noted in several samples as an accessory metamorphic mineral; it is probably iron-bearing (schorlite). Carbonate, sphene, magnetite and sulfides are other common accessories.

An intensive study of the metamorphism of these rocks was not one of the objectives of this project. However, obvious mineral assemblages were noted. The metamorphism generally reached epidote-amphibolite facies, as indicated by the assemblage of plagioclase-epidote-bluegreen hornblende in mafic rocks. The assemblage in one pelitic sample, biotite-muscovite-garnet, is consistent with this grade of metamorphism, as are the assemblages in felsic-volcanic rocks, which contain andesine-epidote-biotite. Some rocks contain an assemblage of chlorite-actinolite-epidote(?), and this may imply that locally metamorphism reached only greenschist grade. Local veins of prehnite-calcite-chlorite indicate a retrogressive event in the prehnite-pumpelleyite facies. Systematic changes in grade relative to location were not sought during this study.

Listerud (1974) has determined that the Birchdale pluton has superposed a contact metamorphic mineral assemblage characteristic of the albite-epidote-hornfels facies upon the volcanogenic rocks adjacent to the pluton.

Hanson and Malhotra (1971) ascribed the low grade metamorphism of the northwest-trending Middle Precambrian mafic dikes to burial. Sims and Mudrey (1972) suggested that a Middle Precambrian deformation and metamorphism affected mafic dikes in the vicinity of the Mesabi Range. It is also quite possible that the metamorphism, especially the uralitization of the gabbroic dike rocks, may be the result of automorphism (deuteric alteration).

STRUCTURE

The Birchdale-Indus-Emo area constitutes a fault block between two major right-lateral strike-slip faults, as described in the section on Regional Geology. The volcanic-sedimentary sequence within the fault block is isoclinally folded (fig. 15); bedding and foliation are generally steep to vertical and parallel or subparallel to one another, but divergences are not uncommon. Drag folds are rare. Two major fold axes with northeasterly trends cross the Birchdale-Indus area.

Discordant granitic plutons have intruded the sequence in Minnesota; most of the foliations in the plutons are parallel to regional structure of the metavolcanic rocks, indicating the plutons are pre- or synkinematic in age (pl. 1). In the Emo and Fort Frances areas, larger granitic plutons as well as several small and large mafic plutons are also present (Fletcher and Irvine, 1954; Davies, 1973). Many of these appear to have been intruded along fold axes; this relationship is not obvious in the Birchdale-Indus area, although the Birchdale pluton is located on a synclinal axis.

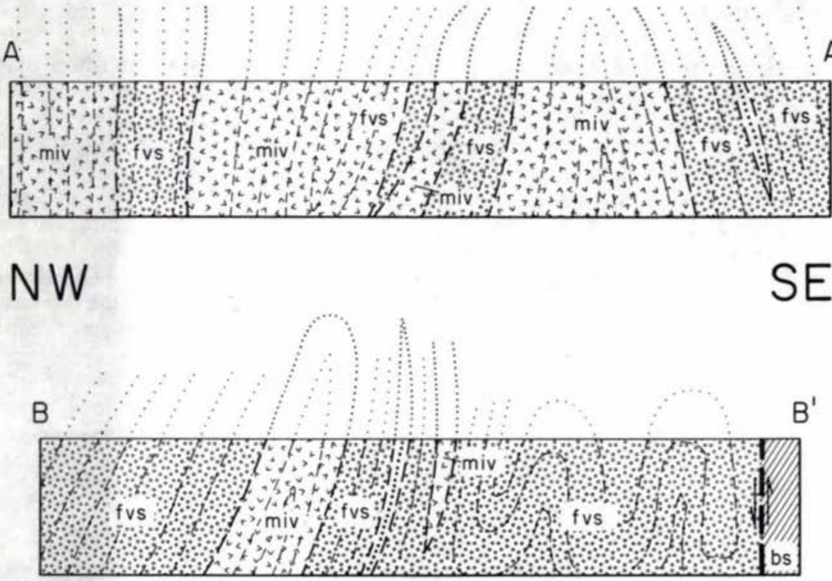

Figure 15 - Structure sections. See Figure 2 and Plate 1; fvs, felsic-intermediate volcanic rocks; miv, mafic-intermediate volcanic rocks; bs, biotite schist with minor hornblende schist.

Folds

The lack of outcrops makes detailed mapping of folds difficult. Nevertheless, sufficient stratigraphic top indicators (mostly pillowed lavas) were available for the delineation of two major fold axes, an anticline and a syncline, within the Birchdale-Indus area (pl. 1). Projection of fold axes into the area from adjacent Ontario helped to verify the presence of these axes (fig. 2).

The northeast-trending synclinal axis southwest of the Birchdale pluton is fairly well established from pillow tops in 8 outcrops and 3 additional tops obtained from a few thin graded beds in drill cores. One of these tops, in drill hole R-5-2, suggests that the axis might pass southeast of the hole, rather than 0.75 miles (1.2 km) to the northwest as shown on the map. However, due to other considerations, it was not drawn here; the southeast-facing top in thin bedded tuff may be the result of minor folding.

The syncline has not been mapped in the Emo area near the International boundary, but a northwest-facing pillow lava top about 6 miles northeast of the Birchdale pluton would fall on the southeast flank of this syncline if indeed it extends into Canada (fig. 2). A synclinal axis shown on the Emo map is not aligned with the Birchdale-Indus syncline, but it could be interpreted as lying further to the southeast, in line with the Birchdale-Indus syncline, for only the aforementioned northwest-facing pillow top defines its southern flank.

The northeast-trending anticlinal axis is less firmly established than the syncline, but is based on a reasonably sound interpretation. The four northwest-facing tops on the southeast flank of the syncline southwest of the Birchdale pluton, plus two pillowed lava outcrops along the Sault Rapids dike and one on the Manitou Rapids dike, delineate the north flank of the anticline; only one pillowed lava top in Section 23, T.159N., R.26W. and one thin graded bed in drill hole R-1-1 face southeast and delineate the southeast flank. This anticlinal axis is drawn in the Emo area on the basis of only two stratigraphic tops (Fletcher and Irvine, 1954). Two additional questionable northwest-facing tops in the easternmost mafic-intermediate unit on the east edge of the Birchdale-Indus map could signify minor folding on the flanks or the presence of another synclinal axis.

A pervasive foliation, strong to faint, is common in most rock types, with the exception of the late mafic dikes. Commonly the foliation and the bedding are parallel to subparallel, as expected in an area of isoclinal folding.

Structural lineations in the east half of the Birchdale-Indus map area generally plunge to the northeast at angles of 25 to 70°; the average plunge is about 40°. In the west half of the map area, they plunge southwest at angles of 15 to 80°; the average plunge is about 45°. The boundary between these areas of different plunges is approximately the Sault Rapids dike (fig. 2). Thus, the anticline in the Birchdale-Indus area is doubly plunging.

The significance of this variation in plunge is conjectural, but one possibility is that the initial isoclinal fold, with a subhorizontal northeast-trending fold axis, was refolded along a north-northwest-trending axis. The broad bends in the lithologic units on the map, and the the tight fold in the northeast corner of the Birchdale-Indus map, best exemplified by the magnetic anomaly, also suggest refolding. Additional evidence for two deformations is found in highly folded rocks just east of the Birchdale pluton, in SW¼, Section 2, T.159N., R.27W. There an S_1 foliation parallel to bedding with an original northeasterly trend has been intricately refolded into small folds varying in wave length from one inch to several feet and plunging at 60 to 65° to the north and northwest. Some evidence for a third fold system is also present here, for a vertical cleavage trending east-northeast cuts across the F_2 folds. About 1.5 miles to the southeast, near the east edge of Section 14, T.159N., R.27W., an outcrop of mafic rocks displays two foliations on different parts of the same outcrop, one trending due north and dipping 80° E., and a vertical one trending east-southeast; thin sections show an intense crinkling of amphibole and chlorite.

In a thin section of a foliated dacite from Manitou Rapids, a faint second cleavage cuts the prominent foliation at about 35°, and in a thin section from nearby, in the SW¼, NW¼, Section 6, T.159N., R.25W., two foliations cross at about 80° (fig. 16).

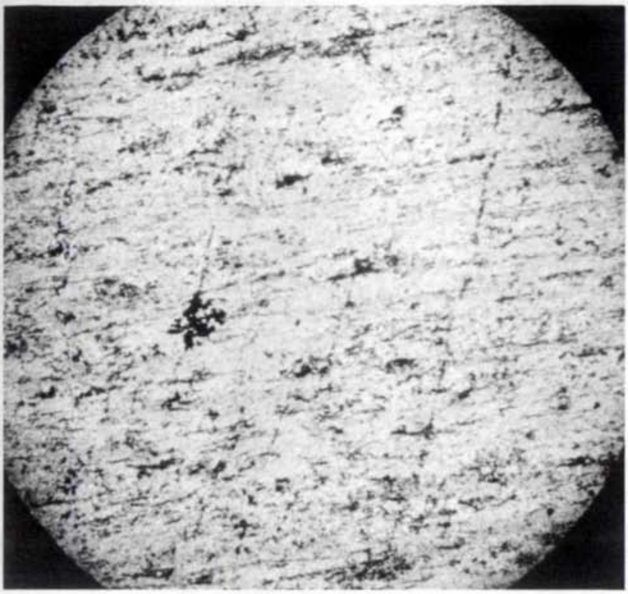

Figure 16 - Photomicrograph of felsic tuff with two foliations, from NW 1/4 Section 6, T.159N., R.25W. Field of view 5 mm across.

In the area of the Fort Frances map sheet, just to the east of the Emo-Birchdale-Indus area, Davies (1973) shows east-trending major folds cut by north-northeast-trending cross folds, and cites some evidence for three deformations.

In addition to the anticline and syncline in the Birchdale-Indus area, two additional folds, an anticline and a syncline, can be mapped in the vicinity of Clementson, about 8 miles (13 km) west of the west edge of the Birchdale-Indus map. Judging from the wave lengths of the folds in the two areas (a quarter of a mile to a few miles), it is likely that additional axes are present between these two areas, but the lack of outcrop prohibits verification of this.

Two northeast-trending anomalies along zones of iron-formation are prominent in the region. One in the Birchdale-Indus-Emo area has already been discussed; the other crosses the International boundary about three miles north of the northwest corner of the Birchdale-Indus map (Meuschke and others, 1957; Bath and others, 1964). This magnetic trend was traced over a distance of about 35 miles (55 km), from the northeast corner of T.158N., R.34W. to the northwest corner of T.160N., R.28W., by John Gruner in 1936 (notes in files of the Minnesota Geological Survey), and can be traced further to the southwest as intermittent magnetic anomalies. Outcrops of metamorphosed iron-formation, now biotite schist, amphibole gneiss, and migmatite, all with appreciable amounts of magnetite, are situated on this trend in the center of Section 17, T.159N., R.30W. (Sims and Ojakangas, 1973).

In the central part of the Emo map sheet, there is a zone of iron-formation with a similar trend. If allowance is made for structural complications, it is approximately on strike with the trend in Minnesota and may be the same unit. It might be suggested that these two elongate zones of iron-formation are remnants of the same stratigraphic unit, now separated by about 12 miles (19 km) of largely volcanogenic rocks in Minnesota and by 6 miles (9.5 km) of similar rocks in the Emo area. If so, then a major anticlinorium may be located between the two anomalies, with the Birchdale-Indus-Emo folds being smaller amplitude folds on the major structure. In addition, the iron-formation appears to delineate the northwestern and southeastern boundaries of a single felsic-intermediate volcanic center.

Faults

Faults and fractures, evidently at least of three different ages, are abundant in the region and are visible on aerial photos and photoquadrangles as lineaments. These lineaments are clearly visible north of the Rainy River. In the Birchdale-Indus area they are more obscure and are visible for a distance of only a few miles south of the river; further south, the swamps and bogs totally obscure them.

The oldest faults appear to be the generally east-trending Quetico and Rainy Lake-Seine River strike-slip faults, which form the northern and southern boundaries respectively of the fault block in which the Birchdale-Indus-Emo area is situated (fig. 1). A west-southwest-trending splay from the Quetico fault enters the Birchdale-Indus area in the northwest corner of the map; it is a prominent lineament north of the Rainy River, is perceptible just south of the river, and then disappears beneath the swamp.

A prominent northwest-trending set of fractures occupied by the wide, Middle Precambrian mafic dikes that transect the older bedrock has no apparent horizontal or vertical displacement, but outcrops are too sparse to verify possible small-scale shift. Several of the dikes on ODM map 2115 (Davies and Pryslak, 1967), including those we have named the Sault Rapids and Manitou Rapids dikes, cross the Quetico fault without being displaced. Similarly, northwest-trending dikes in the Rainy Lake area are aligned with dikes to the south in the vicinity of Kabetogama Lake across the Rainy Lake-Seine River fault (Southwick and Ojakangas, 1973); one of these dikes crosses the Quetico fault 12 miles (19 km) north of Fort Frances (Davies and Pryslak, 1967) without apparent displacement. There may be some late movement along the Rainy Lake-Seine River fault, for the southerly extension of the Manitou Rapids dike appears to be displaced about 300 meters in a left-lateral sense just north of the southeast corner of the Birchdale-Indus map (Fletcher and Irvine, 1954). However, nearby the dike has been displaced about 600 meters along a northeast-trending fault and lineament that intersects the Rainy Lake-Seine River fault at a very low angle, and it is possible that the apparent displacement along the Rainy Lake-Seine River fault may in fact be movement along this northeast-trending fault (fig. 2).

The northwest-trending fracture system includes numerous well-developed lineaments on ODM Map 2115 (Davies and Pryslak, 1967) and one prominent lineament on the Birchdale-Indus map. Evidently such lineaments are fractures not occupied by mafic dikes, for such dikes generally form topographic highs rather than lows.

Several northeast-trending lineaments are present within the Birchdale-Indus area and are also prominent on ODM Map 2115 (Davies and Pryslak, 1967). The Sault Rapids and Manitou Rapids dikes have apparently been displaced along faults which are part of this fracture set, but lack of outcrops in critical areas makes this uncertain. This set of lineaments and minor faults is also parallel to the dominant set of glacial striations in the region. This could mean that many of the lineaments are glacially scoured and are unrelated to structure, but it may better be explained as a control on the ice movement by pre-existing, weathered fracture systems.

Small scale features indicative of brittle deformation are fairly common in several outcrops. Small-scale northwest-trending faults having a few inches of displacement were noted on some outcrops; shearing and fractures with the same trend also are present on a few exposures. Kink bands, quartz-filled gashes and joints, and northeast-trending minor faults are not uncommon. Prominent northeast-trending late joints are present in a Middle Precambrian mafic dike in Section 10, T.159N., R.25W. Two sets of fractures were noted in pillowed mafic volcanic rocks near the south edge of Section 12, T.159N., R.28W., one set trending north with a dip to the west of 75-80°, and the other trending northwest with a dip of 60° to the northeast.

STRATIGRAPHIC RELATIONSHIPS

The stratigraphic relationships of the various map units were presented in the introduction to the section on General Geology and Petrography. Evidence for the determined relationships is discussed in this section.

The biotite schist unit in the southeast part of the Birchdale-Indus map area (pl. 1) was interpreted as Coutchiching and pre-volcanic by Fletcher and Irvine (1954), following the stratigraphic relationships established by Lawson (1888; 1913). In some of the original mapping in the region, Lawson determined that the Coutchiching mica schist units in the Rainy Lake area are older than the Keewatin volcanics (greenstones). Recent mapping and field studies in the Rainy Lake area by Ojakangas (1972) indicated the existence of some biotite schist units younger than some volcanic (greenstone) units; however, the most widespread schist unit mapped by Lawson as Coutchiching--that south of the Rainy Lake-Seine River fault--probably is older than the volcanic rocks. As this unit continues into the southeast corner of the Birchdale-Indus area, it can be interpreted as the oldest unit in the map area.

The mafic-intermediate rocks exposed in the core of the anticline (fig. 2) are the oldest volcanic rocks; they plunge northeastward beneath the felsic-intermediate agglomerate and tuff. Mafic-intermediate volcanic rocks are interpreted as being present in the northwest corner of the map area because of outcrops across the International boundary. They are correlative with the rocks exposed in the core of the anticline if the structural interpretation in Figure 15 is correct.

The felsic-intermediate rocks found on the northwest, north, and northeast sides of the anticline, and repeated west of the Birchdale pluton by folding (fig. 15), compose the next younger unit and apparently are the same age as the iron-formation and associated volcaniclastic rocks on the southeast side of the anticline.

The mafic-intermediate volcanic rocks exposed along the synclinal axis southwest of the Birchdale pluton constitute a younger mafic accumulation lying on the felsic volcanic pile. Fletcher and Irvine (1954) showed that the mafic volcanic rocks stratigraphically above the iron-formation-metasedimentary unit in the eastern part of the Emo map area are the youngest volcanic rocks in the area. Davies (1973) also showed this unit and another one exposed east of a synclinal axis in the Fort Frances map area as being the youngest volcanic rocks. The mafic-intermediate lens at the south end of the Manitou Rapids dike would be about on strike with this unit. If the structural interpretation (fig. 15) is correct, these mafic-intermediate units approximately correlate with the mafic-intermediate unit in the synclinal axis southwest of the Birchdale pluton.

Map units within the volcanic sequence of the Emo map area, as delineated by Fletcher and Irvine (1954), can be related to the units of the Birchdale-Indus area. The older mafic-intermediate platform is represented by the rocks in the southwest part of the Emo map sheet, the felsic pile is represented by rocks in the south-central part of the Emo area (west and northwest of the village of Emo), and the iron-formation-metasedimentary units peripheral to the felsic rocks are more distal facies of the felsic volcaniclastic accumulation. (See Figure 2.)

The above correlations do not assume a simple layer-cake stratigraphy. Each of the volcanic units is undoubtedly lensoid in gross geometry, and grades both vertically and laterally into adjacent lithologies, with intertonguing relationships the rule. Smaller lenses of mafic-intermediate volcanic rocks occur within the felsic-intermediate volcanic rocks, and vice versa. If the bedrock were exposed throughout the entire area, the original lensoid nature of the lithologies, coupled with later intrusion, folding, and faulting, undoubtedly would present a very complex pattern.

With one exception, the rock units mapped in the Birchdale-Indus area agree closely with the units mapped in the Emo area (fig. 2). The exception is the graywacke and iron-formation unit of the Emo map area which impinges on the International boundary in the northeast corner of the Birchdale-Indus map (fig. 2). The limited data available in the Birchdale-Indus area, including the study of drill core, indicate that this unit--which was mapped as metasedimentary rock in the Emo area--is largely composed of felsic volcaniclastic rock with an included iron-formation. The iron-formation appears to be an exhalative deposit found within a pyroclastic-volcaniclastic unit. Either the metasedimentary unit on the Emo map area was established on limited data, or the unit grades southward from a metasedimentary to a metavolcanic unit.

Fletcher and Irvine (1954) correlated the three graywacke units (two with iron-formation) within the Emo map area on the basis on their overall structural interpretation. Apparently the northern graywacke unit is the only one that contains excellent graded beds and could be interpreted as simply being a few to several miles more distal from the Birchdale-Indus-Emo felsic volcanic center than are the two metasedimentary units that contain iron-formation. In this interpretation, the graded graywackes with good sedimentary features are more distal deposits, whereas the iron-formation and associated metasediments are in general more proximal exhalative and little-reworked felsic volcaniclastic accumulations. However, Fletcher and Irvine apparently did not attach any importance to possible right-lateral movement along the Quetico fault which cuts through the length of the northern graywacke unit (Davies and Pryslak, 1967); such movement would severely complicate the stratigraphic interpretation.

ENVIRONMENT OF DEPOSITION

The volcanic rocks of the Birchdale-Indus-Emo area constitute a rather typical volcanic pile, resembling in a broad way the sequence in the Archean volcanism model of Goodwin (1968). A mafic base was succeeded by explosive intermediate-felsic volcanism.

The mafic-intermediate volcanic and subvolcanic rocks in the core of the anticline in the Birchdale-Indus area evidently comprise a basal accumulation of pillowed lavas and hypabyssal rocks. The pillows generally lack amygdules, and may indicate water depths greater than 2000 meters (Moore, 1965; Jones, 1969). The amygdular pillows shown in Figure 4 are part of the youngest mafic volcanic rocks in the area and may have been deposited in much shallower water upon the felsic edifice. It is also possible, however, that vesicular lavas were developed but that the vesicles were closed and obliterated by deformation.

A highly generalized pre-deformational model of a northwest-southeast cross section across the Birchdale-Indus-Emo area is presented in Figure 17. The line of section is located a few miles west of Indus and Emo. Note that the iron-formation and sedimentary rocks essentially define the boundaries of the volcanic accumulation.

The presence of felsic-intermediate agglomerate in the vicinity of Manitou Rapids and Long Sault Rapids, both in Minnesota and in adjacent Ontario, indicates the existence of a major felsic volcanic center in this area. Judged from the presence of agglomerate, a smaller subsidiary vent may have been located approximately on the present site of the southeastern edge of the Birchdale pluton. Listerud (1974) studied seven drill cores in that area and noted an increase in volcanic rock fragments to the southwest and an increase in graphite to the northeast; he suggested that the volcanic center was to the west or southwest with deeper water situated to the northeast. Minor pillowed mafic-intermediate volcanic rocks are interbedded with the felsic-intermediate rocks, indicating that the entire pile accumulated in a submarine environment.

Additional possible evidence for a felsic volcanic center in the area is the hypabyssal nature of the small, felsic low-K-spar stock between the Manitou Rapids and Sault Rapids dikes, near the center of T.159N., R.26W. Perhaps this somewhat granulated stock was part of a feeder system cutting through the older mafic-intermediate basal part of the pile that brought felsic magma to the overlying explosive felsic edifice (fig. 2; pl.1).

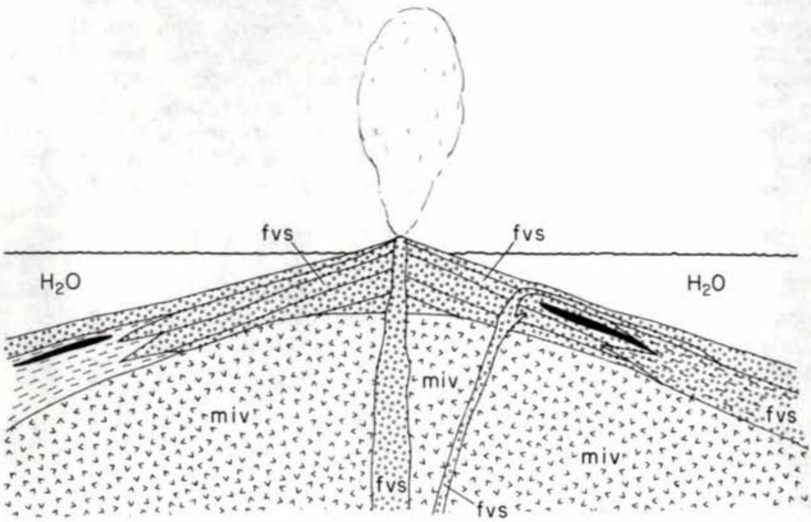

Figure 17 - Generalized pre-deformational model across the Birchdale-Indus-Emo area. Area shown is about 15 miles wide. Iron-formation shown in black; graywackes and associated fine-grained sedimentary rocks shown as short dashes. See Plate 1 and Figures 2 and 15 for explanation of symbols.

Outward from the agglomeratic center, the rocks are dominantly tuff of varying compositions that have well preserved bedding, indicating deposition below wave base in still water. Poorly bedded volcaniclastic rocks are common, and although the significance of the poorly developed bedding is not clear, the absence of well defined bedding, cross-bedding, graded bedding, and channeling suggests a lack of reworking of this material. The rocks may have been rather poorly sorted, but this is difficult to verify as recrystallization has largely obscured original textures, especially the finer grains. No evidence of ash-flow deposits, such as welding, was observed.

Graywacke beds with excellent grading are not found in the immediate Birchdale-Indus area, but are present in two nearby outlying areas. The closest are present in the northern part of the Emo map area and can be easily observed on Highway 70, 11 miles north of its junction with Highway 11-71 near Emo. The other locality is on the Minnesota side of the International boundary, in the Clementson area 8 miles (13 km) west of the Birchdale-Indus map sheet (fig. 1); several outcrops occur in the area. Excellent exposures of graded beds from 2 inches to 4 feet thick (5 cm to 1 m), with loading features, can be easily observed beneath and north of the Clementson bridge over the Rapid River on Highway 11. Minor conglomerates occur in both of these areas, but not at the cited localities. The grains in the graywacke beds of the Clementson area are clearly volcanogenic in origin, and based on staining, some apparently are rhyolitic. The graywackes from the northern Emo locality, while more recrystallized and now amphibolite-biotite schist, also appear to have had a volcanogenic protolith. The original sediment in these beds was probably carried and deposited by turbidity currents. These currents may have moved down the slopes of the felsic volcanic accumulation centered in the Birchdale-Indus-Emo area.

However, these graywackes may also be related to other felsic centers. Those in the northern part of the Emo map area are just south of agglomerates in the Pinewood Lake area, and these agglomerates appear to be related to a felsic agglomerate-tuff sequence mapped by Blackburn (1972a, 1972b) in the Off Lake-Burditt Lake area 20 to 25 miles (32 to 40 km) north of Emo. Furthermore, some of these northernmost graywackes are located north of the Quetico fault, and if any appreciable right-lateral strike-slip movement occurred on this fault, as is quite likely, then some of these graywackes are now located far east of their original positions relative to the rocks of the Birchdale-Indus-Emo area. Mackasey and others (1974) diagram possible horizontal movement of about 90 miles (144 km) along the Quetico fault east of Rainy Lake.

The Clementson exposures may be related, not to the Birchdale-Indus-Emo center, but rather to a felsic center located somewhere to the southwest. Several drill holes located 15 to 25 miles (24 to 40 km) southwest of Clementson contain felsic agglomerate, tuff, and iron-formation (fig. 1; tbl. A-2).

GEOLOGY OF THE ROSEAU SHEET

The bedrock of the Roseau 1:250,000 sheet (Sims and Ojakangas, 1973) appears to consist largely of metavolcanic rocks, with metasedimentary rocks (dominantly biotite schist) occupying a large area in the southeastern part. Granitic rocks have intruded the volcanic sequence.

Information on the metavolcanic rocks is largely based on knowledge gleaned from exploration drill holes for massive sulfide deposits (tbi A-1); very few rock exposures are present in the region farther than 10 to 20 miles (16 to 32 km) south of the Rainy River and Lake of the Woods. The volcanic rocks include felsic-intermediate tuff, agglomerates, other volcaniclastic rocks, mafic-intermediate lava and subvolcanic rocks.

Knowledge of the metasedimentary rocks has come from exposures in the International Falls 1:250,000 sheet (Southwick and Ojakangas, 1973), as well as from drill holes in the Roseau sheet. The metasedimentary rocks are largely biotite schist, with amphibole schist and minor amphibolite layers also present. Schist-rich migmatite is common in the International Falls sheet, and based on geophysical interpretations, is present in the eastern part of the Roseau sheet. Southwick (1972) described related rocks, especially in the eastern half of the International Falls sheet.

Several granitic batholiths intruded the metavolcanic and metasedimentary rocks. Knowledge of these is limited and is based on a few water wells that penetrated granitic bedrock and on interpretation of gravity and aeromagnetic information; a few bodies are partially exposed.

A well-exposed batholith northwest of Baudette consists of gray quartz diorite (40 percent plagioclase, 4 percent K-feldspar, 46 percent quartz, 6 percent amphibole and 1 percent biotite) and pink granite with 50 percent K-feldspar.

Two small granitic plutons and a batholith are present just west of the Birchdale-Indus map area. A pink granitic stock adjacent to the northwest corner of the Birchdale-Indus map area is known only from a "near outcrop" of pink granite boulders and a small outcrop of biotitic gneiss (contact rock?) with pink granitic dikes; these rocks coincide with gravity and magnetic lows. This stock could be present at shallow depths in the extreme northwest corner of the Birchdale-Indus map area, but is not so indicated on the map. A fairly well-exposed small pluton of gray to pink granitic rock occurs south of Clementson. A batholith exposed just west of the Birchdale-Indus area consists of red granitic rock cut by gray diorite; 12 miles to the west, it is exposed on and near HIghway 72 and varies from a coarse porphyritic pink monzonite containing 25 percent K-feldspar to a pink granitic rock to a gray granitic gneiss.

A large area of mixed rocks occurs northwest of Baudette, adjacent to Lake of the Woods. This area is north of the Quetico fault and the rocks have a northwesterly regional strike and foliation, at right angles to the northeast-trending foliation and bedding of the other rocks exposed in northwestern Minnesota. Biotite-bearing amphibolitic gneiss with amphibolite pods, cut by at least two phases of granitic rocks, is dominant in the southern part of that area; nearer the northern end of the large peninsula projecting northward into Lake of the Woods, granitic gneiss dominates with lesser amounts of amphibole-rich gneiss. Diorite also is present. These rocks, while enigmatic, may be a highly altered and migmatized westward extension of basaltic and andesitic volcanic rocks mapped on the southeastern side of Lake of the Woods in adjacent Ontario (Davies and Pryslak, 1967). They are worthy of further study.

Northwest-trending mafic dikes similar to those already described in the Birchdale-Indus area also occur south of and northwest of Baudette. Excellent flow banding can be seen in a dike in Section 2, T.162N., R.33W. on the shore of Lake of the Woods at Zippel Bay. A dike on the lake shore in the southwest corner of Section 5, T.163N., R.34W. is porphyritic, with large plagioclase phenocrysts.

ECONOMIC GEOLOGY

This section deals briefly with the economic geology not only of the Birchdale-Indus area but also of the entire Roseau 1:250,000 sheet and the northern part of the Bemidji 1:250,000 sheet as well.

Iron-Formation

Details of the iron-formation within the Birchdale-Indus area have been described in the section on General Geology and Petrography; details of this unit in the Emo area can be found in Fletcher and Irvine (1954).

The northeast-trending magnetic anomaly located northwest of the Birchdale-Indus map and described in the section on Structure (folds) delineates another major iron-formation. This anomaly has not been explored for iron ore, but has been tested for massive sulfides. It will be mentioned again in the section on sulfide mineralization.

In Section 7, T.158N., R.36W., the Ridge Mining Company drilled seven holes in 1972-1973 on a magnetic high; it was evidently originally drilled because of an EM anomaly and then drilled further to test the iron-formation encountered in the first holes. Six of these holes penetrated a thick, commonly brecciated iron-formation. Highly generalized logs of these holes are presented in Table A-2 (holes FT-7, -10, -12, -13, -14, -21, and -22); an additional hole was drilled on private land. The iron oxides (as much as 45 percent Fe) appear to be the result of deep weathering of the sulfide minerals, which are still preserved at depth.

Whereas most of the magnetic anomalies are probably produced by magnetite, pyrrhotite bodies may also contribute to some magnetic anomalies. For example, the pyrrhotite in the Birchdale anomaly that is described below produces a small positive magnetic anomaly.

Sulfide Mineralization in the Birchdale-Indus Area

Massive and disseminated sulfide bodies occur at several locations within the Birchdale-Indus area; several of these were discovered by drilling geophysical anomalies. One massive sulfide body at the location herein called the Indus test pit area, is exposed at the surface; test pits and a shaft have further exposed this sulfide. Pyrrhotite is the dominant sulfide in most occurrences, but massive pyrite has locally replaced the pyrrhotite. Zinc and copper values are low.

The Birchdale Anomaly

This anomaly is located three miles south of the village of Birchdale near the southern edge of the Birchdale pluton, in sections 15, 16 and 21, T.159N., R.27W. (fig. 18). The geophysical anomaly has been explored by three mining companies; a total of nine holes have been completed. Other work in this area includes geochemical and geophysical surveys by the Minerals Division, Minnesota Department of Natural Resources (see below) and an unpublished M.S. thesis by Listerud (1974). Drill holes R-2-2 and R-2-3 were drilled on the southwest extension of the geophysical anomaly, but the rock units that were intersected do not appear to correlate with the rocks intersected in the other holes. The inferred correlations of the rocks intersected in the other seven cores, and the sulfide zones, are shown in Figures 19 and 20.

The sulfide minerals listed in order of decreasing abundance are pyrrhotite, pyrite, chalcopyrite, sphalerite, pentlandite, marcasite, and cubanite (Listerud, 1974). Pyrrhotite exists in both its hexagonal and monoclinic forms with granular and feathery exsolution-type textural relationships. An intermediate phase between pyrrhotite and pyrite was observed in several sections. This phase was also observed by Ramdohr (1969) in localities where pyrite replaces pyrrhotite; he has shown it to be essentially an aggregate of very fine-grained pyrite or marcasite. The most common sulfide assemblages are: (1) pyrrhotite-pyrite-chalcopyrite, (2) pyrrhotite-chalcopyrite, (3) pyrrhotite-chalcopyrite-sphalerite, and (4) pyrrhotite-chalcopyrite-pentlandite. Listerud (1974) found that these four assemblages account for more than half of the total observed assemblages, with the pentlandite-bearing assemblage being present mostly in the mafic intrusive rocks. Marcasite was observed only in late veins and fracture fillings. Cubanite was found in trace amounts in one sample.

Listerud (1974) reported that several massive sulfide zones were intersected within Unit E (fig. 20), the main sulfide-bearing unit. The massive zones range in thickness from about 6 inches to about 10 feet (15 cm to 3 m), and increase in number towards the northeast. The contacts with adjacent disseminated or semi-massive zones vary from sharp to gradational. The massive sulfides are almost entirely pyrrhotite with only traces of chalcopyrite and pyrite; neither pentlandite nor sphalerite was observed in these zones. The pyrrhotite occurs as polygonized grains with traces of chalcopyrite and pyrite along the grain boundaries. The massive sulfides commonly show a swirly flow structure and commonly carry fragments of the host rocks. A zone of massive sulfide, very similar to the sulfide zones in Unit E, was also intersected in Unit D (fig. 19) in the four northeasternmost cores. The mineralogy and textures are virtually identical, including stress twins and kink bands in the polygonized pyrrhotite. Two massive pyrite zones were intersected, one 4-foot-thick zone in NCB-1 and an 18-foot-thick section in R-2-2 (fig. 18). The pyrite zone in NCB-1 is vuggy and is in a very fine-grained tuff. The other pyrite zone contains 10-50 percent pyrite, is massive at the top, and grades downward into disseminated sulfides. The grain size of the pyrite decreases downward in the cores, and there are indications that the pyrite has replaced pyrrhotite. Elongate, commonly oriented inclusions of pyrrhotite in the pyrite grains indicate that this may have originally been a pyrrhotite body which was subsequently replaced by pyrite.

Disseminated sulfides are quite common in the rocks of the area (see Figure 19), and the disseminated zones containing 5-20 percent sulfides have provided the best assay results. These zones also contain more sulfide phases than the massive zones. Pyrrhotite, pyrite, chalcopyrite, and sphalerite are the most common phases, but pentlandite also occurs in some zones. The highest grade zinc mineralization was intersected in S-43-2 between depths of 184.5 and 187 feet in Unit F (figs. 19 and 20). This section of core is missing, but the geologic log of the Ridge Mining Company described the section as being an andesitic tuff with 5 percent pyrrhotite and pyrite and 5-10 percent sphalerite in possible slump structures. Mineralization of this type was also noted in hole NCB-2 (fig. 20); the sphalerite in the disseminated zones in the other cores occurs in bands parallel to bedding. Interesting copper-nickel mineralization consisting of disseminated pyrite, pyrrhotite, chalcopyrite, and pentlandite was observed at the upper contact of a metagabbro (510-531 feet) in core R-2-2 (fig. 18). Photographs showing the minerals and textures of the sulfides in the Birchdale area can be found in Listerud (1974).

The base-metal content of the sulfide zones is generally low. The highest values are from a sphalerite-bearing zone at depths between 184.5 and 187 feet in hole S-43-2, as mentioned in the previous paragraph. The Ridge Mining Company log indicated 4.06 percent zinc and 0.25 oz/ton silver for this interval. The copper-nickel zone in the metagabbro of R-2-2 was shown on the Exxon Company log as having an assay of 0.28 percent copper and 0.23 percent nickel over a six-foot interval. Traces of gold were also found in this zone. Mining company data indicate that the highest values for zones other than those mentioned above are: 0.19 percent copper, 0.21 percent zinc, 0.09 oz/ton silver, and traces of gold.

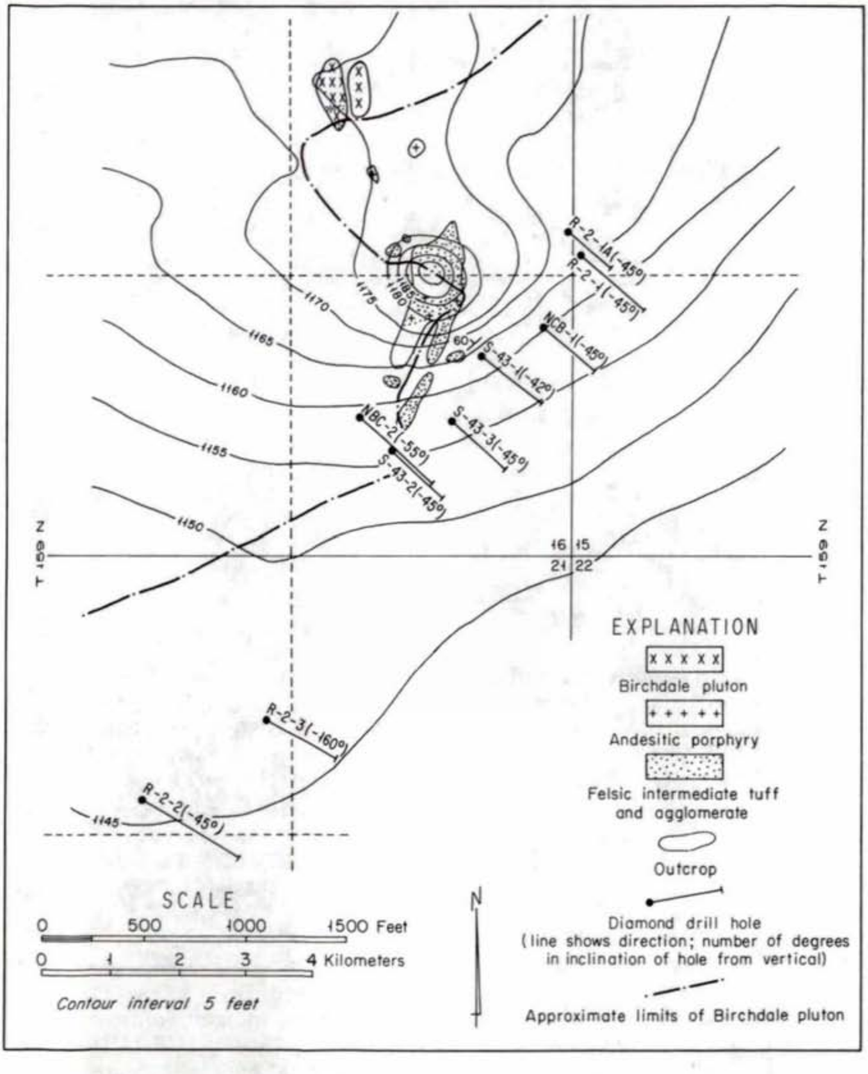

Figure 18 - Map of area of Birchdale sulfide anomaly showing locations of 9 drill holes and outcrops (after Listerud, 1974).

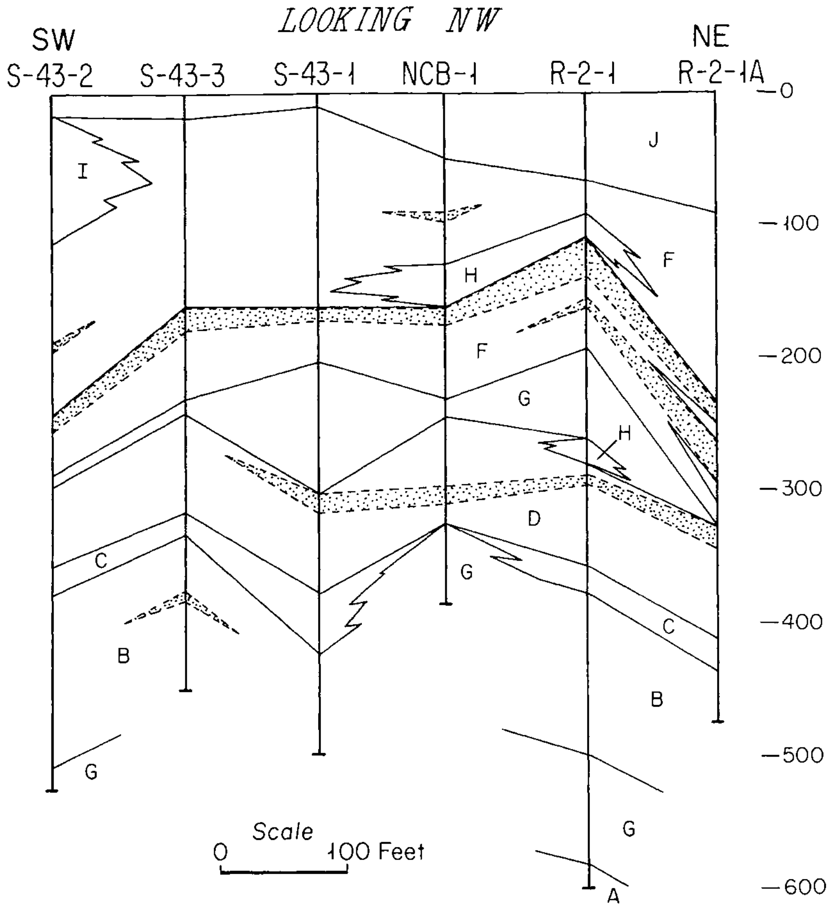

Figure 19 - Cross-section of 6 of the 9 drill holes in vicinity of Birchdale sulfide anomaly (after Listerud, 1974). Stippling indicates sulfide zones. J, GLACIAL TILL AND LAKE SEDIMENTS; I, BIRCHDALE PLUTON--Pink, coarse- to medium-grained, massive granitic rock; H, ANDESITE AND DIORITE INTRUSIVE ROCKS --Fine-grained and porphyritic to coarse-grained and massive; G, MAFIC IGNEOUS ROCKS--Intrusive or extrusive, fine-to medium-grained, massive, dark green; F, FELSIC TO INTERMEDIATE TUFF--Fine to very fine-grained, light-colored, massive to thin banded, with andesitic lapilli zones; E, INTERBEDDED GRAPHITIC METASEDIMENTARY ROCKS AND TUFF--the main sulfide-bearing unit. Metasedimentary rocks are fine-grained, gray to black; tuff is coarser-grained and green; D, VOLCANICLASTIC ROCKS--fine-grained, gray, green, or brown, well-foliated, thick-to thin-banded; rarely graphitic; C, AGGLOMERATIC TUFF--lapilli- to bomb-sized fragments of andesitic composition in a slightly more felsic fine-grained matrix; B, VOLCANICLASTIC ROCKS--fine-to medium-grained, gray or brownish gray, biotite-rich, generally thick-bedded; A, VOLCANICLASTIC ROCKS--very fine-grained, gray, thick-bedded.

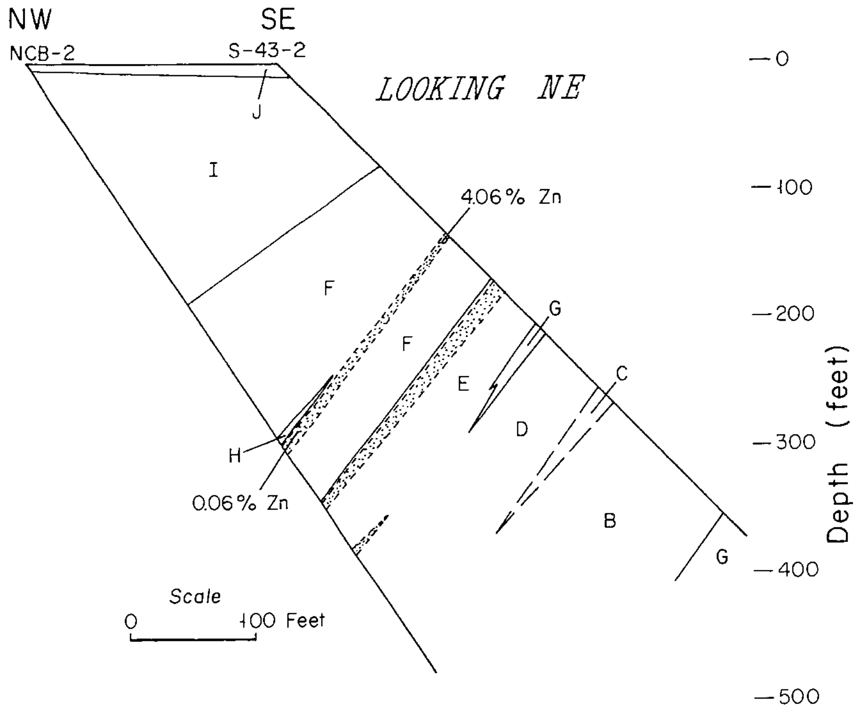

Figure 20 - Diagram of two drill holes that penetrated zinc-bearing sulfides of Birchdale anomaly (after Listerud, 1974). Key same as for FIgure 19. Stippling indicates sulfide zones.

The trace-element distributions along strike in the main sulfide horizon of Unit E and vertically in core R-2-1 were investigated by Listerud (1974). The samples were analyzed for copper, nickel, cobalt, zinc, and manganese, by atomic absorption methods. Although the number of samples (16) was insufficient to make statistically valid comparisons, some trends were observed. The results from samples in the massive sulfide zone of Unit E show that copper values are always higher than zinc, although erratic in absolute values, and that nickel and cobalt generally increase to the northeast. Trends in metal ratios also exist in this zone. Cobalt:nickel, copper:zinc, cobalt:manganese, and copper:copper+zinc all increase to the northeast. The results from the low-sulfide volcaniclastic rocks and tuff of R-2-1 showed no trends in absolute values, but some were shown by metal ratios. Cobalt:nickel, copper:zinc, and copper:copper+zinc increase upwards, whereas nickel:manganese and cobalt:manganese remain constant. The geologic implications of the results are uncertain at this time, but studies such as this may prove useful in exploration when an ore body is discovered and trace element trends for the body are characterized.

The sulfides intersected in this area are thought by Listerud (1974) to be mostly of syngenetic origin. Although the sulfides exhibit very few structures or textures attributable to their original state, he feels that the position in and the relationships with the enclosing rocks, the close association with graphite occurrence and abundance, and the banding of the sphalerite parallel to the bedding indicate deposition of sulfides as primary constituents of the rocks. Additional details of the petrology, mineralogy, and general geology of this area are available in Listerud (1974).

Indus Test Pit Area

This area is located in SW¼, NW¼ of Section 16, T.159N., R.25W. south of Indus. Three test pits and a shaft, all dating from the late 1950's are located adjacent to the Manitou Rapids dike (pl. 1 and fig. 21). Outcrops of felsic-intermediate volcanic, pyroclastic, and volcaniclastic rocks are found on the southwest side of the dike, and contain massive, semimassive, and disseminated sulfide zones. Minnesota Department of Natural Resources (DNR) personnel have done work in this area, including soil geochemistry, various geophysical surveys, and geologic studies; they also drilled three shallow holes. The results of the geochemistry survey are discussed below, in another section of this report, and can also be obtained from the DNR as an open file report by Meineke, Gilgosch, and Vadis (1976). Hole IH-10 penetrated a sulfide-rich felsic tuff from 20.5 to 47.1 feet (6.2 to 14.3 m); the rock becomes agglomeratic towards the base. Downward in the hole, the sericite content increases and the sulfide content decreases. Hole IH-11 penetrated a weathered breccia from 8.7 to 12.7 feet (2.6 to 3.9 m) and felsic tuff from 12.7 to 24.2 feet (3.9 to 7.4 m). The core from Hole IH-12 consists of alternating intermediate volcanic rocks and felsic tuff from depths of 16.8 to 42.8 feet (5.1 to 13.0 m).

The sulfides in this area occur mainly in felsic tuff. Dissemimated sulfides also occur in the more mafic rocks and in the mafic dike rock. The known sulfide-bearing zone on the southwest side of the dike is about 400 feet (122 m) wide. This zone also occurs on the northeast side of the dike as shown by the fact that massive sulfides were intersected in hole IH-10, drilled on a geophysical anomaly on the northeast side of the dike opposite the sulfide-bearing outcrops.

The sulfide minerals from the test pit area that were observed in polished section include pyrrhotite, pyrite, chalcopyrite, marcasite, sphalerite, mackinawite, and unidentified intermediate or alteration phases. One very tiny bleb of gold was also observed in a section from IH-10. Pyrrhotite and pyrite account for at least 90 percent of the sulfides in any sample, with alteration products and marcasite ranging up to 10 percent. Chalcopyrite may constitute as much as one percent of the sulfides; the other sulfides are present in only trace amounts. Pyrrhotite is present in both hexagonal and monoclinic forms.

Textures observed in the massive sulfides are of two basic types. The first consists of polygonized pyrrhotite as the major mineral. The pyrrhotite exhibits strain features such as stress twinning and kink bands. Hexagonal and monoclinic pyrrhotite occurs in an exsolution-like texture similar to that observed by Listerud (1974) in the Birchdale area sulfides. A few polished sections consist of more irregularly shaped grains lacking a well annealed

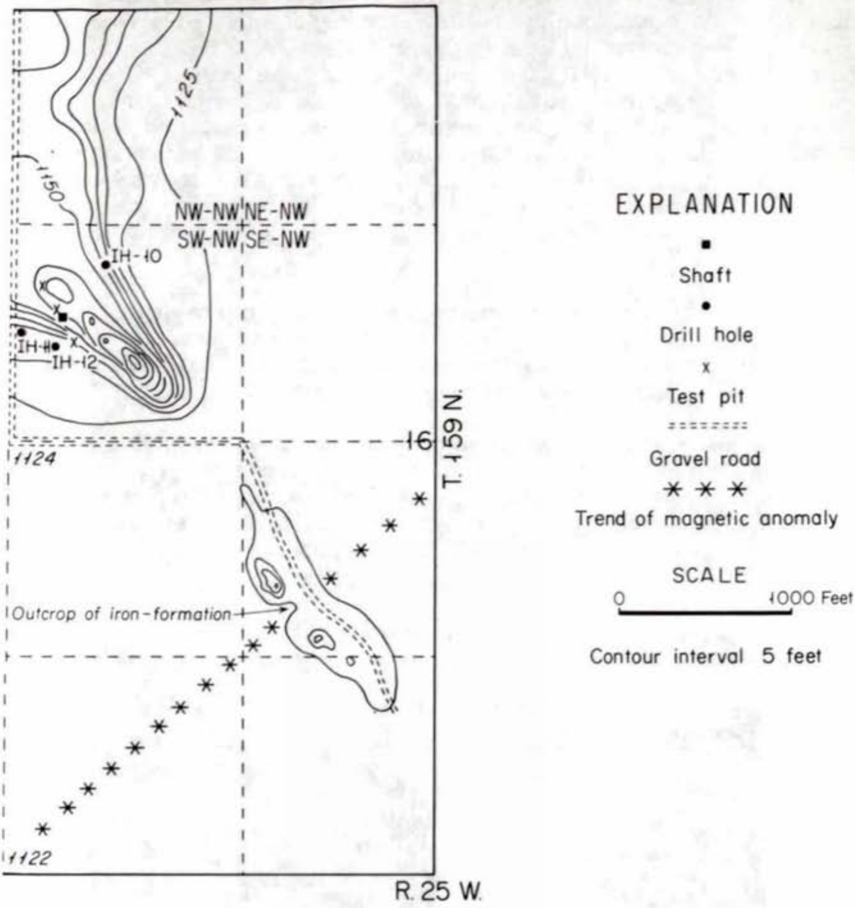

Figure 21 - Detailed map showing locations of Indus sulfide test pits, shaft and drill holes. (Base is part of Loman 7 ½ minute quadrangle, U.S. Geol. Survey, 1970.)

texture. The other minerals mentioned in the previous paragraph occur as inclusions in pyrrhotite, as blebs or grains between pyrrhotite polygons, or as tiny blebs in gangue. Samples from the southeasternmost test pit exhibit an odd alteration along boundaries between pyrrhotite grains and in fractures within pyrrhotite grains. At the centers of these feathery alteration zones is a white, fairly hard, anistropic mineral, with a softer, greenish phase between it and the pyrrhotite. These two phases are harder than pyrrhotite, but possibly softer than pyrite; they are probably close to pyrite in composition and may represent the start of alteration of pyrrhotite to pyrite. The alteration of pyrrhotite to pyrite, with the intermediate phase consisting essentially of an aggregate of very fine-grained pyrite or marcasite, is also found along fractures in these samples. Alteration of sulfides to iron oxides has also occurred.

The other type of massive sulfide is characterized by large pyrite grains which have replaced pyrrhotite. The replacement of pyrrhotite (or growth of pyrite crystals) apparently took place in at least two stages. There are crystals of pyrite that polish well and are inclusion-free; these have been overgrown by a slightly softer, inclusion-rich pyrite. The inclusions are pyrrhotite, chalcopyrite, gangue, oxides, and marcasite. Marcasite is observed both within pyrite grains and with pyrite inclusions. This tends to support a two-stage theory, with marcasite forming between the two pyrite stages or during the second stage. The other trace minerals may occur in pyrite, gangue, or in the pyrrhotite matrix between pyrite grains.

The disseminated sulfides in the country rocks are mostly pyrite and pyrrhotite, but they have not been examined in polished section. The mafic dike rock contains traces of pyrite and chalcopyrite; the chalcopyrite occurs as "clouds" of very fine-grained blebs in gangue minerals.

Much analytical work has been done on the rocks from this area. The cores from the three DNR drill holes have been split and assayed for copper, nickel, zinc, cobalt, silver and gold in one-foot intervals; the highest values obtained for each element are shown below (tbl. 1); values are in parts per million except for gold and silver, which are in ounces per ton.

Table 1--Analyses, Indus Test Pit Area

Element	Hole IH-10	Hole IH-11	Hole IH-12
Cu	172	108	89
Zn	416	1104	220
Ag	0.05	0.01	0.01
Au	0.006	0.003	0
Ni	67	91	510
Co	168	82	92

Sampling and analysis of both float and outcrop samples produced results lower than the values given above.

The sulfides in this area appear to be syngenetic with the enclosing tuff and volcaniclastic rocks. The 400-foot-thick (120 m) section of sulfide-bearing rocks is exposed only intermittently, but the major sulfide zones are in the felsic tuff between more andesitic units. The Indus test pit area is less than half a mile northwest of the only outcrop of magnetic iron-formation in the area (fig. 21).

Geophysical surveys were done in order to define the sulfide zones for a planned geochemical survey and to test various methods including: (1) refraction-seismic, (2) magnetic, (3) resistivity, (4) time-domain induced polarization, and (5) VLF (very low frequency) in-phase/quadrature horizontal loop and dip angle horizontal loop (Crone CEM) electromagnetic.

A VLF conductor about 150 feet (45 m) wide, without a magnetic response, extends southwest from the southernmost test pit shown in Figure 21. IH-12 was drilled over this conductor and encountered zones of 20 percent combined pyrite and pyrrhotite.

From the vicinity of the test pit immediately north of the shaft, a narrow VLF conductor extends to the southwest (strike N 63°E) across hole IH-11. This conductor was also located by dip angle horizontal loop methods. Near the shaft, a 10,000 gamma magnetic anomaly is coincident with the conductor and a 3,000 gamma anomaly occurs over IH-11. This magnetic anomaly is interpreted to have a steep dip. Drill hole IH-11 (tbl. A-1) intersected zones of as much as 5 percent pyrite-pyrrhotite, but this shallow hole probably was not drilled deep enough or in the right location to intersect the main conductor. The conductor has a strike similar to the general strike of the country rock on the southwest side of the dike (pl. 1).

From drill hole IH-10, which contained zones with as much as 70 percent pyrite-pyrrhotite, a narrow VLF conductor extends to the northwest across the north-south road shown on Figure 21. The strike of this conductor ranges from N 53°W to N 74°W. At IH-10, the conductor was also located with dip angle horizontal loop, which indicated a southwesterly dip, and horizontal loop (in-phase/quadrature). In the IH-10 area, this conductor has a coincident 5,000 gamma magnetic anomaly. A time-domain induced polarization survey gave a resistivity low and anomalous chargeability over IH-10.

Four hundred feet north of IH-10 another resistivity low with anamalous chargeability was detected; the strike was not determined.

About 150 feet (45 m) south of IH-10 another narrow VLF conductor, which also dips southwesterly, approximately parallels the conductor located in the vicinity of drill hole IH-10. At 350 feet (107 m) west of IH-10, this same conductor is indicated by a weak dip angle horizontal loop response with a coincident 1,000 gamma magnetic anomaly.

Near the northwest corner of Section 16 (fig. 21), several narrow VLF conductors were located along the road, but their strikes were not determined. No magnetic anomalies accompanied these conductors.

The trends of these buried conductors do not parallel either the regional trends of nearby foliation or bedding or the general trends of the mafic dikes. However, no rock is exposed in the immediate vicinity. Assuming the conductors are stratabound sulfides, they could indicate minor folding of the country rocks; some of the tightest folding in the area occurs about 1½ miles (2.5 m) to the northwest (pl. 1).

Sections 3 and 4, T.158N., R.27W. (Drill holes R-4-1 and R-4-2)

This area was explored by the Exxon Company in 1970-71. Two holes, about 500 feet (150 m) apart, were drilled to intersect a geophysical anomaly. Hole R-4-1 intersected 183 feet (56 m) of massive to semimassive pyrrhotite in brecciated volcaniclastic rocks. Hole R-4-2 cut a 17-foot (5 m) zone of massive pyrite in volcaniclastic rock and a 20-foot (6 m) zone of massive pyrrhotite in a brecciated, felsic tuff (tbl. A-1).

The sulfide minerals observed in polished sections of these zones are: pyrrhotite, pyrite, chalcopyrite, sphalerite, mackinawite, marcasite, cubanite, and pentlandite. Pyrrhotite is by far the most abundant sulfide and pyrite is common. Chalcopyrite, sphalerite, mackinawite, and marcasite are common accessory minerals, although present in only trace amounts. Cubanite and pentlandite each were observed in trace amounts in only one polished section. The most common assemblage is pyrrhotite-pyrite-chalcopyrite. The assemblage pyrrhotite-pyrite-chalcopyrite-sphalerite is the next most common, with most other assemblages found only in one polished section. Textures observed in the massive pyrite zone in R-4-2 are characterized by subhedral to euhedral pyrite crystals having inclusion-rich overgrowths that together have replaced pyrrhotite and gangue minerals. The overgrowth inclusions are pyrrhotite, gangue, chalcopyrite, and marcasite. Traces of chalcopyrite and pyrrhotite also occur as disseminated grains in the gangue. The massive pyrrhotite zones have textures similar to those observed in the massive sulfides at Birchdale. The pyrrhotite is poorly to well polygonized, has both monoclinic and hexagonal types in an exsolution-type intergrowth, and has stress twins and kink bands. Accessory minerals generally occur at the grain boundaries. Pyrite often replaces small grains of pyrrhotite along fractures or grain boundaries.

The base and precious metal contents of these sulfide zones are very low. The highest values found in company assays and some additional grab samples are: 0.024 percent Cu, 0.021 percent Zn, 0.050 percent Co, 0.013 percent Ni, 0.06 oz/ton Ag, and 0.001 oz/ton Au.

Section 20, T.159N., R.27W. (Drill holes RR-6-1 and RR-6-2)

This area was explored by the Texas Gulf Sulfur Company in 1969. The work included drill holes RR-6-1 and RR-6-2, which were drilled 1,200 feet apart on the same conductor in the SE¼ of Section 20. Hole RR-6-1 intersected a 20-foot-thick (6 m) zone of massive to semimassive pyrite-pyrrhotite in felsic tuff and RR-6-2 hit about 10 feet of massive and semimassive pyrite in a felsic tuff and agglomerate sequence (tbl.A-1).

The sulfides examined from RR-6-1 contain from 35 percent to 63 percent total sulfides, averaging about equal amounts of pyrrhotite and pyrite with minor to trace amounts of chalcopyrite, cubanite, and mackinawite. The intermediate phase between pyrite and pyrrhotite, which was described earlier, is also present in minor amounts. The texture consists of pyrite grains in polygonized and slightly stretched pyrrhotite, with the accessory minerals as tiny inclusions or blebs along grain boundaries. The pyrite grains have subhedral to euhedral inclusion-free centers with inclusion-rich overgrowths. Pyrite replaces both gangue and pyrrhotite. The pyrrhotite is intergrown monoclinic and hexagonal types and also shows kink bands and stress twins. Pyrrhotite is also partly replaced by limonite along some grain boundaries. Mackinawite and cubanite occur in chalcopyrite, probably as exsolution products. Some chalcopyrite appears to rim both pyrite and pyrrhotite and may be the youngest stage of the mineralization. The only analytical data available derive from analysis of one grab sample from the middle of the sulfide zone. The results are 0.174 percent Cu, 0.003 percent Zn, 0.013 percent Co, 0.029 percent Ni, 0.081 percent Mn, 0.03 oz/ton Ag, and no Au.

The pyrite zone in RR-6-2 was examined in only one polished section. The sample contained 97 percent sulfide minerals, 99 percent of which was pyrite. Pyrrhotite and chalcopyrite were present as inclusions in the pyrite. Texturally, the sample looks like the samples from RR-6-1 except that the replacement by pyrite is virtually complete. Analytical results include these from one grab sample near the middle of the zone. Base metal content is again very low with the results being: 0.013 percent Cu, 0.010 percent Zn, 0.013 percent Co, 0.004 percent Ni, 0.212 percent Mn, 0.03 oz/ton Ag, and no traces of Au.

Section 30, T.159N., R.27W. (Drill holes R-3-3 and R-3-4)

Exxon Company drilled two holes into a geophysical conductor in the NW¼ of this section. The holes intersected 12 and 8 feet (3.7 and 2.4 m) respectively of massive sulfides in felsic-intermediate volcaniclastic rocks. These zones were not examined microscopically but appear similar to other massive pyrrhotites with scattered pyrite alteration and traces of chalcopyrite. The sulfide content is 10-60 percent and the base metal content is very low. Exxon assay results indicate the highest values are: 0.03 percent Cu, 0.015 percent Zn, 0.011 percent Co, 0.019 percent Ni, and 0.03 oz/ton Ag. Spectrographic analyses indicate traces of Mo, Sn, V, In, Os, and Y.

Section 36, T.169N., R.26W. (Manitou Rapids)

A poorly exposed gossanized outcrop of sulfide-rich tuff or volcaniclastic rock is located on the bank of the Rainy River just west of Manitou Rapids, about 2,800 feet (850 m) west of the section line and about 500 feet (150 m) west of marker #175 as shown on the Manitou 7½ minute quadrangle topographic map. The area was prospected some time ago, for there are shallow test pits on the slope above the outcrop.

Massive pods and disseminations of sulfides, together with sulfides in two fracture or breccia zones, were observed in a very fine-grained, intermediate tuff or volcanic rock. The sulfide minerals are pyrite and pyrrhotite with traces of chalcopyrite. Analysis of a grab sample showed 0.19 oz/ton Ag, 0.003 oz/ton Au, 0.004 percent Co, 0.018 percent Cu, 0.008 percent Ni, and 0.020 percent Zn.

A narrow VLF electromagnetic conductor with a coincident 1,500 to 6,000 gamma magnetic anomaly extends from the test pits to the southwest; the strike of foliation and bedding in this area is about east-west (pl. 1).

Section 18, T.159N., R.27W. (SW Birchdale)

Outcrops of pillowed metavolcanic rocks (greenstones) occur in the west-central part of this section. Sulfide and oxide patches up to one foot in diameter, which are generally interstitial to the pillows, can be observed on the outcrop.

The sulfides have not been examined in polished section, but appear to be mostly highly oxidized pyrite and pyrrhotite. Two samples of this oxidized material were assayed for Cu, Co, Zn, and Ni. The highest results are: 0.015 percent Cu, 0.020 percent Zn, 0.013 percent Co, and 0.010 percent Ni. Fresh unmineralized rock averaged about 0.006 percent Cu. It should be noted that a strong copper geochemical anomaly was detected in soil by the Minnesota Department of Natural Resources; results are discussed in the Exploration Geochemistry section of this report.

As part of a follow-up to the geochemical work, VLF and magnetic surveys were conducted. Several narrow VLF conductors were located along the west side of Section 18, but further work is needed to refine the trends.

S. ½, Section 15, T.159N., R.26W. (SE Manitou)

In this area (see Plate 1), a zinc anomaly was located by a geochemical survey; this anomaly is discussed in the Exploration Geochemistry section of this report. Two or three narrow VLF conductors occur in and parallel to a linear topographic depression which has approximately the same trend as the geologic strike of the country rock. The conductors have weak 100 to 800 gamma magnetic anomalies associated with them.

Section 10, T.159N., R.25W.

The Indus test pit conductors occur approximately 1,700 feet (520 m) northwest of the crest of the major magnetic anomaly, and stratigraphically beneath the iron-formation (pl. 1). In order to test for the existence of similar conductors along strike, ground magnetic measurements were made where the magnetic anomaly was inferred to cross Highway 11 and the Rainy River.

The magnetic anomaly at this locality is well defined; it is characterized by values ranging from 7,000 to 20,000 gammas, the higher value occurring at lower elevations along the Rainy River. Based on inflections of the magnetic profile, the apparent thickness of the rock units producing the anomaly is approximately 900 feet (275 m) with a vertical to steep southerly dip. The strike, based on two magnetic lines spaced 600 feet (183 m) apart, is N 89°E; this is in general agreement with the strikes of rocks in the few outcrops near this locality (pl. 1).

VLF electromagnetic surveys were conducted to determine whether conductors occurred near the magnetic anomaly. Three narrow conductors were located 400 to 900 feet (120 to 275 m) north of the crest of the magnetic anomaly, on the extreme northern flank of the anomaly. Their trends were not determined because only one line was run.

A vertical drill hole, IH-13 (tbl. A-1) was drilled to test one of the conductors. An 8-foot thickness of 5 to 10 percent disseminated pyrite was intersected in mafic-intermediate metavolcanic-metaplutonic rock.

Section 14, T.159N., R.28W.

Minor malachite and sulfide minerals were noted in a thin unit of intermediate-mafic tuff beds in an outcrop of pillowed volcanic rocks. Beds within the tuff unit are about one-fourth inch thick.

Summary of Mineralization in the Birchdale-Indus Area

The known massive sulfide deposits in the Birchdale-Indus map area generally appear to be of two types, one being massive pyrite which appears to have replaced massive pyrrhotite, and the other being massive pyrrhotite which exhibits a polygonized or annealed texture. Hexagonal and monoclinic pyrrhotite in a feathery, exsolution-type texture seems nearly ubiquitous in the pyrrhotite bodies, as are strain features such as stress twinning and kink bands. Thus it appears that these strain features in the Birchdale sulfides, attributed by Listerud (1974) to late adjustments due to the intrusion of the Birchdale pluton, may actually be due to a late regional stress event. The replacement of pyrrhotite by pyrite might also be related to this late regional stress, for the associated marcasite is a low temperature mineral. The pyrrhotite:pyrite ratios in sulfides of the area are now estimated at about 3:1, but may have been higher before this widespread alteration. Some late chalcopyrite mineralization may also have been associated with this event.

Disseminated sulfide minerals are ubiquitous in most rock types of the area, but only certain zones contain significant amounts. The disseminated sulfides differ from the massive sulfides in having a different mineralogy and generally larger base-metal values. A simple explanation for this could be that relatively constant amounts of zinc and copper were available, and their concentrations were diluted by the tremendous quantities of iron sulfides during times of rapid sulfide formation and deposition.

Sulfide Mineralization Elsewhere in the Region

In addition to the six holes that penetrated sulfide-bearing iron-formation in Section 7, T.158N., R.36W., at least four and perhaps seven of the other 35 holes drilled for sulfides in the region west and south of the Birchdale-Indus area (28 in the Roseau sheet and 7 in the Bemidji sheet) for which logs are available, contain iron-formation. (See Figure 1 and Tables A-2 and A-3.) Six other holes (BD-1, -2, -3, B-B-2, 40919 and 40920) are located along the magnetic trend mapped by J.W. Gruner in 1936. Four drill holes for sulfides in the Birchdale-Indus area (R-2-1, R-4-1, R-4-2 and R-4-3) are located close to an iron-formation trend, as is the prospect pit at Indus (fig. 21). Therefore, it seems likely that a number of the sulfide conductors that were drilled may have originated as sulfide facies iron-formation deposited in volcaniclastic sequences.

A second and most common type of conductor appears to be sulfides associated with felsic tuff and agglomerate sequences, without the presence of distinctive iron-formation.

A third type of conductor is graphitic rock; a majority of holes south of the Vermilion fault (fig. 1) in the Roseau sheet and in the Bemidji sheet are of this type. (See Tables A-2 and A-3).

A few small gossans were located during our field work. The two best ones, with old prospect pits on them, are in the Birchdale-Indus area and were described in the previous section.

A sulfide occurrence on the southern edge of a cluster of four small hills in the SE¼, SW¼, SE¼ Section 17 , T.159N., R.28W., just west of the Birchdale-Indus map, consists of about 15 feet of exposed mineralization along a low ledge within one of the northwest-trending mafic dikes. The mineralization appears to occur at or near the edge of the dike, but no volcanic country rock is exposed at this spot. The host dike rock is a medium-grained gabbro. The sulfides occur as irregularly distributed blebs, very fine-grained disseminations, and stringers, and comprise 2 to 4 percent of the rock. The major sulfides are pyrite and pyrrhotite with chalcopyrite locally as high as 0.5 percent; pentlandite and cubanite occur in trace quantities. Three mineralized samples were analyzed, with the results shown in Table 2; values are in ppm, except Au which is shown as ounces per ton. It is possible that this occurrence could be an indication of mineralization in the adjacent, buried country rock. It is not uncommon for these dikes to contain sulfides, but this is the largest concentration observed to date.

Table 2--Analyses of Mineralization in Mafic Dike

Sample No.	Ag	Au	Co	Cu	Ni	Zn	Mn
K-1262	NA	NA	123	1820	500	160	1900
K-1609	4.4	.004 oz/ton	140	710	325	150	1510
K-1610	0	0	140	640	320	140	1645

A rather large area of gossans is present just off the Birchdale-Indus map in the N½, SW¼, Section 7, T.159N., R.28W. The rock type is mainly biotitic schist; microscopic study suggests that at least part of the country rock here may have been a porphyritic rhyolite or rhyodacite, for it contains about 30 percent K-feldspar. Other host rocks here may have been felsic-intermediate volcaniclastic rocks.

Small patches of oxidized sulfides were also observed along the north edge of the SE¼, NW¼, Section 5, T.158N., R.30 W. in biotite schist.

Davies (1973) described some prospects in Ontario, east of the map area. Four holes drilled in 1965 in one anomaly about 8 miles northeast of the northeast corner of this map cut 35 to 156 feet (10.5 to 47.5 m) of 10 percent pyrrhotite with specks of chalcopyrite.

The rather limited analytical data available on the relative abundance of metals in the sulfide deposits suggest that zinc generally is several times more abundant than copper. However, most analyses show both elements present in quantities of only a few hundred ppm.

The prevalence of pyrrhotite over pyrite in many drill holes may be related to regional metamorphism of original pyrite-rich sulfides.

The sulfides of the Birchdale-Indus area and the larger region are clearly stratiform volcanic deposits and very likely owe their genesis to volcanic processes. However, at least minor remobilization of original sulfides has occurred. Chalcopyrite stringers have been observed crossing other sulfides. Some of the sulfide stringers are later than blue-green amphibole, which is a common metamorphic mineral in many volcanogenic rocks of the region; this paragenetic relationship was noted in several thin sections, including some from drill holes R-5-1, RR-12-2, and RR-16-1, and in one case (RR-12-2) sulfide stringers were seen to cut K-feldspar veins, which are presumably related to the pre- or syntectonic granitic intrusions of the area. Also, sulfides have been seen along both cleavage and bedding planes within a single specimen from drill hole R-5-1.

Gold

The Rainy Lake-Seine River fault zone contains small quantities of gold in the Rainy Lake area. The Little American mine on Little American Island produced about $4,600.00 worth of gold in 1894 and 1895 from a quartz vein zone 4 to 60 feet (1 to 18 m) wide (Sims, 1972b). This and several other prospects in that area are situated on or near the Rainy Lake fault zone (Ojakangas, 1972; Minnesota Geological Survey, 1969).

The Rainy Lake-Seine River fault zone crosses the southeastern part of the Birchdale-Indus map, but is covered by more than 100 feet (30 m) of glacial materials. The southwestward extension of the fault can be seen on the Roseau sheet (Sims and Ojakangas, 1973), and the northeastward extension can be seen on the International Falls 1:250,000 sheet (Southwick and Ojakangas, 1973), on the geologic map of the Fort Frances area (Davies, 1973), and on ODM Map 2115 (Davies and Pryslak, 1967).

Ridler (e.g., 1970; 1973) has discussed the common association of gold with iron-formations deposited as exhalites in the felsic portions of volcanic sequences. As the iron-formations of this area appear to be within a felsic volcaniclastic sequence, such relationships should be investigated.

Traces of gold were noted by the Minnesota Department of Natural Resources in assays of some rocks of the Birchdale-Indus area. These include some shallow drill cores (see Table A-1) and grab samples from the sulfide prospect pits at Indus and Manitou Rapids. Traces of gold occur in quartz-tourmaline veins with minor pyrite in Ontario about 8 miles east of the east edge of the Birchadle-Indus map (Davies 1973).

Other deposits

Sand and gravel from several places in the region have been utilized and the peat potential is high. Koochiching County has nearly one million acres of peat; most of this is in muskeg swamps and has a reported average thickness of 7 feet (Emmons and Grout, 1943).

Airborne electromagnetic and magnetic surveys, followed by ground geophysical surveys and drilling of the more promising conductors, were performed by private exploration companies as part of their exploration programs in the region. The Minnesota Department of Natural Resources (DNR) decided to apply geochemical methods in combination with the existing geologic and geophysical data in an attempt to delineate additional potential mineralized areas.

Geochemical exploration methods are not applicable in all terrains. Where residual soils have been developed by weathering of the parent bedrock, mineralization of the bedrock is commonly reflected in the soil and stream sediments. However, glacial drift is not always representative of the bedrock. In most glacial tills, the amount of locally derived bedrock material decreases vertically upward in the till section, so that the basal part is generally the best geochemical sample medium.

The St. Louis sublobe till, informally referred to as the "Indus formation" by C. L. Matsch (written comm., 1973), is by far the most important Quaternary deposit in the region in terms of thickness and areal extent. The St. Louis sublobe generally appears to have caused little erosion of the bedrock, and because it overrode pre-existing glacial deposits in the area, even the basal till may not reflect the underlying bedrock. In some localities south of the Rainy River, however, it appears from the locally derived angular clasts found near the bottom of the Indus formation, that the till clasts are somewhat representative of the underlying bedrock. Furthermore, the low permeability and high alkalinity of the Indus formation greatly inhibit hydromorphic migration of trace elements.

Pilot studies were performed to determine whether any buried mineral deposits were reflected in the Quaternary materials; these pilot studies were completed, with limited success, during the summer of 1972. A pilot reconnaissance soil survey during the summer of 1973 indicated the existence of some areas of anomalous geochemical values, and further studies were conducted in two of these areas. In 1974 an additional pilot study was conducted on yet another mineralized area. Locations are shown in Figure 22.

Till samples were obtained by hand auger and split-tube, power-driven sampler. Samples were run on a Perkins-Elmer Model 303 spectrophotometer atomic absorption unit at the DNR laboratory in Hibbing.

As was to be expected, the results of the geochemical soil surveys were less indicative of the underlying mineralization than were the analyses of the basal till. However, the soil surveys did locate significant anomalies which are described below. The cost of obtaining basal till samples is generally too great for use in reconnaissance work, but geochemical studies of basal till may be useful in evaluating specific target areas. In the Birchdale-Indus area, subcropping mineralization was reflected in the base of the till in some areas and several interesting anomalies were located that deserve further attention; these also are briefly described below. A report that includes detailed descriptions of methods and of metal ratios (Meineke, Gilgosch and Vadis, 1976), together with a considerable number of additional maps, profiles, and charts, is available at the DNR, Division of Minerals, at Hibbing, Minnesota.

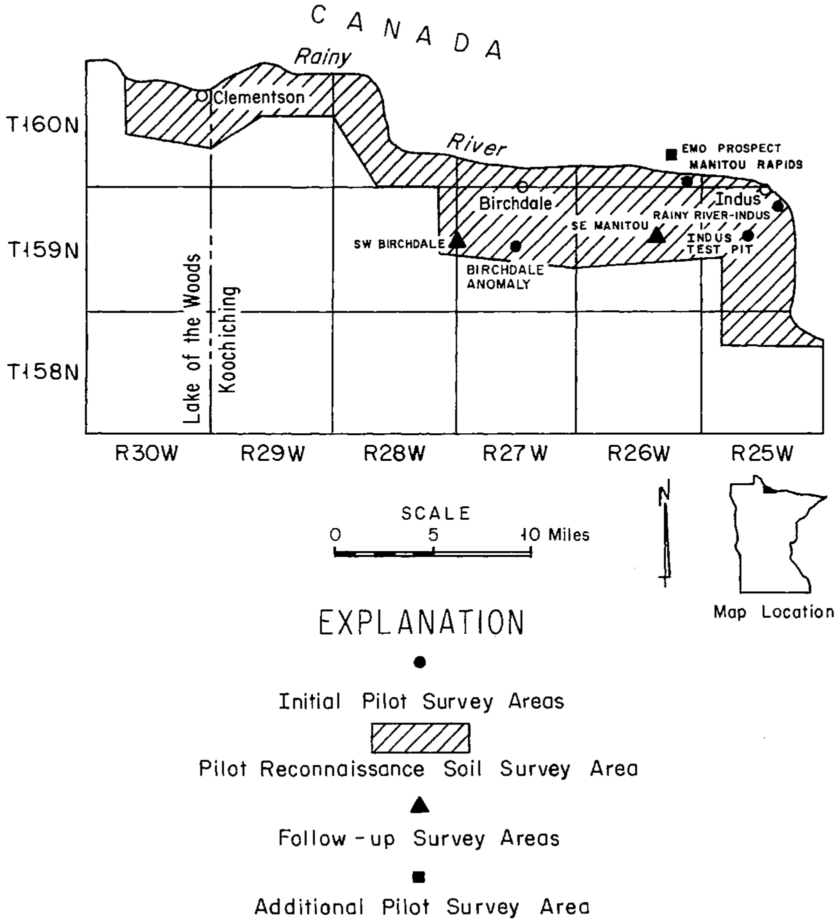

Figure 22 - Map showing locations of geochemical surveys in northwestern Koochiching and northeastern Lake of the Woods Counties, Minnesota.

Initial Pilot Survey

A 2½-foot ((0.8 m) intersection containing 4 percent zinc was drilled on the Birchdale anomaly (SE¼, Section 16, T.159N., R.27W.) (Listerud, 1976). This is the thickest zone of potentially valuable sulfides that has been drilled on the Minnesota side of the Rainy River in this region. In planning the geochemical survey, the assumption was made that this zinc-rich zone extended to the bedrock surface, which is 20 to 30 feet (6 to 9 m) beneath the land surface. Available geologic information was used to project the assumed subcrop location of the mineralized zone. Metal abundances obtained from till and soil samples are given in Table 3.

Table 3--Metal abundances, Birchdale anomally (in ppm)

Metal	Till Samples (hand augered, 7 holes maximum depth 15 feet)		Till Samples (split tube samples, 4 holes, maximum depth 34 feet)		Soil Samples Ah Horizon (20 samples, depth of 3-8 inches)		Soil Samples B Horizon (20 samples, depth of 8-15 inches)	
	Range	50% Cumulative Value	Range	50% Cumulative Value	Range	50% Cumulative Value	Range	50% Cumulative Value
Co	9-66	43	13-42	29	21-70	43	31-74	52
Cu	12-47	26	10-30	20	14-61	21	10-35	17
Ni	25-118	64	22-54	35	19-61	36	31-62	43
Zn	36-300	61	35-90	57	48-176	74	46-76	57
Mn	292-740	410	304-832	420	220-840	not determined	156-680	not determined

Table 4--Metal abundances, Indus test pit area (in ppm)

Metal	Till Samples (hand augered 5 holes, maximum depth 9 feet)	Till Samples (Split tube samples 3 holes, maximum depth 20 feet)	Soil Samples Ah Horizon (29 samples, depth 0.5-3 inches)			Soil Samples B Horizon (47 samples, depth 4.5-16 inches)			Soil Samples C Horizon (48 samples, depth 15-43 inches)		
	Range	Range	Range	Mid-Range	Arith. Mean	Range	Mid-Range	Arith. Mean	Range	Mid-Range	Arith. Mean
Co	26-82	9-45	19-94	57	61	33-110	71	68	20-78	49	50
Cu	7-62	11-45	8-87	48	35	13-36	25	26	15-39	27	23
Ni	36-100	15-69	22-96	59	53	42-103	73	64	27-84	56	50
Zn	34-110	36-109	62-320	191	137	48-252	150	86	34-220	127	65
Mn	260-710	272-728	328-2950	1639	1212	200-705	452	537	298-650	474	441
Pb	18-21 (1 hole)										
Ag	2 (1 hole)										

At the Indus test pit (W½, Section 16, T.159N., R.25W.), generally barren semi-massive to massive pyrite and pyrrhotite occur at the surface within a volcanic sequence covered by as much as 20 feet of glacial deposits. Tills and soils were sampled; see Table 4 and Figure 23 for metal abundances and trace metal profile.

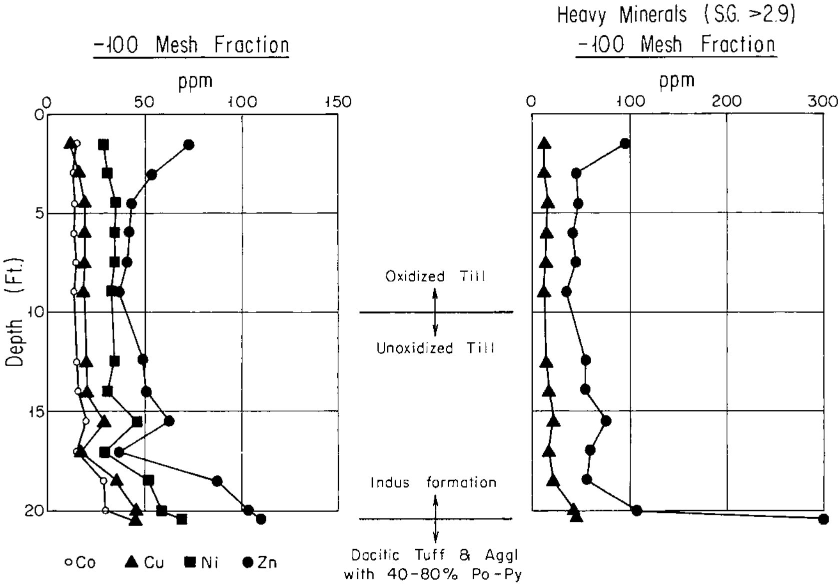

Figure 23 - Trace metal profiles of drill hole IH-10, Indus test pit.

Diamond drilling was conducted in the NE¼, NW¼, Section 10, T.159N, R.25W. (Rainy River-Indus on Figure 22; drill hole IH-13 on Table A-1 and Plate 1) to determine the nature of bedrock over a major magnetic anomaly (Meineke, Vadis and Gilgosh, 1976). Mafic bedrock intersected during drilling contained chromium in the range of 500 to 1,200 ppm. The bedrock at this locality is overlain by 28 feet of till assigned to the Indus formation; samples of till were collected from the surface to a depth of 20 feet (6 m). The chromium concentrations ranged from 21 to 64 ppm, a 300 percent increase in chromium with depth.

Diamond drilling done near Manitou Rapids (SE¼, SE¼, Section 35, T.160N., R.26W.) to determine the nature of the bedrock (drill hole M-1 of Table A-1 and Plate 1) intersected a coarse-grained dacite. The thickness of the overlying till is 50 feet (15 m). The ranges of metal concentrations are given in Table 5.

Table 5--Metal abundances of till, Manitou Rapids area (split-tube samples) (in ppm)

Metal	Range
Co	20-47
Cu	8-77
Ni	22-70
Zn	30-112
Mn	118-744

In some areas, subcropping mineralization is reflected in the lower portion of the Indus formation, and this basal till appears to be the most reliable sample medium for this region. Where the till is generally less than 50 feet (15 m) thick, the underlying mineralization may be reflected in the Ah, B or C horizons of the soil. The Ah horizons yield more widespread anomalies with a higher contrast over background values than the B or C horizons, but the anomalies are more difficult to interpret because of their erratic nature. The Ah horizon samples represent a sampling depth of several feet, with metals brought up by the roots of plants. Through eluviation of the Ah horizon, the B horizon also reflects subsurface mineralization. The C horizon, even though oxidized, does reflect mechanically derived metals, because oxidation and migration of the metals are greatly retarded by the low permeability and high alkalinity of the till.

Pilot Reconnaissance Soil Survey

A pilot reconnaissance soil survey was conducted to determine whether significant trace metal variations existed in the soil that could be related to mineralization. The area selected (fig. 22) has the thinnest Quaternary deposits in the region, generally less than 100 feet (30 m). A half-mile (0.8 km) sample spacing was selected with sampling confined to 50-100 feet (15-30 m) from roads accessible by automobile. The Ah, B and/or C horizons of the soil profile were sampled at 111 sites; metal abundances are presented in Table 6.

The highest concentrations of Co occur in the Ah, B and C horizons in an area one mile (1.6 km) south of Indus (fig. 24). High values of Co were also found at Section 18, T.159N., R.27W., and S½, Section 15. T.159N., R.26W.; these locations are referred to in this report as SW Birchdale and SE Manitou, respectively. The highest Cu values for the entire survey were obtained at SW Birchdale (tbl.6). High Cu values also occur in the Ah horizon 1½ miles (2.4 km) west of Indus (82 ppm) and 1 mile (1.6 km) west of Birchdale (60 ppm). The C horizon also yielded high Cu 4½ miles (7.2 km) south of Indus (50 ppm) and at SE Manitou (53 ppm). A high Ni value (90 ppm) was obtained from a site 1½ miles east of Birchdale. High Zn values occurred in the Ah horizon 1½ miles (2.4 km) west of Indus (160 ppm), 1 to 2 miles west of Birchdale (91 to 135 ppm), at SW Birchdale (132 ppm), and 1 mile (1.6 km) northeast of Birchdale. In the B horizon, high Zn was obtained at the Indus test pit (107 ppm), SE Manitou (105 ppm), and 6 miles (9.7 km)

Table 6--Metal abundances, pilot reconnaissance soil survey (in ppm)

	Ah horizon (108 samples)				B horizon (95 samples)				C horizon (87 samples)			
Metal	Range	Mid-Range	Arith. Mean	% Coeff. of Variation*	Range	Mid-Range	Arith. Mean	% Coeff. of Variation*	Range	Mid-Range	Arith. Mean	% Coeff. of Variation*
Co	16-79	48	44	31	21-96	59	56	30	15-76	46	40	36
Cu	4-540	272	33	187	4-204	104	27	88	10-76	43	26	50
Ni	14-107	61	36	35	19-92	56	51	33	19-98	59	43	34
Zn	27-160	94	77	132	18-110	64	71	30	36-108	72	59	25
Mn	20-2300	1160	546	61	48-1230	639	449	46	160-1086	623	423	49

*Percent coefficient of variation is equal to $\frac{100 \quad S}{\bar{x}}$

(Higher values indicate a greater variation)

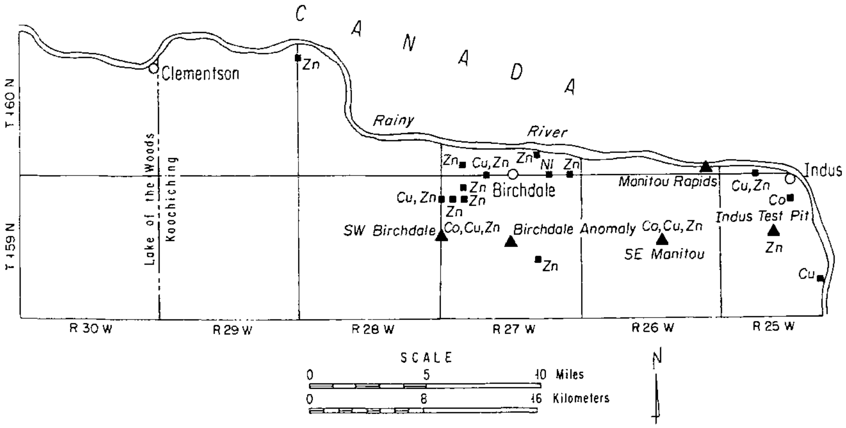

Figure 24 - High metal values in Ah-, B-, and C- horizon soil samples, Pilot Reconnaissance Soil Survey.

east of Clementson (99 ppm). Scattered values of Zn greater than 90 ppm occur in the B horizon 2½ miles (4 km) east of Birchdale, 2 miles (3.2 km) west-southwest of Birchdale, and 3½ miles (5.6 km) south of Birchdale. The C horizon gave 96 ppm Zn 3 miles (4.8 km) west-southwest of Birchdale.

Thus, significant but small variations in metal abundances were noted in the pilot reconnaissance soil survey. The highest values obtained for the various metals analyzed were generally 2 to 3 times the background value for these metals. This low contrast is probably a result of the extensive dilution of locally derived material with material of remote origin and homogenization of the resulting till by the St. Louis Sublobe.

Follow-up Surveys

In order to better define the nature of the anomalies delineated during the pilot reconnaissance soil survey and to locate a source for the anomalous metal values, two areas were selected for follow-up surveys. Both areas had anomalous Cu and Zn values in the reconnaissance survey.

At the area herein called SE Manitou (S.½, Section 15, T.159N., R.26W.) the pilot reconnaissance soil survey located a site where the C horizon contained 53 ppm Cu and the B horizon 105 ppm Zn. High Co values also were obtained (fig. 24).

To determine the extent, nature, and possibly the source of this anomaly, soil samples were taken at 12 sites within approximately 2,500 feet (760 m) of the original site. The metal concentrations of these samples are given in Table 7.

Table 7--Metal abundances, SE Manitou follow-up soil survey

(in ppm)

	Ah horizon (5 samples)		B horizon (11 samples)		C horizon (8 samples)	
Metal	Range	Arithmetic Mean	Range	Arithmetic Mean	Range	Arithmetic Mean
Co	32-64	47	31-82	64	34-71	49
Cu	21-36	28	17-48	29	16-43	26
Ni	34-42	39	34-78	59	35-78	50
Zn	68-124	95	67-115	89	40-140	74
Mn	560-1900	1097	420-672	528	368-540	465

A comparison of Tables 6 and 7 reveals that the Zn in all three soil horizons at SE Manitou is anomalous. The Co in the C horizon is also anomalous. In fact, the 115 ppm Zn in the B horizon and the 140 ppm Zn in the C horizon is higher than the Zn for any samples of those representative horizons in the pilot reconnaissance soil survey. Further work should be done to delineate this anomaly and attempt to locate its source.

At SW Birchdale (Section 18, T.159N., R.27W.) (fig. 24), the pilot reconnaissance soil survey located a site where the Ah horizon contained 540 ppm Cu and 132 ppm Zn, the B horizon 204 ppm Cu, and the C horizon 76 ppm Cu. These Cu values were the highest obtained for the entire reconnaissance survey, and high Co values also were obtained. To determine the extent, nature and possibly the source of this anomaly, soil samples were taken at 89 sites in the area within approximately 3,000 feet (900 m) of the original site. The metal concentrations of these samples are given in Table 8.

Comparing Table 8 with Table 6 of the pilot reconnaissance soil survey reveals that in the Ah and B horizons the mean Cu, and to a lesser degree Zn, is higher for SW Birchdale. However, the C horizon statistics are nearly the same for both surveys. The major portion of the anomaly is 200 to 300 feet (60-90 m) long by not more than 150 feet (45 m) wide. It lies on the up-ice side of a major outcrop. Attempts to trace dispersion of metals up the ice direction were unsuccessful. Glacial striations in nearby outcrops indicate the ice moved in a nearly due east direction.

An electromagnetic survey conducted over the area (Meineke, Vadis and Gilgosch, 1976) located several large conductors with two small shallow conductors in the immediate vicinity of the central portion of the Cu anomaly. Two holes were drilled in this area with the hand auger. Till samples were collected approximately every foot until bedrock was reached at 7 and 12 feet (2.1 and 3.7 m) respectively. Compact basal till with angular clasts was found in the bottom of both holes. Analysis of the till

Table 8--Metal abundances, SW Birchdale follow-up soil survey (in ppm)

	Ah horizon (14 samples)		B horizon (10 samples)		C horizon (89 samples)		C horizon (near original sample site) (10 samples)		Basal Till (hand auger samples) (17 samples)	
Metal	Range	Arith. Mean	Range	Arith. Mean	Range	Arith. Mean	Range	Arith. Mean	Range	Arith. Mean
Co	26-54	42	38-74	56	20-62	39	29-62	43	21-61	37
Cu	11-440	113	12-105	44	13-74	23	22-74	42	26-52	35
Ni	24-54	35	33-61	43	27-64	38	32-50	40	33-57	41
Zn	38-188	86	60-168	87	35-80	50	47-115	62	60-85	71
Mn	172-1400	562	200-1160	519	300-660	440				
Pb					12-41	24				

samples indicated that Cu and Zn were anomalous and consistent with depth; a slight increase observed in the basal till was not enough to indicate nearby mineralization (tbl. 8). The closest known outcrops are 1½ miles (2.4 km) away in an up-ice direction; Ojakangas has reported minor malachite in these outcrops. (See page 55 of this report on sulfide mineralization of the Birchdale-Indus Area for Section 14, T.159N., R.28W.)

Additional Pilot Survey, Emo, Ontario

Upon completion of the follow-up surveys additional studies were conducted over known mineralization in order to further evaluate the use of geochemical exploration methods in this region. Soil, till and stream sediment surveys were conducted at an area herein called the Emo Prospect in Ontario, just west of Emo (figs. 2 and 22), where pods of 0.5 percent Cu+Ni occur in a mafic intrusive complex covering about 5 square miles (Fletcher and Irvine, 1954). Extensive diamond drilling has been done on this prospect. The mineralization is locally exposed; the overlying till is generally less than 60 feet (18 m) thick and averages approximately 15 feet (4.5 m). The metal abundances of the soil, till and stream samples are given in Table 9. A comparison of Table 9 with Table 6 of the pilot reconnaissance soil survey reveals a lack of significantly higher values in the Emo study, indicating that the till generally does not reflect the underlying mineralization at the Emo Prospect.

Examination of the metal distribution and trends over the area indicates that in the Ah horizon Co, Cu and Ni do not produce an anomaly. In the B and C horizons, Co, Cu and Ni give a poorly defined anomaly 1½ times the background, except for one highly anomalous sample site where Cu is 15 times background and Ni is about 5 times background in the B horizon, with Cu 12 to 22 times background and Ni 6-13 times background in the C horizon.

Clastic stream sediments give a well defined anomaly with a contrast twice background, in a down-ice direction from the mineralization. In view of the fact that the Indus formation is not representative of the local bedrock at the Emo Prospect, it is significant that the Cu-Ni mineralization was reflected in the stream sediments.

Conclusions and Recommendations on Geochemistry

In the surveys discussed in this report, the basal till did reflect underlying bedrock and mineralization to a reasonable degree, with some exceptions. It seems that basal till in this region can be used as a geochemical sample medium for detailed exploration. Soil surveys described in this report located anomalies at SW Birchdale, Indus test pit, SE Manitou and other areas shown on Figure 24; these deserve further consideration.

Table 9—Metal abundances in soil, till and stream sediments, Emo prospect, Ontario (in ppm)

Metals	Ah horizon (12 samples)		B horizon (12 samples)		C horizon (64 samples)		Till (hand auger) (9 samples in 2 holes)		Stream Sediments (14 samples)
	Range	Arith. Mean	Range	Arith. Mean	Range	Arith. Mean	Range	Arith. Mean	Range
Co	42-68	55	30-70	59	20-80	46	18-60	36	32-70
Cu	7-64	22	12-202	36	11-246	25	16-30	21	10-30
Ni	28-76	45	26-192	65	18-258	46	28-60	40	40-76
Zn	40-148	74	50-79	67	28-142	58	24-72	49	51-272
Mn	202-874	662	380-586	462	188-1112	459	324-468	382	180-1140

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APPENDIX

Generalized Descriptions of Drill Core

The approximate locations of the drill holes in Tables A-1, A-2, and A-3 are shown on Figure 1 and on Plate 1.

The included information is based on core-logging by R.W. Ojakangas, some by W.H. Listerud, and numerous company personnel. To determine which company logs have been restudied and reinterpreted, it is necessary to compare the general data in these appendices with complete company logs available from the Minnesota Department of Natural Resources, Hibbing, Minnesota, 55746. Additional drill-hole information may have become available since this report was written. Holes for which logs are not yet available are listed without rock descriptions.

All of the rock names used in the tables should be prefixed with "meta", but this was generally not done for the sake of brevity. Abbreviations used include the following: py = pyrite; po = pyrrhotite; chalco = chalcopyrite; hem = hematite; lim = limonite; mag = magnetite; fe-fm = iron-formation.

Table A-1 -- Generalized descriptions of drill cores, Birchdale-Indus area

Drill Hole	Lessee	Core Footage	General Lithology	Conductor
R-1-1	Exxon	200-650	Felsic-intermediate volcaniclastics; chloritic	Scattered py to 1%
R-4-1	Exxon	97-422	Felsic and intermediate tuff; basalt	180' of 5-100% po-py (140' est. true thickness)
R-4-2	Exxon	145-530	Felsic volcaniclastics; basalt at base	26' of 5-80% po-py 38' of 10-90% po-py
R-4-3	Exxon	240-452	Fine graphitic metasediment; 40' felsic tuff at base	Graphite
KC-1	W.S. Moore	167-313	Mag-hem-chert fe-fm; metasediments; felsic volcaniclastics	Drilled for iron ore; py noted

KC-2	W.S. Moore	182-320	Mag-py-chert fe-fm; felsic volcaniclastics	Drilled for iron ore; py noted
KC-3	W.S. Moore	8-220	Mag-po-chert fe-fm; felsic volcaniclastics	Drilled for iron ore; po noted
KC-4	W.S. Moore	175-255	Mag-hem-chert fe-fm; felsic volcaniclastics	Drilled for iron ore
R-3-1	Exxon	126-545	Felsitic tuff and agglomerate; basalt	8' of 5-80% py 8' of 5-40% py-po 10' of 10% po 70' of scattered 2-10% po
R-3-2	Exxon	92-744	Andesite, diorite, dacite; minor felsic volcaniclastics	Scattered 1% po
R-3-3	Exxon	3-758	Basalt, andesite, felsic-intermediate volcaniclastics	14' of as much as 50% po 15' of as much as 10% py Minor scattered py
R-3-4	Exxon	7-553	Basalt; felsic-intermediate volcaniclastics, possible agglomerate	8' of 10-60% po-py 80' of 1-20% po-py
RR-6-1	Texas Gulf Sulfur	143-414	Felsic tuff and agglomerate	Scattered po-py 2.5' of 30-60% po-py
RR-6-2	Texas Gulf Sulfur	142-366	Felsic tuff and agglomerate; andesite	2.5' of pyrite 23' of 5% po-py 7.5' of 15% py-po
R-5-1	Exxon	116-805	Felsic-intermediate volcaniclastics; basalt flows	Scattered po-py to 20%
R-5-2	Exxon	71-633	Felsic tuff (some rhyolite); gabbro, basalt flows; possibly 20' of mag-chert fe-fm	Scattered po-py to 5%
RR-12-1	Texas Gulf Sulfur	66-280	Felsic tuff	12' graphitic metasediment; minor disseminated sulfides
RR-12-2	Texas Gulf Sulfur	95-282	Felsic tuff and lapilli tuff	3.5' graphitic metasediment with py
	Note: The following 9 holes contain much biotite and some garnet; recrystallization moderate to intense.			
S-43-1	Texas Gulf Sulfur	7-498	Felsic and intermediate tuff; gabbro, andesite	9' of 40% po; 58' of 20% po-py; plus other po, traces chalco
S-43-2	Texas Gulf Sulfur	10-524	Felsic and intermediate tuff; granite; diorite	2.5' of 5% po-py with 4.06% Zn and 0.25 Ag; and other zones 3-5% po
S-43-3	Texas Gulf Sulfur	47-450	Felsic tuff; andesite	20' of 40% po; scattered po and py
R-2-1	Exxon	63-600	Felsic and intermediate tuff and agglomerate; diorite, gabbro, diabase	23' of 5-20% py-po; 72' of 2-50% po-py; 13' of 5% po
R-2-1A	Exxon	88-385	Felsic-intermediate tuff and agglomerate; granite	52' of 5-10% po; 20' of 5-20% po; 35' of 2-7% po; 5' of 5% po
R-2-2	Exxon	113-763	Felsic tuff; gabbro	18' of 10-50% py; 30', 20' and 6' of 5-10% po-py
R-2-3	Exxon	107-784	Gabbro; felsic tuff	Minor po
NCB-1	North Central Mineral Ventures	49-384	Felsic-intermediate tuff; diorite, basalt	100' of as much as 10% sulfides 13' of as much as 40% po
NCB-2	North Central Mineral Ventures	5-574	Diorite, granite, amphibolite; felsic-intermediate tuff; andesite	115' of 2% or more sulfides; 11' of 10% po; 15' of 20% py; traces chalco
M-1	Minn. Dept. of Natural Resources	50-55	Dacite	Not drilled on anomaly; traces Ag

IH-10	Minn. Dept. of Natural Resources	20-47	Felsic tuff and agglomerate	27' of 5-80% sulfide; traces Ag and Au
IH-11	Minn. Dept. of Natural Resources	9-24	Felsic tuff	15' of 1-3% sulfide; traces Ag
IH-12	Minn. Dept. of Natural Resources	17-43	Felsic tuff; andesite	26' of 5-20% sulfide; traces Ag
IH-13	Minn. Dept. of Natural Resources	28-73	Gabbro; possible metasediment or intermediate tuff	Minor sulfides; traces of Au and Ag; not drilled on anomaly

Table A-2 -- Generalized descriptions of drill cores, Roseau 1:250,00 sheet

Drill Hole	Lessee	Core Footage	General Lithology	Conductor
FT-15	Ridge	249-335	Fine metasediment (tuffaceous?)	1% sulfides
FT-16	Ridge	215-480	Fine metasediment; iron-formation (?)	160' of 3-60% po-py plus magnetite to 15%
FT-17	Ridge	240-425	Fine metasediment	30' of 5-100% graphite; minor sulfides
FT-18	Ridge	140-435	Fine metasediment; felsic tuff	100' of graphitic metasediment, with zones of as much as 75% graphite and 10% py
FT-6	Ridge	312-643	Fine metasediment; felsic tuff; rhyolite	250' of graphitic metasediment and tuff, locally as much as 20% graphite and 15% py
FT-19	Ridge	300-641	Fine metasediment; felsic tuff; minor hem-chert fe-fm	250' of graphitic metasediment with graphite commonly 50-70% and 2-4% py
G-1	Exxon	213-985	Diorite; felsic-intermediate volcanic rocks; "shale"	14' of pyrite-bearing "shale"
T 20-1	Exxon	393-835	Gneiss; metasediments (tuffaceous)	60' of graphitic metasediments
T 25A-1	Exxon	280-654	Intermediate-mafic volcaniclastics	55' of 75%+ po-py plus other thin zones
T 25B-1	Exxon	402-836	Metasediment (tuffaceous)	None (?)
T25B-2	Exxon	297-695	Metasediment (tuffaceous and chloritic); felsic-intermediate tuff and lapilli tuff	62' of pyrite-rich metasediment and lapilli tuff; graphitic metasediments
B-31-1	Exxon	176-723	Felsic tuff and volcaniclastics; some intermediate-mafic flows and volcaniclastics	Several minor zones of po-py, some as much as 80%
B-31-2	Exxon	266-993	Metasediment (tuffaceous), felsic-intermediate volcaniclastics; intermediate-mafic flows and volcaniclastics	Few thin bands of 50-80% py-po; more at <5% py-po
B-31-3	Exxon	97-535	Gabbro; felsic tuffs at base	87' of 5-90% py
B-31-4	Exxon	96-503	Gabbro; intermediate-mafic volcaniclasts; felsic-intermediate tuffs	2' of massive py; 115' of 25% py
B-31-5	Exxon	81-675	Gabbro; mafic volcanics and intermediate-mafic volcaniclastics	60' of 3-5% po-py and 5-8% magnetite with trace chalco
B-57	Exxon	171-353	Intermediate volcaniclastics	28' of up to 40% sulfide and graphitic metasediments; minor sphalerite
BD-1	Ridge	157-410	Felsic and intermediate-mafic tuffs; possible iron-formation	85' of 2-6% sulfide and 5-10% magnetite
BD-2	Ridge	185-434	Felsic and some intermediate-mafic tuffs, lapilli tuff, agglomerate	100' of 20-25% sulfide; 1-2% magnetite common

BD-3	Ridge	256-424	Felsic tuff	40' of 5-7% sulfide; several thin zones of 3-7%; graphite
40918	INCO	239-607	Felsic-intermediate tuff and agglomerate	Minor sulfides
40926	INCO	105-493	Felsic-intermediate tuff and agglomerate	Minor sulfides and graphite
40917	INCO	183-446	Biotite schist (with garnet)	10' of 5-10% sulfides
40919	INCO	130-564	Mag-py-po fe-fm; gabbro; diorite; felsic tuff and agglomerate	200' of ave. 25% po and up to 90%
40920	INCO	256-524	Intermediate-mafic volcanics (massive, highly weathered)	Zones of 3% py; copper staining
B-B-2	W.S. Moore	177-330	Felsic-intermediate tuff and minor agglomerate	25' of high po
RR-16-1	Texas Gulf Sulfur	157-410	Intermediate tuff	35' of 2% po-py; 5' of 30% po-py
FT-7	Ridge	211-835	Hem-chert and py-chert fe-fm; "mudstone"	Top 200' hem-chert; lower 300' py-chert with py to 60%
FT-10	Ridge	373-800	Felsic-intermediate tuff and minor agglomerate	250' (est. true thk) with sulfide zones, including 75' of 70% sulfide
FT-12	Ridge	261-534	Hem-chert and py-hem-chert fe-fm; "mudstone"	Top 200' hem-chert; 80' py-hem-chert
FT-13	Ridge	193-650	Hem-lim-chert fe-fm; "mudstone"; chert	Top 100" hem-lim-chert
FT-14	Ridge	216-615	Felsic-intermediate tuff; metasediment; hem-chert fe-fm	200' (est. true thk) hem-chert; 12' (est. true thk) massive sulfide
FT-21	Ridge	201-775	Lim-chert and lim-py-chert fe-fm; "mudstone"	125' lim-chert and lim-py-chert
FT-22	Ridge	200-634	Hem-lim-chert and lim-chert fe-fm	225' hem-lim-chert with 25-58% fe; 20' of 95% py; 150' lim-chert with 35-45% fe; 20' of 45-95% py
FT-23	Ridge	225-239		
FT-20	Ridge	300-641		
DDH B 24-1	Exxon	130-614	Felsic tuff; metasediment; minor intrusives; mag-sulfide fe-fm	167' of 2-90% po-py; 159' of 6-30% po-py
DDH B 24-2	Exxon	170-755	Felsic tuff; metasediment	30' of 50-95% py; 42' of 40-80% sulfides; 28' of 5-70% po-py; 55' of 1-40% po-py; trace sphalerite
DDH B 24-3	Exxon	139-855	Metasediment; intermediate-mafic tuff; possible mag-sulfide fe-fm; mafic intrusives	440' of trace-40% py with few high-sulfide zones
DDH B 24-4	Exxon	102-1684	Metasediment; mafic tuff; mafic intursive	6.5' of 40% po-py with chalco; much disseminated minor po-py
DDH B 58-1	Exxon	152-444	Felsic-intermediate tuff and lapilli tuff; metasediments	63' of 2-90% py-po; other minor sulfide zones
DDH B 35-1	Exxon	143-428	Metasediment; possible mafic tuff	5' massive graphite, traces sulfide
DDH B 54-1	Exxon	150-325	Interbedded mafic tuffs and volcanics	To 10% py-po with trace chalco; 5' of trace-0.5% chalco
DDH B 21-1	Exxon	112-453	Tuffaceous metasediment, partially granitized	Several thin zones of 10-25% po-py and minor chalco; 15' graphitic zone
DDH B 21-3	Exxon	129-523	Tuffaceous metasediment, granitized; granite	24' of 2-3% po-py-chalco; 12' of 5% po-py-chalco; other disseminated sulfides
DDH B 21-2	Exxon	126-724		
DDH M-1	Exxon	336-1095		
DDH W 1-1	Exxon	115-296		

DDH W 3-1	Exxon	166-324
DDH W 8-1	Exxon	174-305
DDH W 9-1	Exxon	159-345
DDH W 13-1	Exxon	145-316
DDH B 5-1	Exxon	90-770
A-9-1	Amoco	93-600
A-8-1	Amoco	195-600
A-4-1	Amoco	247-600
A-4-2	Amoco	254-540
A-10-1	Amoco	216-600
A-6-1	Amoco	146-683
A-6-2	Amoco	214-659
A-1-1	Amoco	242-600
B-3-1	Amoco	180-665
B-3-2	Amoco	195-605
B-3-3	Amoco	192-574

Table A-3 -- Generalized descriptions of drill cores, Bemidji 1:250,000 sheet

Drill Hole	Lessee	Core Footage	General Lithology	Conductor
RL-25	Exxon	358-745	Intermediate-mafic volcaniclastics (?); mag-hem-chert fe-fm	Traces of sulfides
RL-39	Exxon	375-783	Metasediments (some graphitic); gabbro	Graphitic metasediments
RL-28-1	Exxon	224-954	Gabbro; ultramafics (320'); diabase; graphitic slate	Up to 1200 ppm Ni; and 1100 ppm Cr in ultra-mafics
RL-31	Exxon	319-493	Metasediments (tuffaceous and graphitic)	Graphitic metasediments
BID-1	Ridge	186-706	Intermediate volcaniclastics; graphitic schist; breccia; andesite	Minor po-py and graphitic schist
BID-2	Ridge	260-473	Andesite; argillite	Minor sulfides
BID-3	Ridge	265-553	Felsic-intermediate volcaniclastics and volcanics; graphitic chert	Minor sulfides; graphitic chert; minor chalco
MIZA-1	Exxon	94-395	Dacite porphyry; gabbro; diorite; cherty felsic-intermediate tuffaceous metasediments (iron-formation?) and tuff	12' and 14' thicknesses metasediments with >5% sulfide (latter has 10% magnetite); 5' of metasediments with 25-30% sulfide; po>py; traces of chalcopyrite; to 3600 ppm Cu and 375 ppm Zn
DDH RL 42-1	Exxon	371-790	Metasediment, possible thin chert-py fe-fm; intermediate metatuffs or metavolcanics	10' of 1-10% py and >300' of trace-3% py in graphitic metasediments; v. minor sphalerite
DDH RL 43-1	Exxon	317-922	Felsic tuff and lapilli tuff; metasediments (some graded); gabbroic flow (?)	Minor scattered py, chalco, sphalerite, po; graphite