GEOLOGY OF LOWER PRECAMBRIAN ROCKS AND ASSOCIATED SULFIDE MINERALIZATION IN AN AREA SOUTH OF INDUS, KOOCHICHING COUNTY, NORTHERN MINNESOTA

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ABSTRACT

The Indus area is located near the Canadian border approximately halfway between International Falls and Baudette in the southwestern part of the Wabigoon greenstone belt. This is an area of interbedded Archean volcanics, related intrusives and metasediments including iron-formation. An outcrop of disseminated to massive sulfides is associated with a felsic volcaniclastic unit. The outcrop of the Archean volcanics is located along the flanks of a northwesterly trending Middle-Precambrian mafic dike which has proved more resistant to weathering.

The Archean volcanic units consist of a sequence of mafic, intermediate, and felsic units that were apparently deposited under deep, still water conditions. Studies of whole rock analyses indicate that these rocks are similar in composition to rocks in other areas of the Superior province. They may have been deposited in a geological environment similar to a modern island arc environment. The area was regionally metamorphosed during the Algoman orogeny and the Archean rocks now contain a mineral assemblage characteristic of the greenschist-amphibolite transition facies.

Based on data from outside the study area, the major structure in the area consists of an overturned, isoclinally folded anticline with a general east-northeast trend. Lineaments observed in aerial

photographs and apparent offsets of the mafic dike suggest that faulting has occurred in three places.

Disseminated to massive sulfides which occur in felsic volcaniclastics are believed to be volcanogenic in origin with both the metals and sulfur being of magmatic derivation. The sulfides are almost entirely pyrite and pyrrhotite with only trace amounts of chalcopyrite and sphalerite. Textural evidence suggests that the sulfides were mobilized and redeposited in favorable sites by a later event, probably the same one producing the folding and metamorphism in the host rocks. Electro magnetic studies suggest that their present form is that of small stratabound lenses. Trace element analyses show that base metal values are low in all cases. The number of analyses is insufficient to be statistically valid. A comparison of trace element ratios from the Birchdale and Indus areas shows a difference between the metal ratios of the two areas. The significance of the observed difference is not known.

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INTRODUCTION

Introduction

This report covers a five-square-mile area of the Birchdale-Indus map of Ojakangas, Meineke and Listerud (1977) which has received the name "Indus Test Pit Area" from three small test pits and a test shaft sunk in a massive sulfide outcrop. The rocks in this area are representative of part of an Archean volcanic pile (Goodwin, 1968). Outcrops are largely limited to the flanks of a northwest trending resistant mafic dike which crops out discontinuously. The remainder of the area is covered by Pleistocene glacial deposits.

Purpose

The "Indus Test Pit Area" was selected for detailed study because it contains the best outcrop in an area that has been explored for base metal massive sulfide deposits. The major objectives were to detail the areal stratigraphy, determine the sulfide mineralogy and paragenesis, and to find possible ore indicators.

Location

The "Indus Test Pit Area" is located near the International Border approximately half-way between Baudette and International

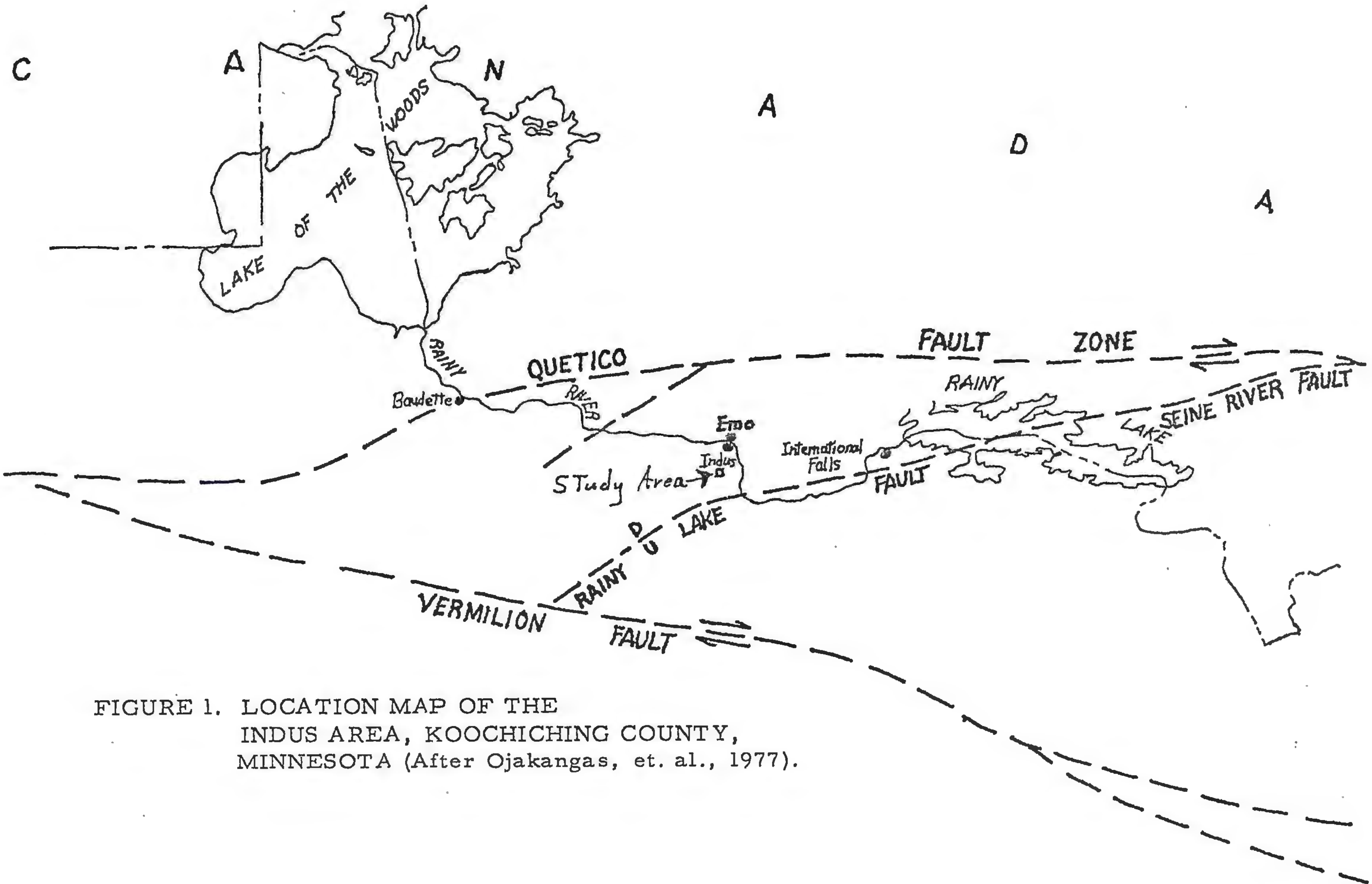


FIGURE 1. LOCATION MAP OF THE INDUS AREA, KOOCHICHING COUNTY, MINNESOTA (After Ojakangas, et. al., 1977).

Falls, Minnesota (Figure 1). The specific area studied includes sections 8, 16, 17, 20 and 21 in T. 159 N., R. 25 W. The test pit, proper, is located 2.4 miles from the old Indus High School on a section line road leading south from Highway 11.

Methods of Study

Study included detailed field mapping and sampling, magnetometer and electromagnetic geophysical surveys, logging and sampling cores from three shallow drill holes, thin and polished section study, staining of thin section heels for recognition of potassium feldspar, analysis of selected samples for trace elements and for major elements by the atomic absorption methods, and whole rock analysis of selected samples.

The field mapping and sampling was completed in a three-week period in late June and early July in the summer of 1977. An additional weekend in October, 1977 was spent gathering further data. The mapping was done on a topographic base map with a scale of 1" = 500'.

The diamond drill cores logged and sampled are from three shallow holes which were drilled by the Minnesota Department of Natural Resources for geologic study purposes. They are stored in the core library of the Minnesota Department of Natural Resources in Hibbing, Minnesota.

The laboratory work and compilation of data began in the fall of 1977 and continued into 1978. One-hundred-twenty-six samples from outcrop and drill holes were collected from which 108 thin sections and 25 polished sections were made. In addition, 12 thin sections from the area made by R. W. Ojakangas and 10 thin sections and five polished sections at the Minnesota Department of Natural Resources, Minerals Division, were examined. Thin section study of the mineralogy and textures was done to determine as closely as possible the original rock types. Polished section study was done using reflected light to identify the opaque minerals, their paragenesis and their relationship to the host rock.

The atomic absorption analyses were made at the geochemical laboratory of the Minnesota Department of Natural Resources at Hibbing, Minnesota by Department of Natural Resources personnel. Twenty-five samples were analyzed for major elements in an effort to obtain more information about the original rocks since the major rock units were very fine-grained, nearly completely recrystallized metavolcanics and metasediments. The elements for which a mode was determined were Ti, Al, Ca, Fe, K, Na and Si. Thirty-six samples were analyzed for the trace elements Ag, Au, Co, Cu, Ni, Pb and Zn to see if trends would develop in trace element ratios, and to compare trace element ratios with those found by other workers in the region.

Seven samples were sent to the University of Manitoba at Winnipeg, Manitoba for whole rock analysis. The oxides of Si, Al, Fe (total), Mg (high), Ca, K, Ti and Mn were determined by x-ray fluorescence spectrometry. The Na_2O, P_2O_5 and MgO (low) were determined by atomic absorption spectrophotometry. The H_2O (total) was found by heating the sample in a stream of dry oxygen in an induction furnace, collecting the H_2O on anhydrone and then weighing. The CO_2 was determined by decomposing the sample with HCl and heating. The evolved CO_2 was passed through a drying train and collected on ascarite.

All thin section heels were etched with hydrofluoric acid and stained with sodium cobaltinitrite for textural studies and potassium feldspar determination. In addition, a number of thin section heels were stained with the food dye amarand for calcium determination in feldspar.

Magnetometer and horizontal shootback and vertical loop EM work was done by the Minnesota Department of Natural Resources during the summer of 1977 to get information regarding the lateral extent of the stratigraphy since there is no outlying outcrop for correlation, and to locate and determine the extent of conductors in the sulfide zone.

Previous Geologic Work

There has been little geologic work in the Birchdale-Indus Emo areas until recently. The Coutchiching and Keewatin were defined by A. C. Lawson (1888) as a result of initial observations along the Rainy River. Few of these observations pertained to

Minnesota. In Minnesota, the location of some outcrops were plotted over the years on county road maps on file in the Minnesota Geological Survey. Later these were utilized in the compilation of aeromagnetic and geologic maps of northwestern Koochiching County (Meuschke, et. al., 1957) and of northwestern and northeastern Minnesota (Bath, et. al., 1964; 1965). Each map includes part of the Birchdale-Indus area.

The first detailed geologic work in the region was Fletcher and Irvine's (1954) "Geology of the Emo Area". This area is located in Ontario across the Rainy River from the Birchdale-Indus area in Minnesota (Figure 1). They reported a sequence of felsic to mafic metavolcanics and metasediments that have been intruded by units ranging from felsic to mafic.

During the 1960's several mining companies were actively exploring northern Minnesota for massive sulfides. They covered much of the Birchdale-Indus area with geologic mapping, airborne and ground geophysical surveys, and diamond drill holes.

Hanson and Malhotra (1971) reported a K-Ar age study of Middle-Precambrian mafic dikes in northern Minnesota and of the low grade metamorphism of these dikes.

Sims and Mudrey (1972) have studied a belt of Middle-Precambrian mafic dikes about 60 miles wide extending from the western part of the Mesabi range into Ontario. These dikes occupy at least three sets of fractures and have K-Ar ages ranging from 1395 to 2240 m. y.

The International Falls 1:250,000 map sheet (Southwick and Ojakangas, 1973) includes the general geology of the eastern part of the Birchdale-Indus area and the Roseau 1:250,000 map sheet (Sims and Ojakangas, 1973) includes the general geology of the western half of the Birchdale-Indus area, but the geology is highly generalized.

Listerud (1974) made a detailed study of the Birchdale anomaly located south of the town of Birchdale in the northern part of the Birchdale-Indus area. The Birchdale Anomaly is a geophysical feature near the Birchdale granite which has intruded a metavolcanic-metasedimentary sequence.

The report and map of the Birchdale-Indus area (Ojakangas, Meineke and Listerud, 1977) provided the framework for this project. This report includes the geology of the Birchdale-Indus area, the results of geochemical and geophysical ground surveys, and discusses the sulfide mineralization of the area. R. W. Ojakangas, under the auspices of the Minnesota Geological Survey and with the support of the Minnesota Department of Natural Resources, mapped the area (Figure 2). D. G. Meineke of the Minnesota Department of Natural Resources was in charge of the geophysical and geochemical investigations and W. H. Listerud, also of the Minnesota Department of Natural Resources, was responsible for the sulfide studies.

Acknowledgements

The writer would like to thank Dr. Ralph W. Marsden and Dr. Richard W. Ojakangas who suggested this study and who served as advisors for the work for their thoughtful advice and helpful suggestions throughout the study. The writer would also like to express his appreciation to Dr. James A. Grant and Dr. John C. Green for their suggestions. The Minnesota Department of Natural Resources is gratefully acknowledged for their financial support and use of their facilities during the project. The assistance of W. H. Listerud, D. G. Meineke, and M. K. Vadis of the Minnesota Department of Natural Resources in gathering field data deserves special mention. The able and willing field assistance of David Drapela was greatly appreciated. Last but not least, I would like to express my appreciation to my wife, Dorothy, for her support and patience while I worked on this study.

REGIONAL GEOLOGY

Introduction

The Indus area is located in the southern part of the exposed portion of the Superior Province of the Canadian Shield in the Wabigoon Volcanic Belt. The rock types include mafic to intermediate lavas and intrusive rocks, felsic intrusives, agglomerate, tuff and volcaniclastic rocks, iron-formation and metasediments. Except for the Middle-Precambrian mafic dikes in the region, all of the bedrock is Lower-Precambrian. The rock units and regional structure have a general northeasterly strike. The region has a total relief of about 150 feet, varying from a minimum in the south which is largely peat bog and swamp to a maximum in the north. As a consequence, the bedrock is poorly exposed. The area was once covered by Glacial Lake Agassiz and is now blanketed by Pleistocene lake sediments, glacial tills and outwash.

Regional mapping has been done by Ojakangas, et. al. (1977) in the Birchdale-Indus area on the Minnesota side of the Rainy River utilizing outcrop, drill cores and geophysical data; and by Fletcher and Irvine (1954) in the adjacent Emo area in Ontario. Figure 2 is a composite of their maps. Listerud (1974) did detailed mapping in sections 15, 16 and 21, T. 159 N., R. 27 W., which are located three miles south of the town of Birchdale in the western

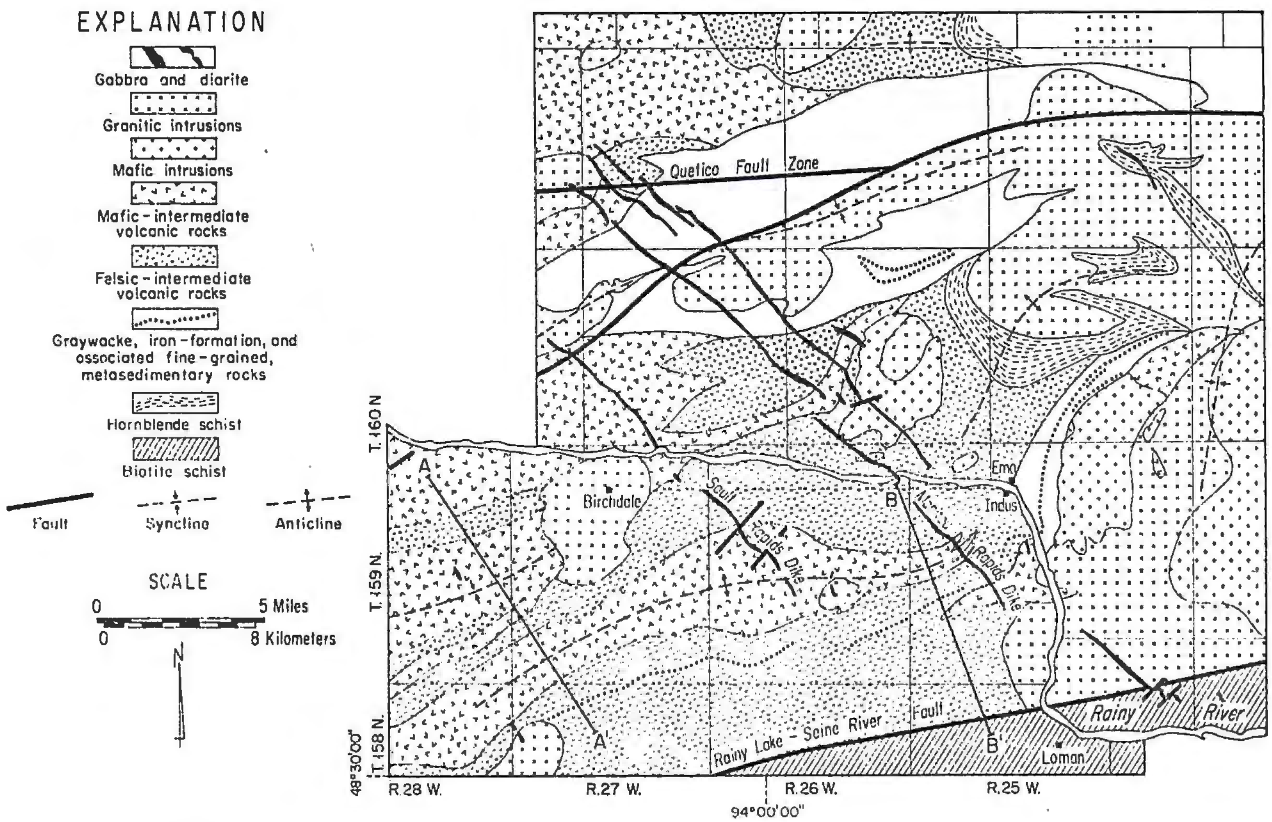


FIGURE 2. GENERALIZED GEOLOGIC MAP OF THE BIRCHDALE-INDUS AND EMO AREAS (After Ojakangas, et. al., 1977). THE EMO MAP AREA IS NORTH OF THE RAINY RIVER.

part of the region. The description of the regional geology which follows is based primarily on Ojakangas, et. al. (1977) and to a lesser extent on Fletcher and Irvine (1954) and Listerud (1974).

The rock classification system used is the Canadian system. In this system, aphanitic rocks with a compositional range from rhyolite to dacite are classified as felsic, andesites are intermediate and basalts are mafic.

Stratigraphy

Introduction

The stratigraphy in the area is a sequence of Archean volcanic rocks consisting of mafic, intermediate and felsic flows, agglomeratic tuff, tuff, iron-formation and sediments, and related intrusives. These units have been strongly folded about east-northeasterly trending axes and metamorphosed to lower amphibolite grade. A northwesterly trending uralitized diabasic gabbro dike cuts all other units. Nearly all outcrop is found in a narrow border along this dike.

Biotite Schist

The biotite schist shown in the southeast part of the map does not crop out in the Birchdale-Indus area, but is interpreted to be present on the basis of regional geology and geophysics. This unit crops out in Ontario, one to two miles north of the southeast corner of the Birchdale-Indus map. Here it is an intensely sheared, foliated unit of interbedded biotite and hornblende schist and siliceous tuff (Fletcher and Irvine, 1954). They suggest that this unit is Koochiching and therefore older than the metavolcanics on the region.

Felsic-Intermediate Volcanic Rocks

Felsic-intermediate volcanic rocks form a major part of the bedrock in the region. The term volcanic rocks includes volcaniclastic rocks, lava flows and dikes. Since it is difficult to determine if a clastic rock composed of sand-sized volcanic detritus in an Archean terrain is a true pyroclastic, a reworked pyroclastic or an epiclastic rock, these rocks are grouped as volcaniclastic rocks unless sufficient evidence is available to be more specific (Ojakangas, et. al., 1977). Felsic-intermediate volcanic rocks include agglomerate, lapilli tuff, tuff, volcaniclastic rocks, flows and dikes.

Felsic Agglomerate and Lapilli Tuff

Agglomerate and lapilli tuff are common in the region, especially in the central felsic-intermediate belt. The agglomeratic texture is well developed along the north one-third of the Manitou Rapids dike, the north end of the Sault Rapids dike, the area immediately to the east of the Birchdale pluton, and the Emo area. The clasts in the Birchdale-Indus part of the region are usually about an inch in diameter with the larger ones reaching about six inches in diameter in the vicinity of the Manitou Rapids roadside park (Ojakangas, et. al., 1977). Fletcher and Irvine (1954) report a size range of one to eight inches, occasionally reaching one foot in diameter in the Emo area. Some of these agglomeratic rocks may be epiclastic, but the uniformity of clast composition suggests either a pyroclastic origin or a reworked pyroclastic origin (Ojakangas, et. al., 1977). In the Birchdale-Indus area these clasts are well stretched; however, in the Emo area they are subangular to subrounded and constitute ten to 40 percent of the rock (Fletcher and Irvine, 1954).

These rocks appear to be dacitic to rhyodacitic in composition with the plageoclase being in the albite to oligoclase range. Alteration products include biotite, muscovite, epidote, carbonate, chlorite, sphene, and blue-green amphibole and occur in the finer grained parts of these rocks. Ojakangas, et. al. (1977) and Fletcher and Irvine (1954) report that on weathered surfaces the lighter colored clasts stand out against the darker matrix. Fletcher and Irvine (1954) note that the matrix has the same mineralogy as the clasts, but that the mafic constituents are slightly more prevalent. However, Listerud (1974) noted that the clasts in the Birchdale-Indus area are usually slightly more mafic than the matrix.

Felsic Tuff and Volcaniclastic Rocks

Units of sand-sized particles classified as tuff or reworked tuff because of their association with coarser pyroclastics are interbedded with agglomeratic and lapilli tuff as well as forming the matrix for the agglomeratic units. Fletcher and Irvine (1954) report thin tuff units between dacite flows.

Bedding characteristics show a wide variation; locally, a series of beds may include some a few inches thick and others several feet thick with the thicker being coarser-grained. Some are very thinly stratified. In some outcrops thinly bedded felsic laminations alternate with more mafic. Bedding, where seen, is usually even with straight top and bottom contacts.

Ojakangas, et. al. (1977) suggest that turbidity currents apparently were not an important mechanism of sedimentation in the Birchdale-Indus area since there is a complete lack of Bouma (Bouma, 1964) bedding characteristics.

Most of these units appear to be dacitic, but staining for potassium shows the presence of some rhyodacitic or rhyolitic fragments. The primary composition of these units is plagioclase (frequently zoned), volcanic quartz and volcanic rock fragments. The units with the alternating mafic-felsic laminae are characterized by alternations of feldspar rich felsic laminae with amphibole-biotite-epidote-rich layers.

Felsic-Intermediate Flows and Dikes

Felsic dikes are common in the Birchdale-Indus area, especially in the felsic-intermediate volcanic units. Felsic flows may be present, but due to limited exposure identification is difficult. Most dikes are less than ten feet wide, although there is one 225 feet wide in Section 13, T. 159 N., R. 26 W. Most appear to be porphyritic dacites or rhyodacites with abundant plagioclase and lesser quartz phenocrysts. The percentage of phenocrysts varies from zero to 50 with ten to 20 percent being common. Plagioclase phenocrysts frequently show normal zoning and are usually highly altered, but have retained their shape. The quartz phenocrysts (up to eight mm. in diameter) are often strained or polygonized and stretched into eyes. The matrix usually consists of fine, equigranular, allotriomorphic feldspar and quartz. Minor alteration products include biotite, muscovite, epidote, carbonate, chlorite, sphene and blue-green amphibole. Amphibole is a minor constituent compared with the content of amphibole in the mafic-intermediate units.

Fletcher and Irvine (1954) mention both dacite and rhyolite flows in the Emo area. The rhyolite occurs in minor flows interbedded with tuff in southwestern Dobie Township. The dacites are light greenish-gray weathering creamy-white to buff. They are massive and vary from aphanitic to porphyritic texturally. The porphyritic units have quartz and oligoglase feldspar phenocrysts up to one-fourth inch making up ten to 40 percent of the rock. Mineralogically, they are a microgranular intergrowth of equal parts of quartz and plagioclase with an average of ten percent of muscovite, biotite, chlorite and hornblende.

Mafic-Intermediate Volcanic and Subvolcanic Rocks

Mafic-intermediate volcanic and subvolcanic rocks apparently form a major lithologic unit in the region. The major exposures in the Birchdale-Indus part of the region occur in three northeast trending belts with minor occurrences in the felsic intermediate units. Numerous mafic-intermediate units have been intersected in drill holes.

This unit includes flows (locally pillowed), tuff and agglomeratic tuff, dikes and possible sills. In most cases recrystallization has been thorough enough to obliterate original textures and mineralogy making it difficult to determine the protolith. Since plagioclase determination is seldom possible because of recrystallization, the presence of greater than 90 percent blue-green amphibole was used by Ojakangas, et. al. (1977) as an indication of a basaltic protolith. Fletcher and Irvine (1954) did note some plagioclase phenocrysts that proved to be bytownite in basic lavas in the Emo area. Samples with only a minor to moderate amount of amphibole are classed as andesites. Most flows, however, are mafic.

Fine-grained dark-green pillows are common in the flows and provided all the stratigraphic top information. They are generally fine-grained and massive, but highly fractured although Fletcher and Irvine (1954) report local schistose material. A felty texture is occasionally well preserved, but trachytic texture is rare. Vesicular and amygdular lavas are minor in both the

Birchdale-Indus and Emo areas and are usually associated with pillows. Fletcher and Irvine (1954) noted infrequent porphyritic lavas containing one-fourth to one inch feldspar phenocrysts aligned in a dark basaltic matrix.

Medium- to coarse-grained gabbroic, dioritic and diabasic subvolcanic rocks are common in the southwestern part of the Birchdale-Indus area and in the northern part of the Emo area. These may be slowly cooled interiors of thick flows or sills.

Interbedded with the mafic-intermediate lavas are thin units of mafic-intermediate tuff and tuffaceous agglomerates. Mafic volcaniclastic units are also frequently found interbedded with felsic volcaniclastics. Foliation and shearing obscure the bedding, but allow delineation from the more massive flow units. Original lamination may be reflected by alternate layers of epidote and amphibole and by differing grain size. As with the mafic flows, shearing and metamorphism make determination of the protolith difficult.

Blue-green amphibole is the most common metamorphic mineral in these mafic volcaniclastics. Some are composed almost entirely of blue-green amphibole and reddish garnets. Epidote and chlorite are locally abundant and disseminated opaques, carbonate and to a lesser extent, quartz veins are common. The mafic volcaniclastics in the Emo area are composed mainly of hornblende, diopsite, plagioclase, and quartz (Fletcher and Irvine, 1954).

Listerud (1974) found that the mafic units in the Birchdale area are composed of plagioclase, amphibole, epidote, calcite, apatite, biotite, chlorite, and opaques with traces of pyrrhotite, pyrite, chalcopyrite, and pentlandite.

Ojakangas, et. al., (1977) found bomb-like structures up to five inches long in a thin bed of volcaniclastic material in a pillow unit. Fletcher and Irvine (1954) found that the agglomerate in the Emo area consists of fragments of porphyritic basalt and fine-grained lava in a matrix of basic tuff. The fragments are subangular, one to six inches long and make up ten to 40 percent of the rock.

Metasedimentary Rocks and Iron-Formation

These rocks are best exposed in the Emo area so the major part of the description is from Fletcher and Irvine's (1954) report. The metasedimentary units included here are: (1) a biotite-hornblende schist that Fletcher and Irvine classify as Coutchiching; (2) hornblende schists and garnetiferous hornblende schists from the lower Keewatin; (3) graywacke, iron-formation and conglomerate from the upper Keewatin.

The biotite-hornblende schist occurs in the south part of the Emo area and is separated from other units to the north by granitic intrusives so its true age relationship to other units is unknown. It does not crop out in the Birchdale-Indus area, but its presence is inferred from regional geology and geophysics south of the Rainy

Lake-Seine River fault. The rock is a mafic-rich sedimentary schist that is thinly bedded and dark gray in color, composed of plagioclase, quartz, hornblende and biotite.

The hornblende schists and garnetiferous hornblende schists occur in two bands in the Emo area, one in the east central part of the area and the other in the extreme north. From their lithologic and structural similarities, they are believed to be the same age and are considered to be the oldest unit of Keewatin rocks. These outcrops consists of fine-grained, well bedded, dark gray clastic sediments with minor amounts of light brownish sandy material. Fresh fractures usually show lustrous black hornblende and frequently show a banded effect owing to fine laminations of feldspathic material. Red garnets are common and lenses of garnet and hornblende have developed along the bedding planes in many places. The composition is 40 percent hornblende, 25 percent quartz, 20 percent plagioclase and 15 percent diopside. This rock is completely recrystallized, the result of regional metamorphism. In the Birchdale-Indus part of the region, Ojakangas, et. al. (1977) reported three small occurrences of similar rocks, two in outcrop and one in drill core. A small outcrop of hornblende-quartz-andesine schist is present in the bank of the Rainy River in Section 3, T. 159 N., R. 25 W., and a similar, but coarser rock was found in a drill hole about one mile to the south. The other outcrop is a fine-grained, biotite-quartz-plagioclase schist in Section 16, T. 159 N., R. 25 W., near a small outcrop of iron-formation.

There are three graywacke units in the Emo part of the region. Two are in parallel, steeply dipping hands separated by a narrow granitic intrusive that extends across the area at about N. 70 E. They are believed to represent opposite limbs of a synclinal fold. The other occurrence extends northeasterly from Emo in an arc-shaped pattern. These units have minor basal conglomerate associated with them and two units contain iron-formation. The bedding varies from thin laminations to beds several feet thick. Many outcrops are massive. The weathered surface is brown to grayish-brown with a sandy appearance. On the fresh surface, the rock appears massive, fine-grained and is gray to greenish-gray in color. The rock appears quite uniform throughout although locally a slight schistosity may be in evidence as is an occasionally spotty appearance from the development of poikilitic biotite. The average composition is quartz 25 percent, oligoclase 45 percent, and biotite 30 percent. Locally, minor amounts of hornblende, garnet and sericite may occur. Chlorite that is partially altered to biotite is present. Accessory minerals are apatite, zircon, magnetite and hematite.

The conglomerate associated with the graywacke occurs in very minor amounts in the graywacke near its contact with the volcanics. It consists of pebbles and cobbles from one to ten inches in size with a graywacke matrix. Clasts make up ten to

35 percent of the rock and consist of quartzite, fine-grained granitic material and dacite.

The iron-formation occurs in several bands in the two southern graywacke units. The longest of the bands extends seven miles in the Emo area and discontinuously for 28 miles in the Birchdale-Indus area. The only outcrop of the iron-formation is in Minnesota, southwest of Emo, but its extent has been well defined on the basis of an aeromagnetic anomaly. Ojakangas, et. al. (1977) found the iron-formation to consist of highly contorted thin laminae of magnetite, chert, and felsic tuff. Alteration products include hematite, biotite and minor amphibole, tourmaline and microcrystalline iron silicates. Fletcher and Irvine (1954) suggest that the magnetite has apparently resulted from the recrystallization of hematite.

Granitic Intrusives

Granitic intrusives are more common in the Emo part of the region than in the Birchdale-Indus area. Most of them fall in the monzonite to quartz diorite range, but include granite, pegmatite, and aplite dikes. Fletcher and Irvine (1954) report that true granites were found only in small dikes. Most of these rocks are composed of quartz, potassium feldspars, sodic plagioclase, hornblende, biotite and locally, augite. Accessory minerals include apatite, magnetite, sphene and zircon. Abundance of these accessory minerals varies from scarce to normal amounts for the rock types.

Textures vary from fine- to medium-grained equigranular to coarse-grained porphyritic. Both Ojakangas, et. al. (1977) and Fletcher and Irvine (1954) noted that the foliation near the borders of these intrusives was parallel or subparallel to that in the country rock and that these intrusives were either pretectonic or syntectonic.

Fletcher and Irvine (1954) mention that dikes of granitic composition occur in all parts of the Emo area, but are not abundant. The Birchdale pluton has associated small diorite and andesite dikes cutting both the pluton and the country rock. Listerud (1974) noted simple granite pegmatite veins cutting the granite and andesite dikes. A tourmaline bearing pegmatite dike found there is the only complex pegmatite found in the Birchdale-Indus area.

Mafic Intrusives

The only mafic intrusives known in the region are found in the Emo area. These occur as a mafic stock in Dobie Township and as a hypersthene gabbro stock in Carpenter and Lash Townships (Figure 2). In addition, there are numerous smaller bodies of hornblende diotite and gabbro cutting the sediments and volcanics and present as small inclusions in granitic intrusives.

The Dobie Township stock is a U-shaped body with the arms extending to the northeast that has differentiated into three main phases: coarse-grained diabasic gabbro, hypersthene gabbro, and norite. The diabasic gabbro forms the central part of the southern section of the intrusive. It is composed of about 70 percent sodic laboradorite, 20 percent augite and ten percent hypersthene and uralite. The hypersthene gabbro occurs in a narrow band around the southeast side, partially enclosing the diabasic gabbro and making up most of the arms. It is medium-grained and composed of about 50 percent laboradorite, 30 percent augite, and 20 percent hypersthene and uralite. The fine- to medium-grained norite occurs in two lobes along the southern contact of the intrusive. Hypersthene is the predominant mineral and makes up 75 percent of the rock, the remainder is calcic laboradorite, enstatite, minor olivine, and massive and disseminated pyrrhotite and pentlandite. Due to its lack of alteration, it is probably younger than the granites.

The Carpenter-Lash intrusive (Figure 2) is a fine- to medium-grained equigranular hypersthene gabbro. It is mostly massive and is composed of about 50 to 60 percent laboradorite with the remainder being augite and hypersthene. Since this intrusive truncates the basic volcanics and contains dikes of monzonite, it is post-Keewatin and older than at least some granites.

The small bodies of hornblende diorites and gabbros are usually fine- to medium grained equigranular. The hornblende diorite is the most common and is composed of hornblende and andesine in about equal proportions, with minor biotite and epidote and accessory apatite and magnetite.

Mafic Dikes

Several diabasic mafic dikes with a uniform bearing of N. 45 W., and fair continuity cut all the previously mentioned lithologies. They vary in width from 100 to 400 feet, but usually average 100 to 200 feet wide. Small mafic dikes varying from a few inches to a few feet are common along the margins of the major dikes. These major dikes form conspicuous, hummocky, topographic highs in the region. One dike in the Rainy Lake area has a K-ar date of 2.1 b.y. (Hanson, 1968) which is a minimum age.

The dikes are composed of laboradorite, clinopyroxene, orthopyroxene, quartz and minor hornblende and biotite. Accessory minerals include magnetite, ilmenite, chalcopyrite and apatite. Fletcher and Irvine (1954) mention magnetic anomalies associated with these dikes as a result of disseminated magnetite. These dikes are quite highly uralitized. Grain size varies from fine along the chilled margins to medium to coarse in the interior.

Metamorphism

All of the Archean rocks of the Birchdale-Indus area were regionally metamorphosed by the Algoman event. In most cases metamorphism reached epidote-amphibolite facies as evidenced by plagioclase-epidote-hornblende assemblages in mafic volcanic rocks and andesine-epidote-biotite assemblages in felsic volcanic rocks. Ojakangas, et. al. (1977) noted assemblages of chlorite-actinolite-epidote indicating that locally, metamorphism may have only reached greenschist facies.

Locally, metamorphism has been influenced by granitic intrusions. Listerud (1974) found that an assemblage characteristic of the albite-epidote hornfels facies had been superimposed on the Archean rocks by the intrusion of the Birchdale pluton.

In the Emo area, Fletcher and Irvine (1954) noted both thermal and regional metamorphism varying from low to high grade. In the hornblende schist and graywacke units they noted medium to high grade regional metamorphism near the contacts with the granitic rocks which decreases to low grade with increasing distance from the contact. They suggested that the regional stress and heat were due to the intrusive granites.

The uralitization of the major mafic dikes has been attributed to burial (Hanson, 1971) or to deuteric alteration (Ojakangas, et. al., 1977).

Structure

The Birchdale-Indus region constitutes a fault block lying between two major right-lateral strikeslip faults, the Quetico to the north and the Rainy Lake-Seine River fault to the south

(Figure 1). The structure within the block consists of a doubly plunging, isoclinally folded anticline and syncline with general northeasterly trends. The limbs of the folds generally dip steeply and the fold axes have variable plunges. Ojakangas, et. al. (1977) cites these doubly plunging folds together with minor fold axes trending north to northwest just east of the Birchdale pluton as evidence that the area has undergone two deformations. The first produced fold axes with general northeasterly trends and these were refolded about axes with north-northwest trends.

The folding in the Emo area, as determined by Fletcher and Irvine (1954), appears to be a continuation of that in the Birchdale-Indus area, although a study of the Emo and Fort Frances (Davies, 1974) area maps suggests that the second deformation may have increased in intensity to the east.

The Quetico and Rainy Lake-Seine River faults are apparently the oldest of at least three different ages of faulting (Ojakangas, et. al., 1977). The northwest-trending fracture system occupied by the Middle-Precambrian mafic dikes is next in age. Northeast-trending lineaments apparently define a third fault system. The Sault Rapids and Manitou Rapids dikes have evidently been slightly displaced along northeast-trending faults that are part of this sytem; lack of outcrop makes this uncertain (Ojakangas, et. al., 1977, p. 37).

Stratigraphic Relationships

The stratigraphic sequence in the Birchdale-Indus area was determined from outcrop within the area and from adjacent areas (Ojakangas, et. al., 1977). Much is conjectural because of faults and poor outcrop. The biotite schist unit south of the Rainy Lake-Seine River fault in the southeast corner of the Birchdale-Indus area (Figure 2) is pre-volcanic and therefore the oldest unit in the area. This is a westward extension of a schist unit south of the Rainy Lake-Seine River fault in the Rainy Lake area which was first mapped by Lawson (1888) who determined it to be older than the volcanic rocks in the region. Mafic-intermediate rocks exposed in the core of the major anticline (Figure 2) are the oldest volcanic rocks in the Birchdale-Indus area. The presence of mafic-intermediate rocks in the northwest part of the Birchdale-Indus map is based on outcrop in adjacent Ontario. These are correlative with the mafic-intermediate rocks in the core of the anticline if the structural interpretation is correct. The felsic-intermediate rocks on the flanks of the anticline and to the northeast under which the rocks in the anticlinal core plunge are next in age. The iron-formation and associated volcaniclastics on the southeast side of the anticline are apparently the same general age. The mafic-intermediate rocks exposed in the syncline southwest of the Birchdale Pluton are a younger accumulation on the volcanic pile. The lense of mafic-intermediate rock near the south end of the Manitou Rapids dike is approximately on strike with a mafic-volcanic unit in the Emo area which Fletcher and Irvine (1954) determined was stratigraphically above the iron-formation and was the youngest volcanic unit in the area.

The above relationships can be extended into the Emo area (Figure 2). The older, mafic-intermediate rocks of the Birchdale-Indus area are presented by rocks in the southwest part of the Emo area. The overlying felsic volcanic rocks of the Birchdale-Indus area are represented by rocks in the south central part of the Emo area and the iron-formation and associated volcaniclastics present in the Birchdale-Indus area are represented in the Emo area as iron-formation-metasedimentary units representing more distal facies of a felsic volcaniclastic accumulation.

The stratigraphic relationships determined take into account that the volcanic units are lensoid in their geometry and grade vertically and laterally into adjacent lithologies with inter-tonguing relationships the rule. Small units of mafic-intermediate rocks frequently occur in felsic-intermediate units and vice versa.

Economic Geology

Several massive and disseminated sulfide bodies occur in the region. Some are exposed at the surface and others have been located by drilling geophysical anomalies. Pyrrhotite and pyrite are the dominant sulfies; base metal values are usually very low (Fletcher and Irvine, 1954). Two of the more promising occurrences are copper-nickel sulfides associated with the norite phase of the Dobie Township intrusive and copper-zinc sulfides in metavolcanic-metasedimentary rocks southeast of the Birchdale pluton (Fletcher and Irvine, 1954), (Listerud, 1974).

The sulfides in the Dobie intrusive occur as local disseminations and minor pockets without evident structural control (Fletcher and Irvine, 1954, p. 23). The principal sulfides are pyrrhotite, pyrite, pentlandite, and chalcopyrite with minor violarite, sphalerite, and magnetite. The major nickel mineral is pentlandite which occurs as exsolution blebs and grains in the predominent pyrrhotite. Chalcopyrite is interstitial between pyrrhotite and pyrite. Fletcher and Irvine (1954) report that a grab sample from a massive sulfide test pit assayed 2.52 percent nickel with a trace of copper. Two grab samples of disseminated sulfides yielded 0.30 percent copper and 0.31 percent nickel and 0.40 percent copper and 0.41 percent nickel, respectively. The area of this intrusive has been subject to detailed exploration, but to date only minor deposits have been found although larger deposits may exist at depth (Fletcher and Irvine, 1954).

Sulfides associated with the Birchdale anomaly were the subject of a detailed investigation by Listerud (1974). This area has been explored by three mining companies who have drilled a total of nine holes in a metavolcanic-metasedimentary sequence. The sulfides occur as massive, semi-massive and disseminated sulfides. The disseminated zones with five to 20 percent sulfides provided the best base metal assay results. As in the other sulfide occurrences in the region, the base metal values are low. The highest assay values reported were for a 2.5 foot section of drill core containing 4.06 percent zinc and 0.25 ounces per ton silver. The sulfide minerals in order of decreasing abundance are pyrrhotite, pyrite, chalcopyrite, sphalerite, pentlandite, marcasite, and cubanite.

The Indus test pit area located in the SW 1/4 of the NE 1/4 of Section 16, T. 159 N., R. 25 W. south of Indus, has outcrops of felsic-intermediate volcanic rocks containing massive, semi-massive, and disseminated sulfides. Minnesota Department of Natural Resources personnel have conducted soil geochemical and geophysical surveys and geologic studies and have drilled three shallow holes. Assay reports indicate very low base metal values. This area will be discussed in detail in this report.

A poorly exposed outcrop of volcanic rocks on the bank of the Rainy River just west of Manitou Rapids contains massive and disseminated sulfides. The highest value reported was 2.5 percent zinc (Listerud, pers. comm., 1977). A number of other sulfide occurrences have been located by mining companies drilling geophysical anomalies further west and southwest of the Birchdale-Indus area. In all cases, the base metal values are low.

The previously mentioned iron-formation has been drilled in both the Birchdale-Indus area and in the Emo area. Holes drilled in the southwest part of the Birchdale-Indus area encountered two 20-foot zones described as magnetic iron-formation and graywacke slate (Ojakangas, et. al., 1977). The highest reported iron content is 23 percent. Fletcher and Irvine (1954, p. 25) state that one drill core sample from Carpenter Township contained 34.8 percent iron and 49.0 percent solubles (mostly silica). On grinding to 100 mesh, 89.1 percent of the iron content was recovered as a magnetic concentrate containing 65.6 percent iron. The best 100-foot section from a drill core in Dobie Township contained 24.44 percent iron and 55.75 percent silica, but the overall grade of the section appears to be considerably lower than 25 percent.

GEOLOGY OF THE INDUS AREA

The bedrock of the Indus area consists of a Lower-Precambrian metavolcanic-metasedimentary (greenstone) sequence; apparently it is quite typical of part of an Archean volcanic pile. Most deposition was evidently subaqueous under still water conditions. After being isoclinally folded and metamorphosed during the Algoman event, the Archean volcanics were intruded by a Middle-Precambrian mafic dike (the Manitou Rapids dike) which has since been uralitized. This dike has proved more resistant to weathering than the country rock and has formed a series of northwest trending topographic highs along the flanks of which are located outcrops of the Archean rocks. All outcrops, except for one minor exposure, were found along these highs.

Stratigraphy

The geology of the Indus area (Plate 1) consists of interbedded volcanic flows; agglomerate and lapilli tuff; tuff and volcaniclastic rocks; iron-formation and associated metasediments; and both mafic and felsic intrusives. The volcanic rocks vary from mafic to rhyolite in composition and the felsic intrusives range from rhyodacitic to rhyolitic.

Determination of the protoliths of the volcanic rocks was difficult since they are very fine-grained and composed almost

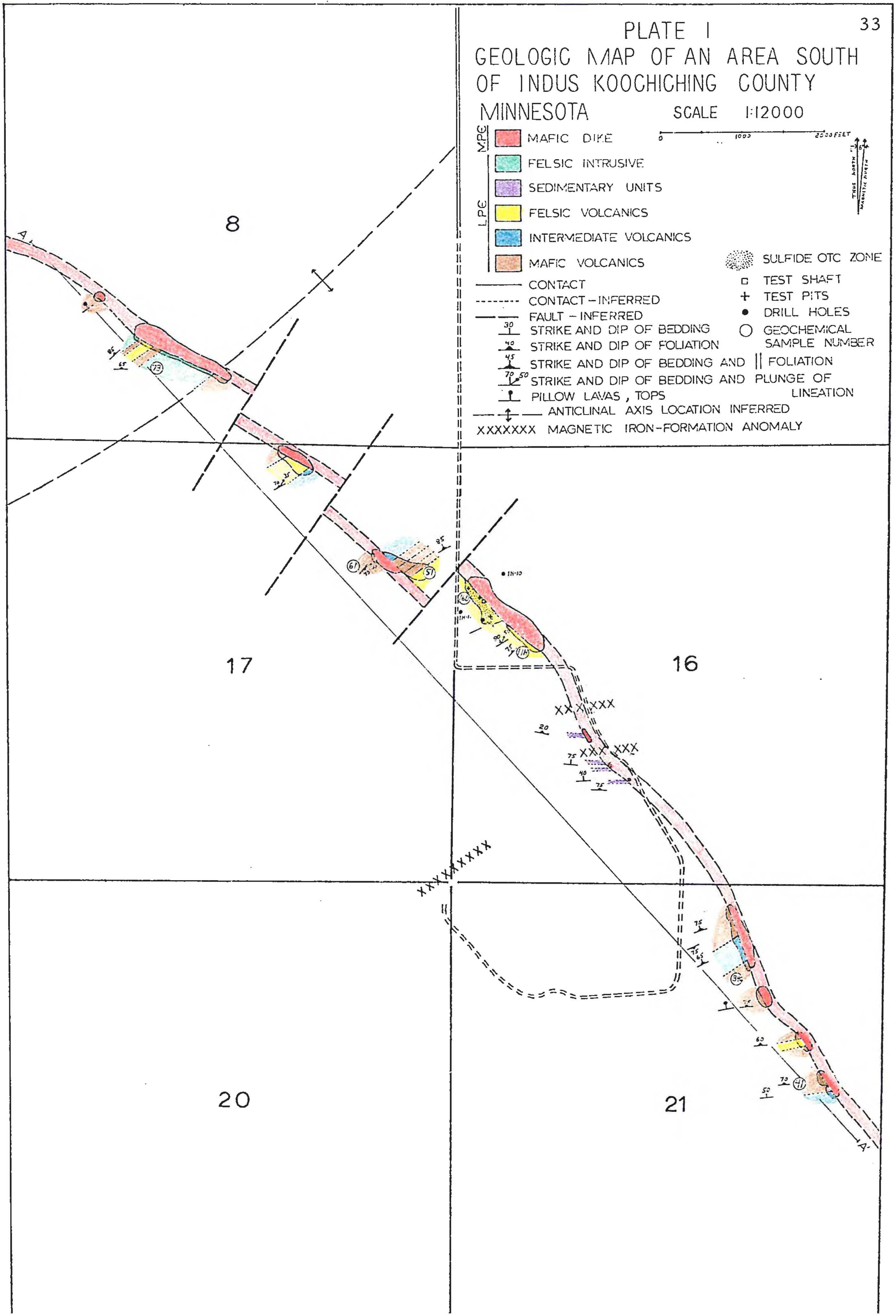


PLATE I
GEOLOGIC MAP OF AN AREA SOUTH OF INDUS KOOCHICHING COUNTY MINNESOTA
SCALE 1:12000
0
1000
2000 FEET
TRUE NORTH
MAGNETIC NORTH
M.P€
L.P€
MAFIC DIKE
FELSIC INTRUSIVE
SEDIMENTARY UNITS
FELSIC VOLCANICS
INTERMEDIATE VOLCANICS
MAFIC VOLCANICS
SULFIDE OTC ZONE
TEST SHAFT
TEST PITS
DRILL HOLES
GEOCHEMICAL SAMPLE NUMBER
CONTACT
CONTACT - INFERRED
FAULT - INFERRED
STRIKE AND DIP OF BEDDING
STRIKE AND DIP OF FOLIATION
STRIKE AND DIP OF BEDDING AND || FOLIATION
STRIKE AND DIP OF BEDDING AND PLUNGE OF LINEATION
PILLOW LAVAS, TOPS
ANTICLINAL AXIS LOCATION INFERRED
XXXXXXX MAGNETIC IRON-FORMATION ANOMALY
8
17
16
20
21
A
A'

entirely of secondary minerals. Therefore, they were classifed as to origin by their present mineralogy in comparison to the mineralogy of a limited number of rocks on which whole rock analyses were performed and on a report by M. R. Stauffer, et. al. (1975) in which present mineral assemblages and chemical analyses were compared. So a rock containing greater than 60 percent mafic minerals is classified as mafic; intermediate when the mafic mineral content is between 30 and 60 percent; and felsic when the mafic mineral content was less than 30 percent.

Following the Canadian system, a rock of basaltic composition in termed mafic, andesites are intermediate, and dacites through rhyolites are felsic. This system is based on the silica content of the rocks as follows (Goodwin, 1968, p. 71):

basalt	- less than 52 percent SiO_2
andesite	- 52 to 58 percent SiO_2
dacite	- 58 to 64 percent SiO_2
rhyodacite	- 64 to 71 percent SiO_2
rhyolite	- greater than 71 percent SiO_2

The fine-grained, recrystallized nature of these rocks also precluded plagioclase determination except in the case of relict phenocrysts with recognizable albite twinning. Then it was found by the Michel-Levy method and by optic sign.

Textures indicative of origin were best observed on the weathered outcrop surface. A pervasive foliation, which is more pronounced in the clastic units, is present in all volcanics.

Foliation and other bedding features which are often evident on a weathered surface are difficult to see on a fresh surface, especially in the more mafic units.

Individual flow and volcaniclastic units are commonly thin; the greatest thickness noted was approximately 100 feet and the average thickness is 50 feet or less. The rock units shown in Plate 1 are based on dominant lithology, but other rock types are frequently interbedded.

The clast size classification system proposed by Fisher (1961) for volcanic rocks was used:

Ash	- less than 2 mm.
Lapilli	- 2 to 64 mm.
Agglomerate	- greater than 64 mm.

Mafic Volcanic and Subvolcanic Rocks

Mafic volcanic and subvolcanic rocks as a related geological unit form a major part of the outcrops present in the Indus area. Flows, frequently pillowed, constitute the greater part of this unit with subvolcanic and clastic mafic rocks being relatively minor. The term subvolcanic is used for those rocks whose grain size suggests that they may be sills or the interiors of thick flows, but for which there is no reliable evidence suggested in field relationships. Mafic rocks are concentrated in the northwest one-third and the southeast one-third of the area. Thicknesses of individual flow units were difficult to determine since they are frequently interbedded with relatively thin units of mafic tuff, and it is difficult to determine contacts since the two units are distinguishable only by a difference in degree of foliation.

Mafic Flows and Subvolcanic Rocks

The weathered surface of the mafic flow units varies from buff-gray to greenish-gray and commonly has a very rusty appearance. On fresh surfaces they are dark greenish-gray to greenish-black. Although the mafic flows may show fine foliation on the weathered surfaces, they appear massive when unweathered. Grain size varies from aphanitic to very fine-grained.

The pillowed units show considerable variation in degree of deformation; most are highly deformed. The few relatively undeformed pillow units provide the only stratigraphic top information in the area (Plate 2). Most pillows were approximately 12 inches by 24 inches, but one highly deformed unit contained pillows that were on the order of six inches by 30 inches (Plate 3). The chilled rinds vary from one to two cm. in thickness. Amygdules are rare in both pillowed and unpillowed flow units which suggests deposition under deep water which would prevent vesiculation of gases.

The mafic flows are composed almost entirely of metamorphic amphibole, plagioclase, chlorite, biotite, garnet, epidote, calcite, sericite-muscovite, apatite, quartz, prehnite, pumpellyite, and opaques. There is little evidence of remaining primary minerals. Blue-green hornblende and actinolite are the dominant mafic minerals,

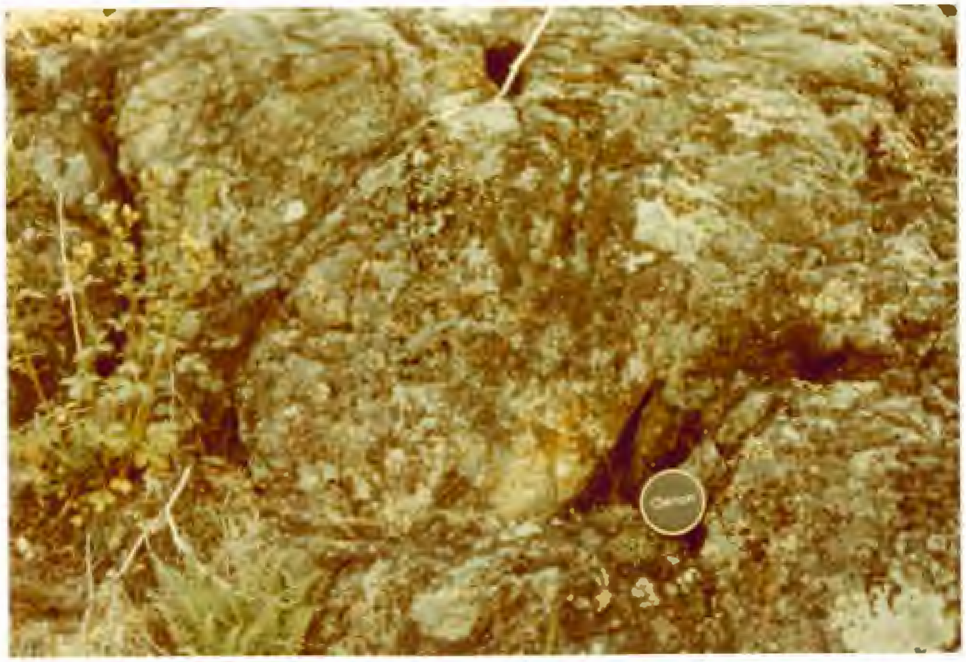


PLATE 2 - RELATIVELY UNDEFORMED MAFIC PILLOWS, NW 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

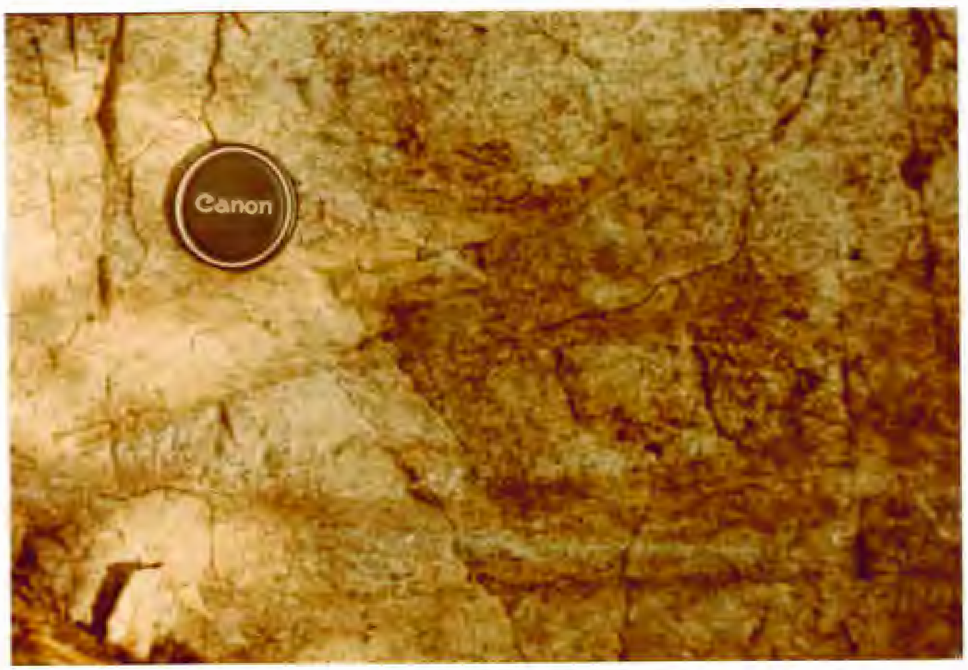


PLATE 3 - HIGHLY DEFORMED MAFIC PILLOWS, NW 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

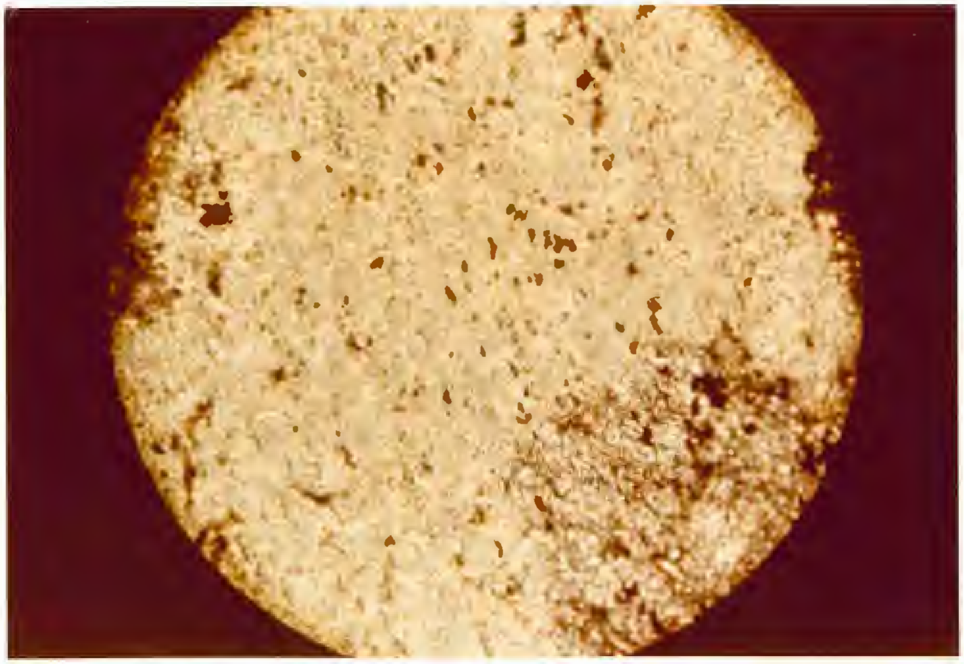


PLATE 4 - PHOTOMICROGRAPH OF TYPICAL MAFIC FLOW. THE LARGE GRAIN IN THE LOWER RIGHT IS GARNET, THE REMAINDER IS MOSTLY BLUE-GREEN HORNBLENDE. FIELD OF VIEW 1.57 mm. UNCROSSED NICOLS. SAMPLE NO. 61 FROM SE 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

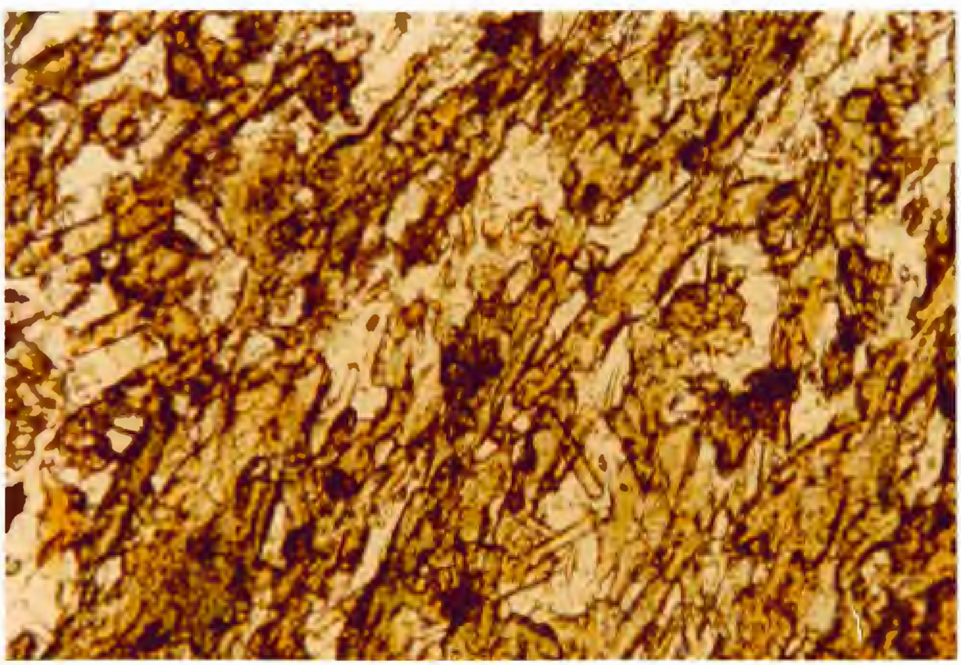


PLATE 5 - PHOTOMICROGRAPH OF TYPICAL MAFIC FLOW. BLUE-GREEN HORNBLENDE AND UNTWINNED GRANOBLASTI PLAGIOCLASE. FIELD OF VIEW 1.57 mm. UNCROSSED NICOLS. SAMPLE NO. 41 FROM SE 1/4-NE 1/4, SECTION 21, T. 159 N., R. 25 W.

making up from 60 to 90 percent of the rock. Normally, actinolite is minor although it is locally common. The hornblende occurs as anhedral to euhedral grains in a felty-textured mat (Plates 4 and 5) which the actinolite occurs either as randomly oriented needles or as anhedral to euhedral grains in the same felty texture as the hornblende.

Fine-grained, recrystallized, untwinned plagioclase occurs in amounts varying from a trace to 30 percent. Outlines of a few possible relict phenocrysts of plagioclase were found, but most occur in a granoblastic texture interstitial to the amphibole. In appearance they vary from quite fresh to heavily sericitized.

Chlorite is usually minor although locally it constitutes 20 percent of the rock, occurring as amorphous masses interstitial to the more abundant amphibole. Biotite, calcite, quartz, and sericite are all minor; none is more abundant than approximately five percent. They commonly occur as disseminated subhedral to anhedral grains and amorphous masses. Apatite occurs in trace amounts while the opaques are present in amounts varying from two to ten percent. Anhedral, very fine-grained magnetite or magnetite-ilmenite with traces of leucoxene alteration are the most common opaques, although locally pyrrhotite or pyrite may be more abundant. Prehnite and pumpellyite occur as vein and fracture fillings, frequently accompanied by calcite and chlorite.

The weathered surfaces of the mafic subvolcanic rocks show the same rusty, buff-gray to light greenish-gray colors as do the mafic flows, but have an irregular surface suggestive of a differential weathering of coarser grained minerals. The fresh surface is a dark greenish-gray to greenish-black and appears to be dominantly medium-grained dark green amphibole. Both weathered and fresh surfaces are massive in appearance.

Fibrous-appearing, medium-grained, blue-green hornblende with minor actinolite is the dominant mineral followed by fine-grained, untwinned plagioclase with minor quartz in a granoblastic texture interstitial to the hornblende. The actinolite is difficult to distinguish from blue-green hornblende and may constitute more than a minor percentage of the amphibole. Apatite, chlorite, sericite and opaques are minor; none constitutes more than five percent of the rock. The sericite occurs as alteration on plagioclase while the apatite, chlorite, and opaques are disseminated throughout. The opaques are fine-grained, anhedral, magnetite-ilmenite partially altered to leucoxene.

Mafic Tuff and Lapilli Tuff

Thin units of what appear to be mafic tuff and lapilli tuff are found interbedded with mafic flow sequences. Their more pronounced foliation (Plate 6) permits their being distinguished from flow units. Frequently, very thin beds of mafic or possibly intermediate tuff

PLATE 6 - MAFIC TUFF, FOLIATION IS SUB-PARALLEL TO HAMMER HANDLE. SAMPLE NO. 43 FROM SE 1/4-NE 1/4, SECTION 21, T. 159 N., R. 25 W.

are found interbedded with very thin beds of more felsic tuff. In this case, bedding is very obvious because of the differences in color.

The outcrop surface of the mafic tuff is a rusty-greenish gray with a distinct, often crenulated foliation pattern, but is a massive, dark, greenish-gray-black on a fresh surface. Grain size varies from aphanitic to very fine-grained. Blue-green, anhedral to euhedral hornblende with minor brown hornblende and actinolite in a felty texture is the dominant mineral. Granoblastic, very fine-grained plagioclase with blebs of recrystallized quartz occurs in zones or bands suggestive of stretched lapilli. Minor chlorite, calcite, epidote, garnet and opaques occur as anhedral disseminations in the amphibole rich zones. The only opaque mineral present is very fine-grained anhedral magnetite.

Intermediate Volcanic Rocks

This group includes flows, agglomerate, lapilli tuff and tuff. The flow units are subordinate to the clastic units in both volume and number. While intermediate volcanic rocks occur in felsic sequences, they are more frequently found interbedded with mafic units. Only one flow unit contained pillows and these were too deformed for stratigraphic top determination.

Intermediate Flows

The intermediate flow units are gray to a rusty, buff, greenish-gray on a weathered surface and medium gray to dark greenish-gray-black on a fresh surface. They are aphanitic to very fine-grained and massive to faintly foliated.

Plagioclase and blue-green hornblende are the dominant minerals, each occurring in amounts varying from 30 to 55 percent. The hornblende occurs as anhedral to euhedral grains in a texture that varies from randomly oriented to lineated (Plate 7). Very fine, recrystallized plagioclase in a granoblastic texture occurs as matrix. Occasional outlines of relict plagioclase pheno-

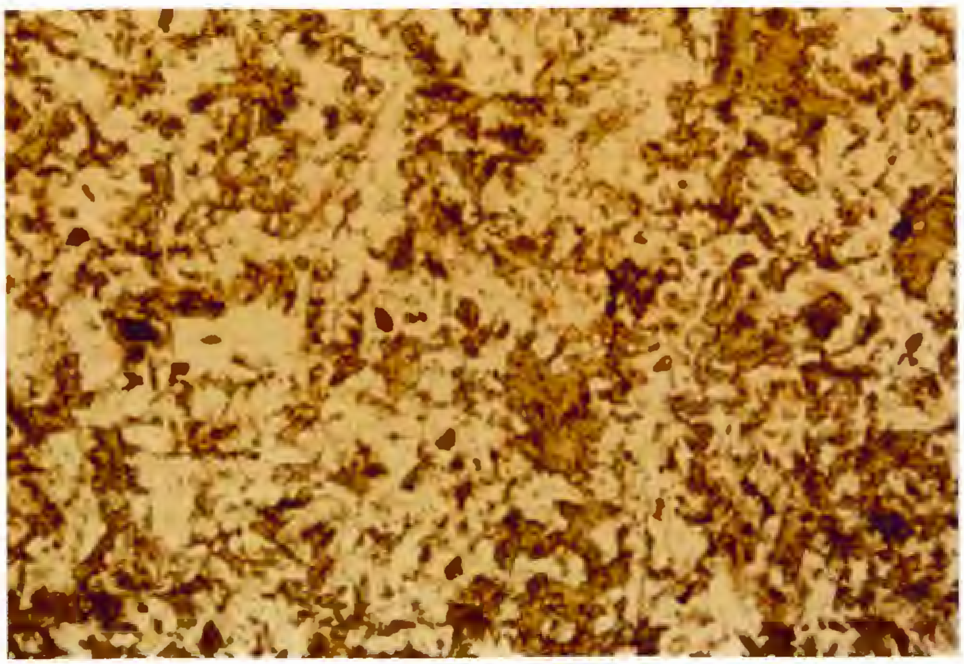


PLATE 7 - PHOTOMICROGRAPH OF TYPICAL INTERMEDIATE FLOW. THE MINERALOGY IS LARGELY BLUE-GREEN HORNBLENDE AND UNTWINNED PLAGIOCLASE, FIELD OF VIEW, 1.57 mm. UNCROSSED NICOLS. SAMPLE NO. 40 FROM SE 1/4-NE 1/4, SECTION 21, T. 159 N., R. 25 W.

crysts were seen, but no plagioclase determination was possible. Biotite, sericite, quartz, and opaques are minor, seldom constituting ten percent of the rock. Sericite occurs as an alteration product on plagioclase while biotite and quartz occur as disseminated grains. Anhedral magnetite is the dominant opaque mineral with lesser anhedral pyrite.

Intermediate Agglomerate, Lapilli Tuff and Tuff

Clastic rock units form the most common type of intermediate volcanic rock units. They occur most frequently as units of lapilli tuff as well as being often found in sequences of very thin (one to three cm.) beds of intermediate (or mafic) composition alternating with very thin more felsic beds and often form the matrix in agglomerate units. These thinly bedded, alternating sequences have a very distinct appearance on a weathered surface (Plate 8). The agglomerate and lapilli in these units also form a distinctive weathering pattern (Plate 10) which is often much less apparent on a fresh surface. These clasts are usually highly stretched and often have a length-to-width ratio on the order of six to eight to one although one unit contained relatively undeformed blocks as large as approximately three by eight inches.

The weathered surfaces of these units varies from medium gray to a rusty greenish-gray. A fresh surface is gray to dark greenish-gray-black. They are aphanitic to very fine-grained and are strongly foliated.

PLATE 8 - SEQUENCE OF VERY THINLY BEDDED ALTERNATING FELSIC AND INTERMEDIATE OR MAFIC TUFFS. SAMPLE NO. 64 FROM NW 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

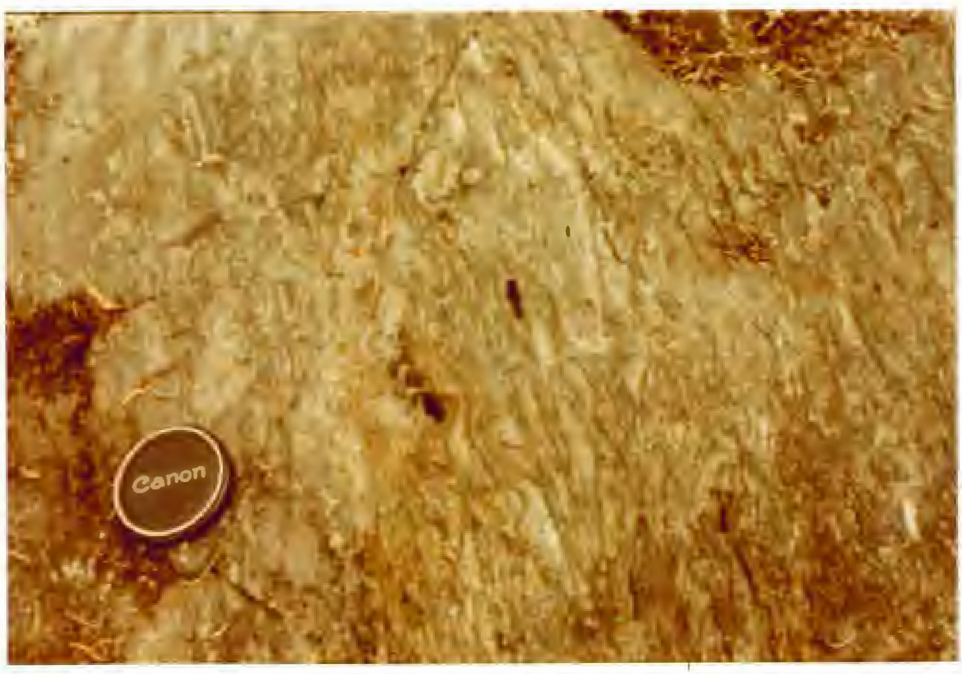


PLATE 9 - MAFIC-INTERMEDIATE AGGLOMERATE WITH HIGHLY STRETCHED CLASTS. FROM A THIN BED OF AGGLOMERATE IN OUTCROP NO. 64 IN THE NW 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

Amphibole and plagioclase are the major minerals in these units. The amphibole is anhedral to euhedral blue-green hornblende in a texture that varies from felty to lineated (Plate 10). Very fine, untwinned, granoblastic plagioclase, frequently with sericite alteration is interstitial to the hornblende and also occurs in compositional bands or stretched lapilli size fragments. Occasional outlines of relict plagioclase phenocrysts were seen, but plagioclase determination was not possible. It was not possible to establish a mode for rock fragments because recrystallization prevented positive identification. Epidote, varying in habit from amorphous masses to euhedral crystals, was usually minor, but locally reached concentrations of 25 percent. Anhedral to subhedral biotite, chlorite, and quartz were present as minor disseminations. Apatite, calcite, garnet, prehnite, pumpellyite, and sphene are present in trace amounts. Prehnite and pumpellyite, frequently with calcite, is present as vein or fracture fillings. The opaques are mostly anhedral magnetite-ilmenite with traces of leucoxene alteration and minor pyrite.

Felsic Volcanic Rocks

Felsic volcanic rocks are a major lithology in the Indus area. They occur most commonly as lapilli tuff, but are present also as agglomeratic tuff, tuff, volcaniclastic rocks and felsic intrusives. Initial petrographic study indicated that these rocks were primarily

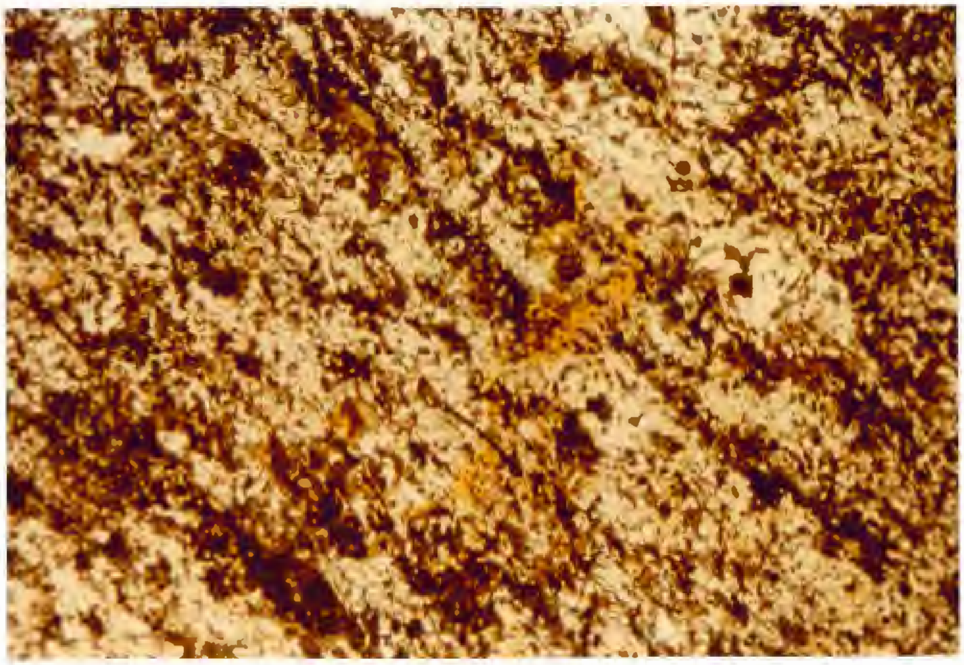


PLATE 10 - PHOTOMICROGRAPH OF INTERMEDIATE LAPILLI TUFF. BLUE-GREEN HORNBLENDE AND UNTWINNED PLAGIOCLASE ARE THE MAJOR MINERALS. FIELD OF VIEW 6.2 mm. UNCROSSED NICOLS. SAMPLE NO. 59 FROM SE 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

dacitic in composition with lesser rhyodacites and rhyolites as staining for potassium recognition indicated little potassium feldspar. Staining indicates that most of the potassium is in the micas. However, whole rock analysis of three felsic tuff samples and one felsic intrusive (Table 1 , p. 61) indicate that by the Canadian classification system (p. 34) based on chemical analysis most of these felsic units are rhyodacitic to rhyolitic in composition.

The rocks frequently contain phenocrysts of quartz and plagioclase as large as three to four mm. Percentages vary from zero to 40, but ten to 20 percent is common. Often the quartz phenocrysts have been sheared or stretched into eyes with highly undulose extinction and show other characteristics indicative of strain when examined microscopically. Embayed and occasional euhedral quartz phenocrysts are fairly common. The plagioclase phenocrysts usually held their shape well despite frequent heavy sericitization and the strong shearing of these rocks. Plagioclase determination, where possible, usually showed the plagioclase phenocrysts to be oligoclase or andesine. Normal zoning is common and occasional oscillatory zoning is present.

Felsic Agglomerate and Lapilli Tuff

Felsic agglomerate and lapilli tuff are widespread in the Indus area. The most extensive outcrop area is in the SW 1/4-NE 1/4 of Section 16, T. 159 N., R. 25 W., but they occur interbedded with other lithologies throughout the area. These rocks are generally well foliated with the foliation wrapping around the clasts and phenocrysts (Plates 11, 12 and 13). Clasts are usually highly stretched with a length-to-width ratio on the order of six to one. The largest clasts noted are six to eight inches long, most are lapilli size. On a weathered surface the light gray to greenish-gray clasts stand out well in contrast to a rusty, greenish-gray matrix while on a fresh surface both clasts and matrix are medium gray to greenish-gray. In many samples phenocrysts of feldspar and quartz of two to three mm. are common in a fine-grained to aphanitic matrix.

Plagioclase is the dominant mineral in these rocks, averaging between 50 to 70 percent, present as both phenocrysts and a very

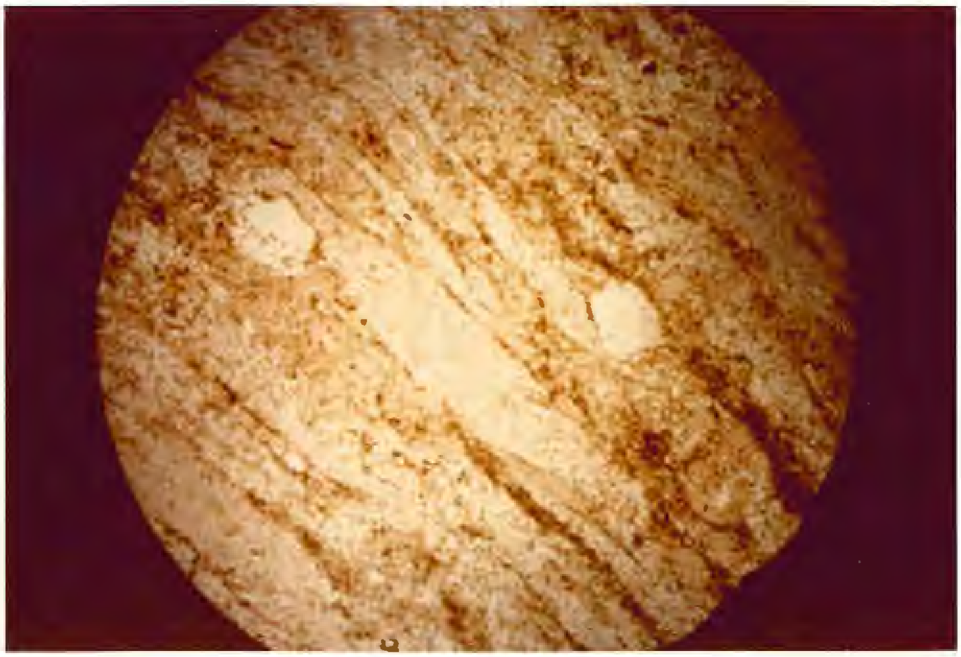


PLATE 11 - PHOTOMICROGRAPH OF FELSIC LAPILLI CRYSTAL TUFF. STAINING INDICATES THAT THESE ROCKS HAVE LITTLE K-FELDSPAR AND THAT MOST OF THE POTASSIUM IS IN MICAS. FIELD OF VIEW 6.2 mm. UNCROSSED NICOLS. SAMPLE NO. 11H FROM SW 1/4-NE 1/4, SECTION 16, T. 159 N., R. 25 W.

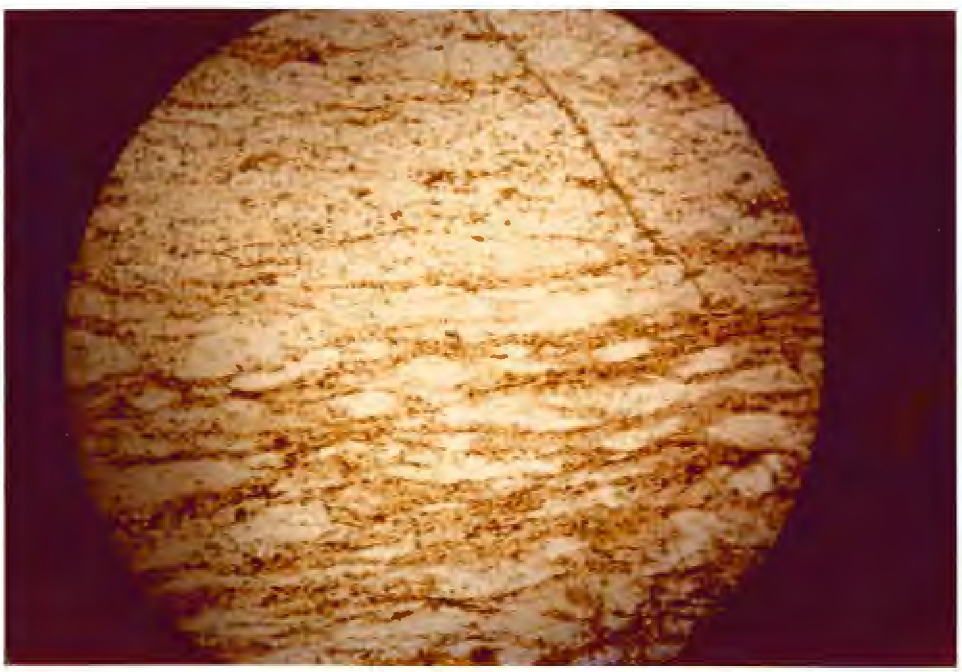


PLATE 12 - PHOTOMICROGRAPH OF FELSIC LAPILLI TUFF. MICACEOUS MINERALS ARE CONCENTRATED IN THE FOLIATION PLANES. FIELD OF VIEW 6.2 mm. UNCROSSED NICOLS. SAMPLE NO. 51 FROM SE 1/4-NE 1/4, SECTION 17, T. 159 N., R. 25 W.

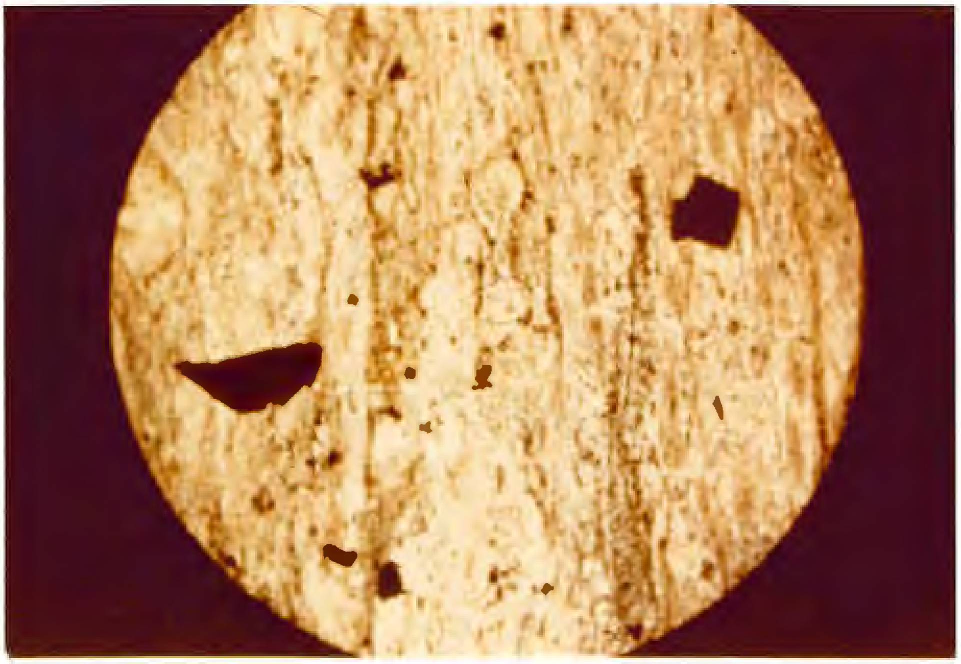


PLATE 13 - PHOTOMICROGRAPH OF FELSIC LAPILLI TUFF WITH PYRITE CROSSCUTTING FOLIATION. FIELD OF VIEW 6.2 mm. UNCROSSED NICOLS. SAMPLE NO. 16D FROM SW 1/4-NE 1/4, SECTION 16, T. 159 N., R. 25 W.

fine granoblastic matrix. Normally, these phenocrysts are anhedral and heavily altered. Except for one unit with significant amounts, potassium feldspar is minor, occurring mostly as an alteration along fractures and trace dissemination throughout the rock. The rock fragments noted were usually felsic in composition. Quartz is present, usually in amounts of ten to 15 percent, locally 20 percent, as phenocrysts and in the matrix with plagioclase. Blue-green hornblende, biotite, chlorite, and epidote are all minor and occur most frequently as subhedral to anhedral grains concentrated in foliation planes. Sericite is common, both in foliation planes and as an alteration of plagioclase. Accessory minerals include apatite, garnet, sphene, tourmaline, and opaques. The opaques include disseminated pyrite, magnetite, and ilmenite with traces of leucoxene alteration. Prehnite was noted in one sample as a fracture or vein filling.

Felsic Tuff and Volcaniclastic Rocks

Units of sand-sized felsic crystal tuff, tuff and volcaniclastic rocks are interbedded with the previously described felsic agglomerates and lapilli tuff. Due to the extensive recrystallization, there is little direct evidence to indicate whether these rocks are true pyroclastics or are epiclastic in origin. Therefore, these rocks are called tuff or reworked tuff (Ojakangas, et. al., 1977) since bedding features characteristic of reworking and transportation are lacking and since the mafic rock fragments one would expect to find if the clasts were the result of erosion of a lithified terrane are almost entirely lacking. Bedding varies from very thinly bedded to quite massive and all have a well developed foliation. The weathered surface of these rocks is usually buff-gray to reddish-gray and a fresh surface varies from reddish-gray to greenish-gray. Most are aphanitic to very fine-grained with phenocrysts of feldspar and quartz to two mm.

As with the felsic agglomerates and lapilli tuff, plagioclase is the dominant mineral, being present in amounts varying from 30 to 80 percent. Plagioclase phenocrysts make up from zero to 20 percent of the rock; the rest occurs as very fine-grained, untwinned plagioclase in a granoblastic texture with quartz. Frequently, the plagioclase is heavily sericitized; locally the sericite content reaches 25 percent. Normally, quartz constitutes about 15 percent (locally to 30 percent) of the rock, occurring as phenocrysts and as very fine grains distributed with the fine-grained plagioclase. Potassium feldspar is minor although in a few samples it reaches 40 to 45 percent. The mafic minerals are represented by biotite, chlorite, and epidote, usually concentrated in the foliation planes, but also disseminated throughout. Each is present in amounts ranging from a trace to seven to eight percent. It was difficult to estimate the percentage of rock fragments since most appeared to be the same composition as the matrix and because of their extensive recrystallization. In thin section, some appeared to contain up to 50 percent ash size fragments. Apatite, tourmaline, and opaques are present as accessory minerals. The opaques include anhedral pyrite and magnetite-ilmenite with traces of leucoxene alteration.

Felsic Intrusives

Felsic intrusives into the Archean volcanics are common. Usually they are small dikes or plugs a few inches to a few feet in width, but one hypabbyssal intrusive in the SE 1/4-SW 1/4 of Section 8, T. 159 N., R. 25 W., extends for approximately 700 feet along the Manitou Rapids dike. They are pinkish-gray to medium greenish-gray on a fresh surface and pinkish-gray to light gray or greenish-gray on a weathered surface. Grain size is aphanitic to fine-grained with phenocrysts of feldspar and quartz.

In composition they vary from rhyolite porphyry to dacite porphyry with abundant, often sheared, plagioclase, lesser quartz, and locally potassium feldspar phenocrysts to three mm. in an aphanitic to fine-grained matrix (Plate 14). The percentage of phenocrysts varies from zero to 40 with ten to 20 percent being common. The matrix consists of fine-grained quartz and feldspar in a granoblastic texture with amphibole, biotite, chlorite, and epidote as the mafic minerals. The amphibole is blue-green hornblende and is minor as a mafic mineral. Except for one heavily altered dacite dike in which the epidote content was 25 percent, none of the mafic minerals exceeded 15 percent. Apatite, calcite, garnet, sphene, tourmaline, and zircon were found in trace amounts. Anhedral magnetite-ilmenite with traces of leucoxene alteration and anhedral to euhedral pyrite were present in amounts up to one to two percent as opaque minerals.

Metasedimentary Rocks

Metasedimentary rocks are a minor lithology in the area occurring as a series of minor outcrops in the SW 1/4 of Section 16, T. 159 N., R. 25 W. Although there may be minor beds of metasediments interbedded in felsic volcaniclastic units, none

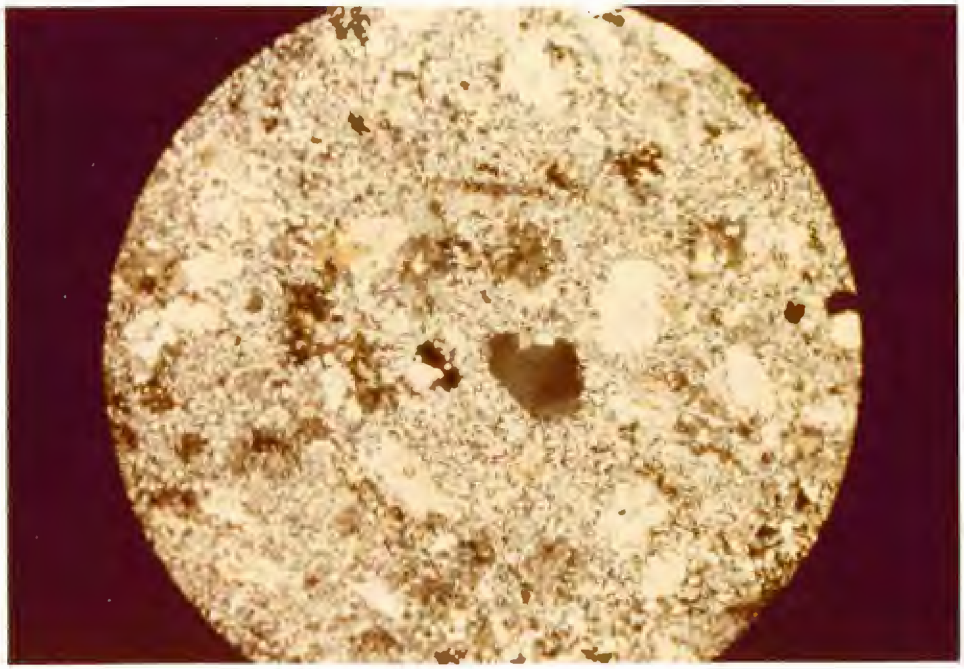


PLATE 14 - PHOTOMICROGRAPH OF FELSIC INTRUSIVE. FIELD OF VIEW 6.2 mm. SAMPLE NO. 73 FROM SE 1/4-SW 1/4, SECTION 8, T. 159 N., R. 25 W.

were noted. Included in this group are tuffaceous metasediments, tuffaceous iron-formation, and a biotite-hornblende-quartz-plagioclase schist.

Tuffaceous Metasediments

The tuffaceous metasediments are usually buff-gray to grayish-white on a weathered surface and medium to dark gray or locally reddish on a fresh surface. They are aphanitic to very fine-grained. Most show a lineation or foliation of micaceous minerals which is often crenulated, although some appear massive in outcrop. Compositional banding was observed in one small outcrop.

Plagioclase and quartz are the most abundant minerals with up to 70 percent plagioclase and 40 percent quartz. These have a recrystallized granoblastic appearance and often occur in thin laminae which may be highly stretched lapilli. Potassium feldspar is minor; five percent was the greatest amount observed. The biotite (occasionally leached), chlorite, epidote, and muscovite-sericite contents are highly variable; each has a range of from one to 30 percent. The micas occur as subhedral grains and frequently define a lineation or foliation while the chlorite and epidote occur as amorphous masses interstitial to other minerals. Epidote shows a great range in crystallinity varying from brown amorphous masses to granules. Only trace amounts of hornblende and felsic-intermediate volcanic rock fragments were noted. Anhedral to subhedral magnetite and pyrite in amounts up to ten percent are frequently aligned in foliation planes. Trace amounts of apatite, garnet, sphene, tourmaline, and zircon were noted as accessory minerals.

Iron-Formation

A poorly exposed outcrop of iron-formation is found in the SE 1/4-SW 1/4 of Section 16, T. 159 N., R. 25 W (Plate 15). It consists of alternating, highly crenulated layers of magnetite and hematite, chert, and felsic tuff varying in thickness from one mm. to three mm. Quartz and untwinned plagioclase make up about 35 percent each of the iron-formation occurring in a granoblastic texture in layers which alternate with magnetite-rich layers. The magnetite and hematite content is about 15 percent and is concentrated

PLATE 15 - OUTCROP OF IRON-FORMATION LOCATED IN NE 1/4-SW 1/4, SECTION 16, T. 159 N., R. 25 W.

in bands with some very fine magnetite disseminated in the felsic layers. Secondary alteration minerals are emphibole (to ten percent), biotite and chlorite (five percent each), stilpnomelane (two to three percent), and traces of pyrite and garnet. These are usually closely associated with the magnetite layers or in discrete bands.

Biotite-Hornblende-Quartz-Plagioclase Schist

The biotite-hornblende-quartz-plagioclase schists are a rusty, gray-brown color on weathered surfaces and greenish-gray-black on fresh surfaces. They are very fine-grained with a well developed foliation. The weathering pattern suggests compositional layering with a differential weathering of minerals. In one sample, this foliation is contorted and contains blebs or veins of quartz.

Quartz, biotite, and hornblende are the major minerals with minor plagioclase, calcite, chlorite, epidote, garnet, apatite, and zircon. Very fine quartz constitutes about 45 percent of the rock and is disseminated throughout as well as in layers in a granoblastic texture with minor, frequently sericitized plagioclase. No potassium feldspar was observed. Biotite and hornblende compose about 30 percent of the rock and are disseminated through or in bands which alternate with the felsic layers. The biotite occurs as highly lineated subhedral grains. Amphibole occurs as subhedral blue-green hornblende that shows a general lineation. Calcite, chlorite, epidote, and garnet are minor constituents with trace amounts of apatite and zircon. Epidote, chlorite, and garnet are concentrated in bands of mafic minerals. Pyrite composes about ten percent of the rock as disseminated anhedral to euhedral grains.

Mafic Dikes

The Manitou Rapids dike (Plate 1) is a major mafic dike in the Indus area and cuts all other lithologies. Its average width is probably on the order of 150 to 200 feet, but this is difficult to ascertain since ordinarily only one margin is exposed. The maximum exposed width is about 250 feet. Minor mafic dikes a few inches to a few feet in width are common along the flanks of this dike. Most are subparallel to the main dike, but in the SE 1/4-NE 1/4 of Section 17, T. 159 N., R. 25 W. these minor mafic dikes are both subparallel and normal to the main dike. All dikes show chilled margins and are usually quite altered, although locally they may be quite fresh. Grain size varies from aphanitic in the small dikes and at the margins of the Manitou Rapids to coarse-grained in its interior. These dikes are a rusty-gray on a weathered surface and a medium, greenish-gray-black on a fresh surface.

The Manitou Rapids dike is composed of plagioclase (laboradorite) and pyroxene in a diabasic texture (Plate 16). The pyroxene includes clinopyroxene and orthopyroxene that are frequently heavily altered to blue-green hornblende, chlorite, epidote, biotite, and actinolite. Other minerals include sericite alteration on the plagioclase, traces of apatite, quartz, sphene, and opaques to seven to eight percent. The opaques include anhedral to subhedral pyrite and anhedral magnetite-ilmenite which shows traces of leucoxene in the more altered samples.

The small dikes contain phenocrysts of plagioclase and clinopyroxene to two mm. in a microcrystalline to cryptocrystalline matrix that includes amphibole, plagioclase, epidote, and magnetite. The plagioclase phenocrysts are laboradorite in the only sample in which plagioclase determination was possible.

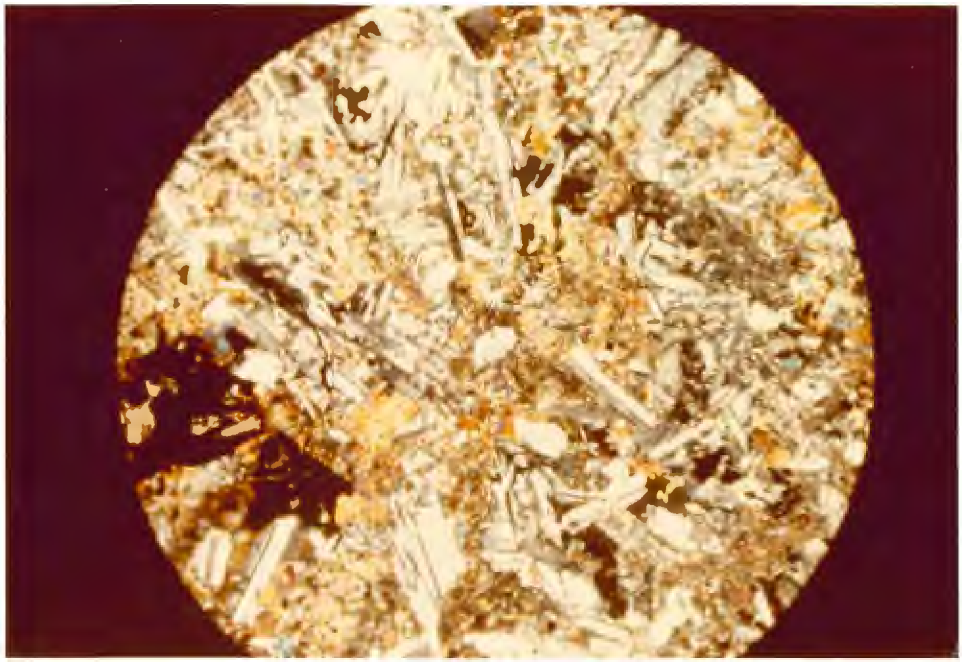


PLATE 16 - PHOTOMICROGRAPH OF THE MANITOU RAPIDS DIKE. PLAGIOCLASE AND URALITIZED PYROXENE IN A DIABASIC TEXTURE. SAMPLE NO. 34C FROM NW 1/4-NE 1/4, SECTION 21, T. 159 N., R. 25 W.

Geochemistry of the Indus Area Rocks

Seven rock samples were sent to the University of Manitoba at Winnipeg, Manitoba for whole rock analysis to permit a comparison with similar rocks in the Superior province of the Canadian shield and in the Vermilion district of the Superior province. The Vermilion district is located in northeastern Minnesota about 200 miles southeast of the Indus area. The Vermilion district rocks are also Archean. Three samples of felsic lapilli tuff (11H, 16D, and 51) were selected to see if there is a significant change in the rock chemistry across the zone of sulfide mineralization. Two samples of mafic flows (41 and 61) were chosen from different levels of mafic volcanism in the volcanic pile. Sample 73 is from a felsic intrusive and sample number 34C, a diabasic gabbro, is from the Manitou Rapids dike. The rock samples were selected after petrographic study to secure samples with the least evidence of metasomatism to best show the original composition of the rock. Locations for the Indus samples are shown on Figure 4, p. 33, analysis are given in Table 1, and petrographic reports for the Indus samples analyses are in Appendix A. The average chemical compositions of Archean volcanic rocks in the Superior province of the Canadian shield are shown in Table 2, and other analyses from the Vermilion district are shown on Table 3.

Sample analyses were run through a computer program designed to calculate the normative minerals, A-F-M ratios, Ab-An-Or ratios, the normative plagioclase composition, Niggli values, and the normative color index for use in Irvine and Baragar's (1971) classification scheme for volcanic rocks. Additional information for each sample includes a classification based on the lime-alkali index, magmatic types, rock name, and comparative potassium content.

The computer program results show that all rocks are subalkaline. In an alkali vs. silica plot (Figure 4) using Irvine and Baragar's (1971) line dividing the alkaline field from the subalkaline fields, all samples plot within the subalkaline field.

	11H	16D	51	73	41	61	34C
SiO_2	66.05	65.25	65.40	71.05	51.15	47.90	48.65
Al_2O_3	17.41	17.94	15.82	15.11	13.96	13.81	13.58
Fe_2O_3	1.22	2.57	1.26	0.72	2.94	2.86	3.83
FeO	1.80	1.76	3.19	0.84	7.00	13.41	11.34
MgO	1.39	0.90	0.59	0.68	7.95	5.15	6.15
CaO	1.31	1.11	1.97	1.86	9.82	9.18	10.41
Na_2O	5.22	5.57	7.43	5.80	3.55	2.31	2.05
K_2O	3.26	2.14	0.28	2.05	0.42	0.98	0.28
H_2O +) H_2O -)	1.39	1.21	1.20	0.80	1.48	2.15	1.13
CO_2	0.17	0.69	0.62	0.64	0.14	0.35	0.13
TiO_2	0.48	0.44	1.64	0.21	0.74	0.92	1.68
P_2O_5	0.11	0.13	0.18	0.07	0.42	0.11	0.13
MnO	0.04	0.04	0.17	0.02	0.19	0.41	0.24
Total	99.85	99.75	99.75	99.85	99.76	99.54	99.60

TABLE 1 - CHEMICAL ANALYSES OF INDUS AREA ROCKS. K. RAMLAL, ANALYST.

TABLE 1. Continued

Sample No., name after Irvine and Baragar (1971), descriptive name, location.

11H -- Sodic rhyolite, Felsic lapilli tuff, SW 1/4-NW 1/4, S. 16, T. 159 N., R. 25 W.

16D -- Sodic rhyolite, Felsic lapilli crystal tuff (same location)

51 -- Sodic rhyolite, Felsic lapilli tuff, SE 1/4-NE 1/4, S. 17, T. 159 N., R. 25 W.

73 -- Sodic rhyolite, porphyritic Felsic intrusive, SE 1/4-SW 1/4, S. 8, T. 159 N., R. 25 W.

41 -- Basalt, mafic flow, SE 1/4-NE 1/4, S. 21, T. 159 N., R. 25 W.

61 -- Basalt, mafic flow, SE 1/4-NE 1/4, S. 17, T. 159 N., R. 25 W.

34C -- Basalt, diabasic gabbro dike (Manitou Rapids dike)

	Basalt	Andesite	Dacite	Rhyodacite	Rhyolite
SiO_2	48.90	54.70	61.50	67.30	74.30
Al_2O_3	14.30	15.00	15.70	14.80	12.90
Fe_2O_3	2.14	2.00	1.83	1.17	0.74
FeO	9.03	7.64	4.49	3.44	2.22
MgO	6.27	4.50	2.38	1.55	0.85
CaO	8.74	6.39	4.41	3.13	1.48
Na_2O	2.51	2.79	3.15	3.07	2.47
K_2O	0.45	0.55	1.16	1.40	2.10
H_2O	3.34	2.92	2.27	1.56	1.17
CO_2	1.93	1.93	2.18	0.98	0.86
TiO_2	1.06	0.99	0.63	0.51	0.26
MnO	0.21	0.28	0.16	0.08	0.10
P_2O_5	0.07	0.12	0.12	0.07	0.07

TABLE 2 - AVERAGE CHEMICAL COMPOSITIONS OF ARCHEAN VOLCANIC ROCKS IN THE SUPERIOR PROVINCE OF THE CANADIAN SHIELD (AFTER GOODWIN, 1968)

M-7251	M-7251 1	EG-17 2	M-7441 3	M-7112 4	M-7509 5
SiO_2	51.06	50.90	63.61	66.75	69.55
TiO_2	1.44	1.33	0.61	0.28	0.37
Al_2O_3	13.85	16.05	13.91	15.56	17.05
Fe_2O_3	1.79	2.33	1.64	1.42	0.62
FeO	10.86	8.66	3.90	1.20	0.44
MnO	0.22	0.18	0.09	0.03	0.01
MgO	5.31	6.15	4.00	0.92	0.68
CaO	10.66	9.30	4.27	3.18	1.77
Na_2O	2.49	2.06	5.23	5.60	5.84
K_2O	.25	0.76	0.43	1.73	1.72
H_2O +	1.83	1.74	2.27	1.42	1.81
H_2O -	0.06	n.d.	0.11	n.d.	0.18
CO_2	0.33	0.00	0.53	1.62	0.58
P_2O_5	0.13	0.20	0.14	0.07	0.09
	100.28	99.66	100.77	99.78	100.72

TABLE 3 - CHEMICAL COMPOSITION OF ARCHEAN VOLCANIC ROCKS FROM THE VERMILION DISTRICT (AFTER GREEN, 1970)

Sample No., normative name, descriptive name

1 -- Basalt, pillowed greenstone, p. 16, sample N-7251.
2 -- Basalt, subdiabasic basalt, p. 16, sample EG-17.
3 -- Intermediate dacite, pillowed metavolcanic, p. 23, sample M-7441.
4 -- Rhyodacite, sheared porphyry, p. 23, sample M-7112
5 -- Rhyodacite, Trachytic felsite, p. 23, sample M-7509.

The calc-alkaline vs. tholeiitic classification is not as clear cut. The computer results showed all samples to be calc-alkaline in origin except sample 51, a felsic tuff, and number 61, a mafic flow, which are of tholeiitic origin. Using different parameters, the calc-alkaline vs. tholeiitic fields are shown in Figures 5 thru 7. All samples do not group consistently in the same class, but it appears that samples 51 and 61 are tholeiitic and that 11H, 16D, 41, and 73 are calc-alkaline. If the stratigraphic relations shown in Plate 1 and Figure 13 are correct, the stratigraphic positions of these samples, from bottom to top, are: 61, 51, 16D, 11H, and 41. Sample number 73 is from an intrusive into the lower part of the volcanic pile. The number of samples is insufficient to give adequate information, but it suggests that the two lower units are tholeiitic and the overlying units are calc-alkaline. Further, it suggests that the felsic intrusive may be related to the overlying felsic volcanics. More analyses are needed to confirm that there was a change in the character of the magma source for these rocks.

There is not complete agreement as to the geochemical nature of the rocks of the Superior province. Wilson and others (1965) after a study of rocks from ten areas of the Superior province suggested that, in general, they show considerable similarity to an orogenic calc-alkaline trend. Baragar (1968) suggests that they may be of tholeiitic descent. A plot of Niggli Alk vs. Si values (Figure 8) for the Indus rocks using the line of Wilson and others

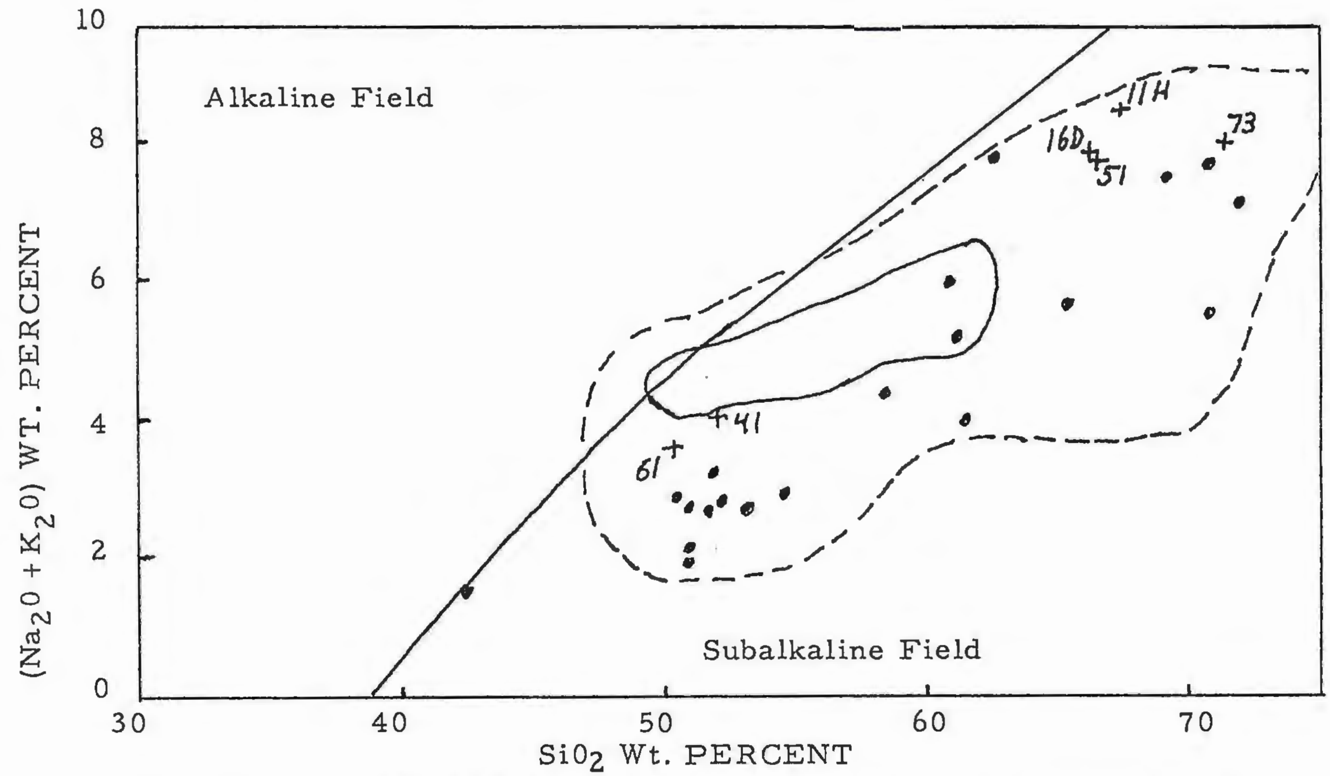


FIGURE 4 . ALKALI-SILICA PLOT, IN WEIGHT PERCENT; THE DIVIDING LINE IS AFTER IRVINE AND BARAGAR (1971).

\+ INDUS AREA ROCKS

. Vermilion DISTRICT (AFTER GREEN, 1970)

\- - - - - ALEUTIANS (AFTER IRVINE AND BARAGAR, 1971)

_____ PARICUTIN REGION (AFTER IRVINE AND BARAGAR, 1971)

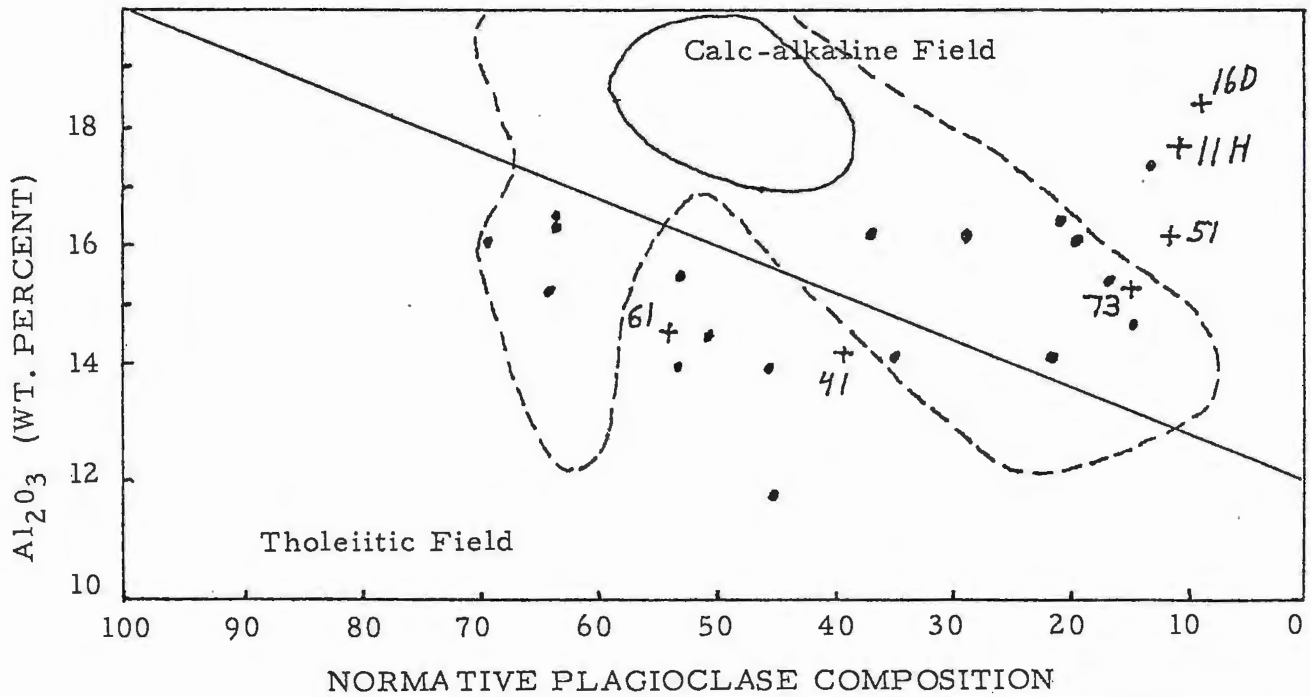


FIGURE 5 . PLOTS OF WT. % AL_2O_3 VERSUS NORMATIVE PLAGIOCLASE. LINE DIVIDES PREDOMINANTLY THOLEIITIC SUITES FROM CALC-ALKALINE. AFTER IRVINE AND BARAGAR (1971).

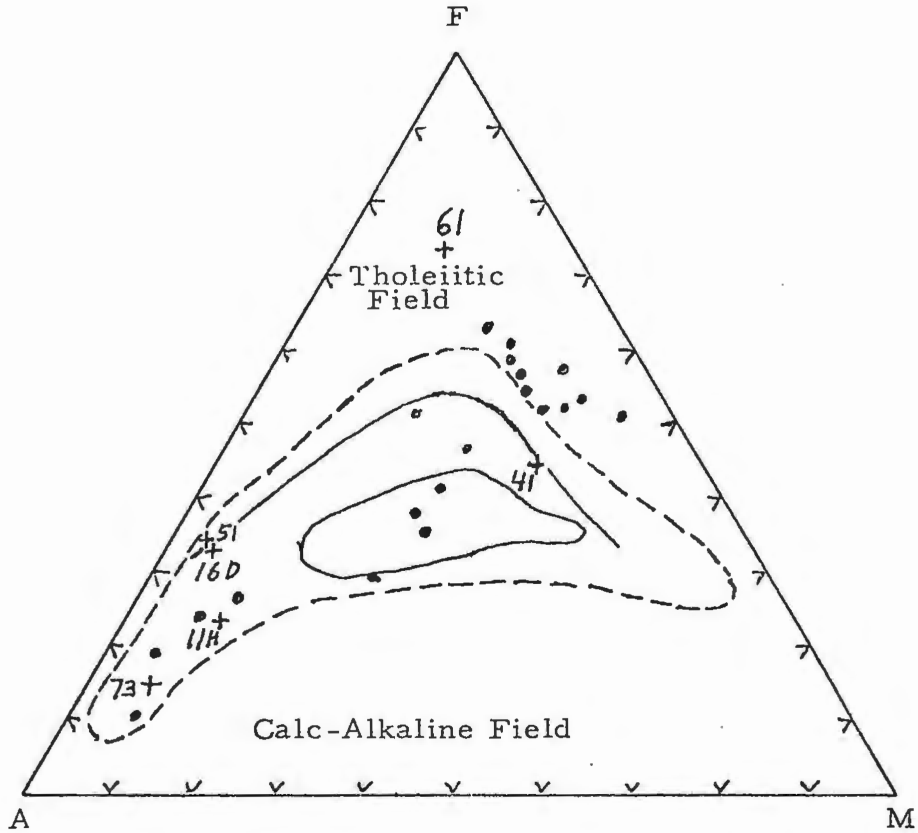


FIGURE 6 . AFM PLOT, LINE SEPARATES THOLEIITIC FIELD FROM CALC-ALKALINE

+ INDUS AREA ROCKS

. VERMILION DISTRICT (AFTER GREEN, 1970)

---- ALEUTIANS (AFTER IRVINE AND BARAGAR, 1971)

____ PARICUTIN REGION (AFTER IRVINE AND BARAGAR, 1971)

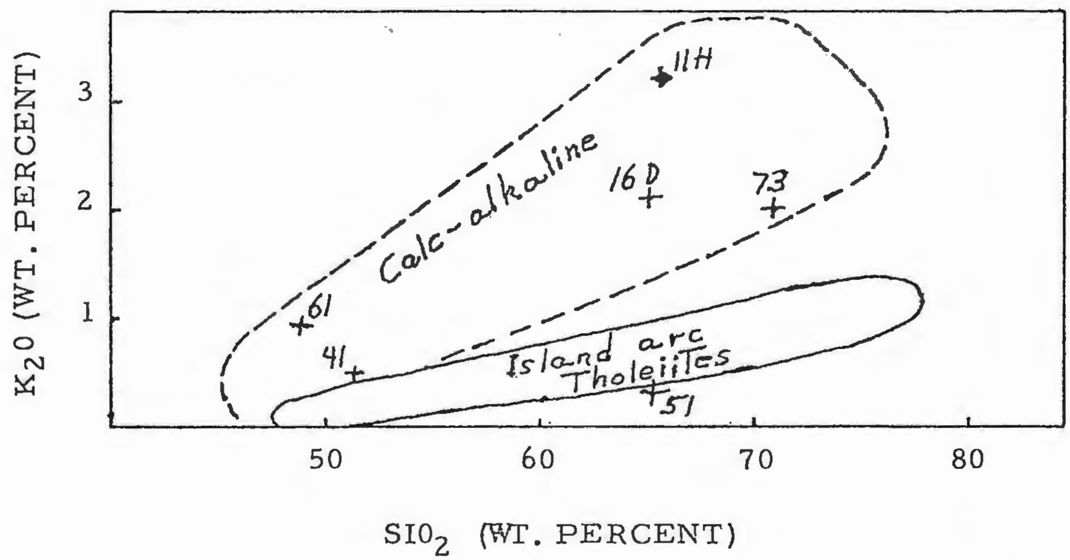


FIGURE 7 . K_2O - SIO_2 DIAGRAM - CALC-ALKALINE AND ISLAND ARC THOLEIITE FIELDS FROM JAKES AND GILL (1970).

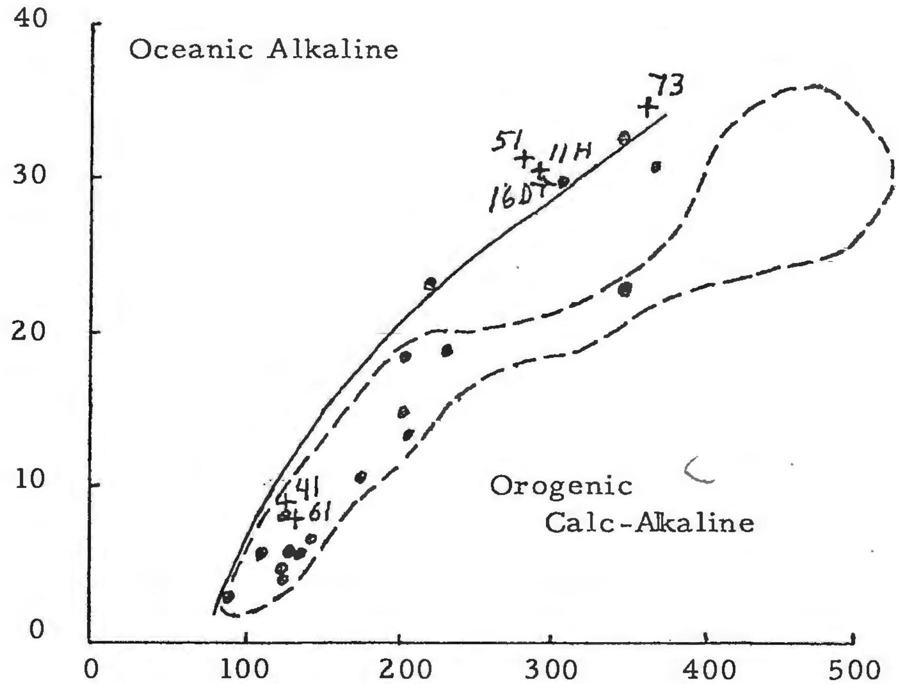


FIGURE 8. PLOT OF NIGGLI ALK VERSUS SI VALUES. SOLID LINE DIVIDING OCEANIC ALKALINE FROM OROGENIC ALKALINE AFTER WILSON AND OTHERS (1965).

\+ INDUS AREA ROCKS

. VERMILION DISTRICT (AFTER GREEN, 1970)

---- PLOT OF TYPICAL ISLAND ARC CALC-ALKALINE SUITES (AFTER WILSON, ET. AL., 1965).

(1965) separating the oceanic alkaline from orogenic calc-alkaline shows Indus rocks on both sides of the line while analyses from the Vermilion district, Green (1970) plot, for the most part, on the orogenic calc-alkaline side. Hutchinson (1973, p. 1225) suggests that "these volcanic rocks may have affinities to both tholeiitic and calc-alkaline families with chemical properties intermediate between the two".

Figures 9 and 10 are two different schemes using different parameters for naming volcanic rocks. In Figure 9, normative color index is plotted versus normative plagioclase composition while Figure 10 is based on the Ab-An-Or ratio.

A limited sampling of the Indus rocks shows many of the distinctive chemical properties characteristic of Archean volcanic rocks (Goodwin, 1968, p. 75) such as: (a) high $FeO:Fe_2O_3$ ratios, (b) low alkalic content, especially K_2O, and (c) low TiO_2 content. Indus rocks are also similar to rocks of the Vermilion district (Green, 1970), with the most notable differences being a somewhat lower volatile content and a greater range of Al_2O_3 content. This may be due to the limited number of Indus samples. The low K_2O content is shown in Figure 10 where most rocks plot on the Ab side of the Ab-An-Or projection. A comparison of the analyses of the Indus rocks with those of Green (1970) and Goodwin (1968) show that this is common in the Superior province.

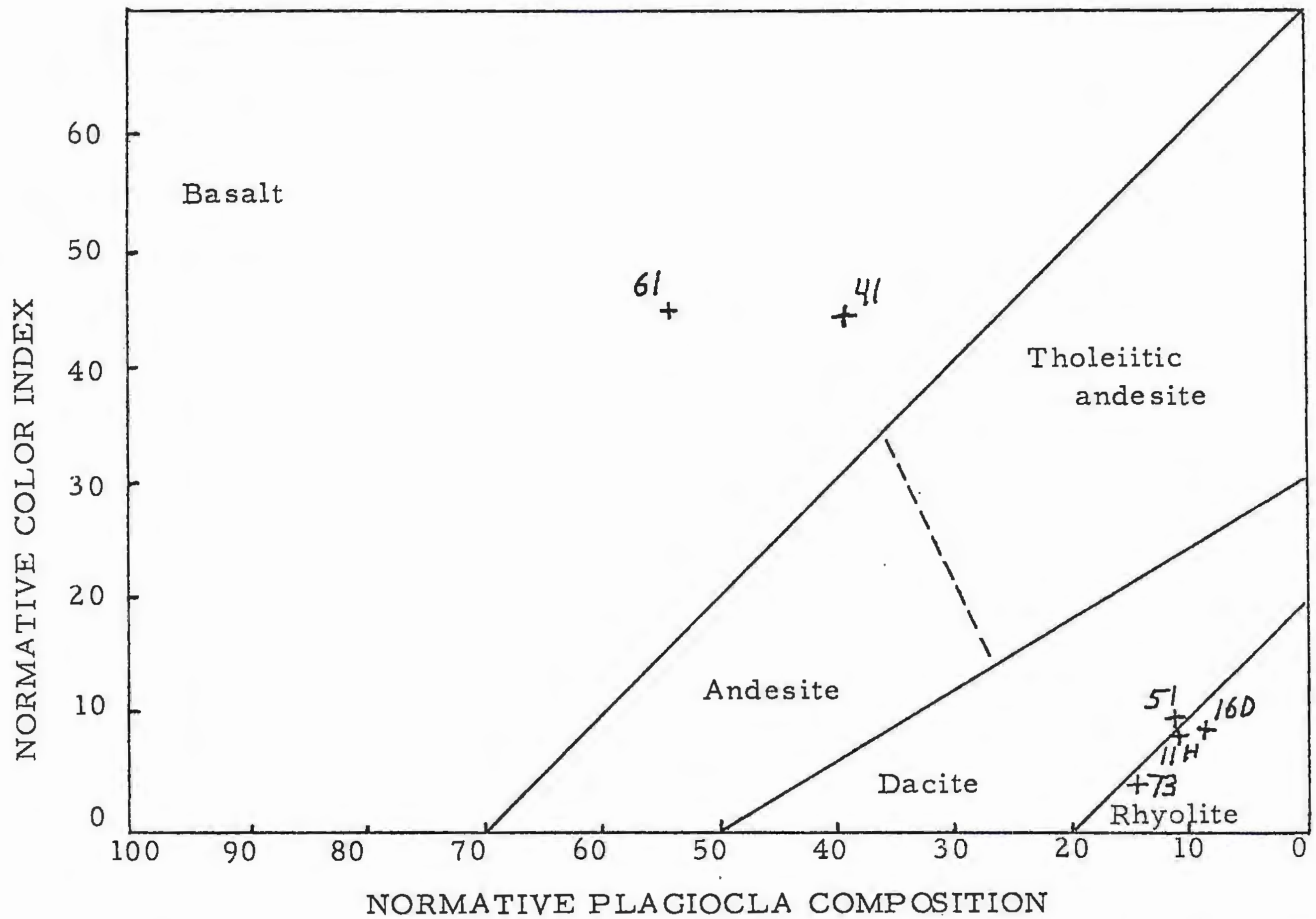


FIGURE 9 PLOTS OF NORMATIVE COLOR INDEX VERSUS NORMATIVE PLAGIOCLASE COMPOSITION WITH DIVIDING LINES (AFTER IRVINE AND BARAGAR (1971).

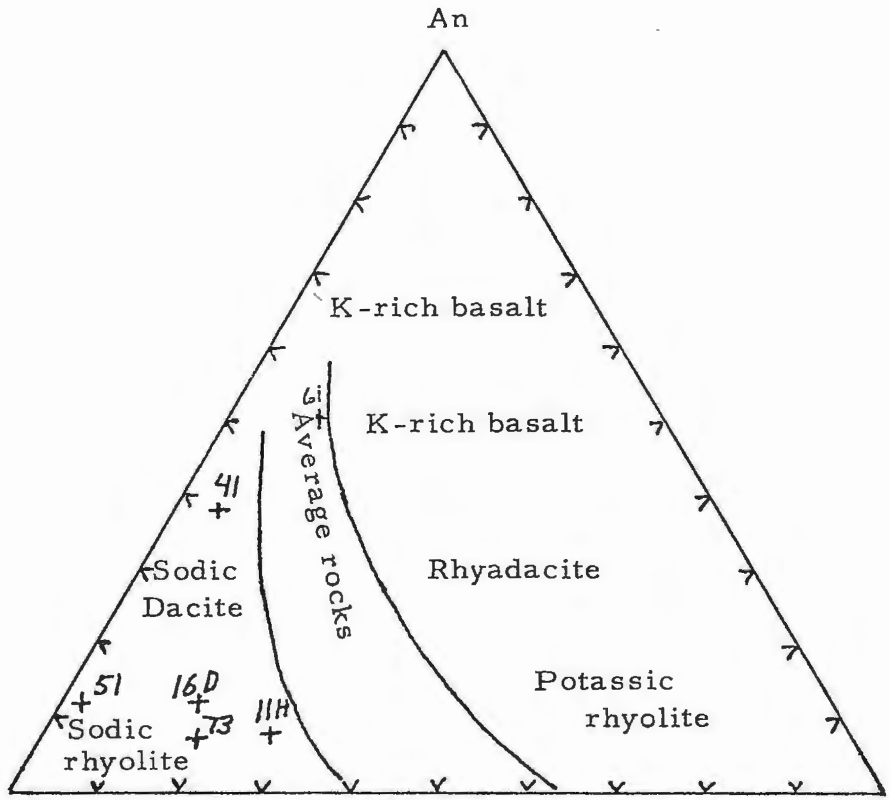


FIGURE 10. Ab-An-Or PROJECTION WITH IRVINE AND BARAGARS (1971) BOUNDARIES FOR K-POOR, K-AVERAGE, AND K-RICH ROCKS.

To summarize the geochemical interpretation, it seems that the similarities of Indus rock analyses to those from the Superior province given by Goodwin (1968) and Wilson and others (1965) suggest that these rocks are much like other rocks of the Superior province and may have the same continental orogenic or island arc origin as suggested by Wilson for the Superior province.

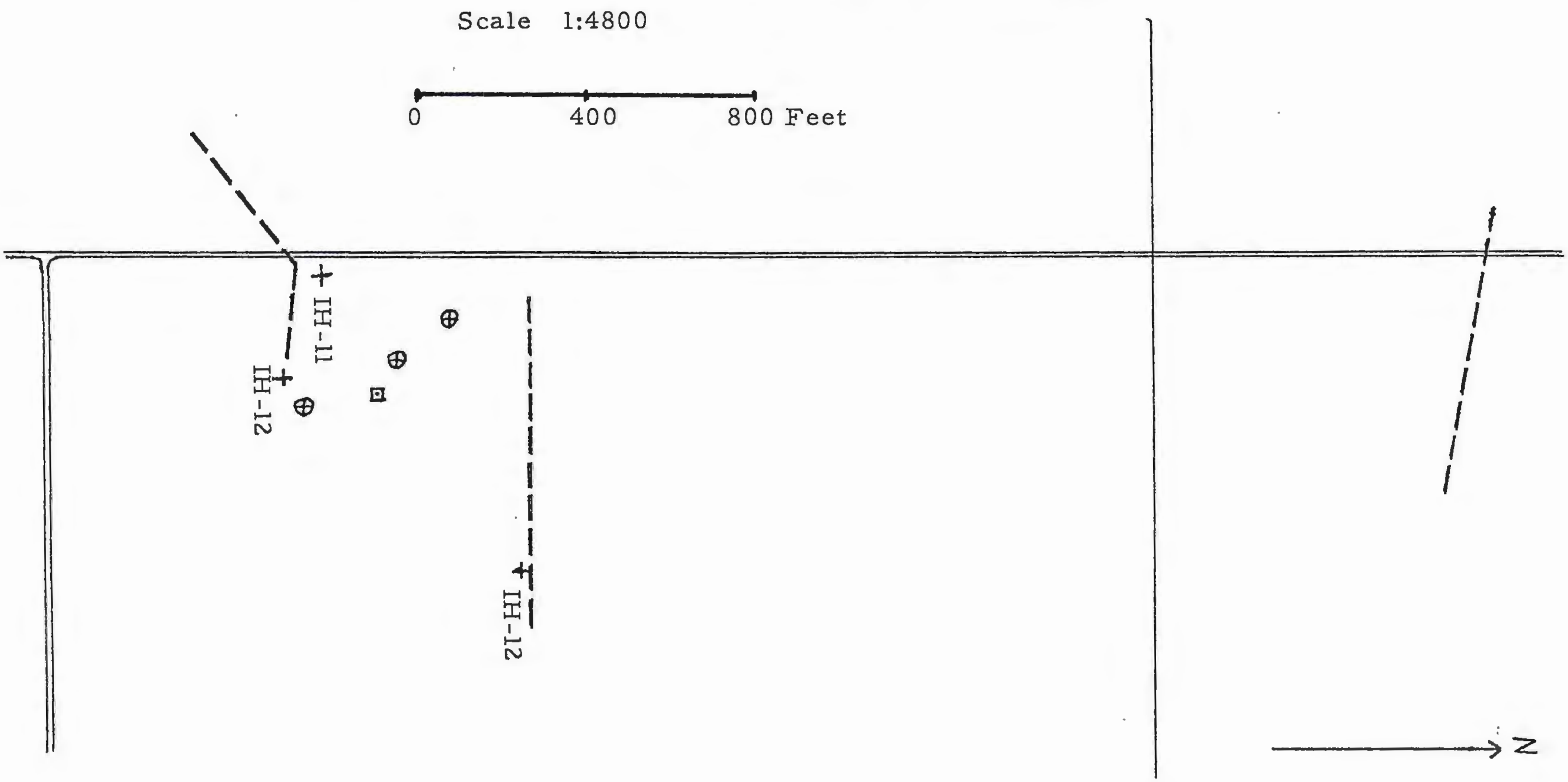
Geophysical Surveys

Horizontal shootback EM, fixed transmitter vertical loop EM, and total field proton precession magnetometer surveys were run by Minnesota Department of Natural Resources personnel during the summer of 1977 with the objectives of establishing geologic control on the orientation of rock units in the area and identifying geophysical conductors which may reflect economic mineralization. All systems were run over the same traverses except for over the iron-formation where only a magnetic survey was run.

Several conductors were indicated by horizontal shootback EM, most of which were in the area of sulfide mineralization. Most conductors intersected are of limited extent, but three conductors (Figure 11) were indicated by horizontal shootback EM which are more extensive and were confirmed by fixed transmitter vertical loop EM. Two of them are north of the Manitou Rapids dike, one in the SW 1/4-SW 1/4 of Section 9,

FIGURE 11. EM CONDUCTORS IN THE INDUS AREA. SECTIONS 9, 16, 17, T. 159 N., R. 25 W.

— — — Trace of Conductor, + Drill Hole, + Test Pit, . Test Shaft



T. 159 N., R. 25 W. and the other is in the NW 1/4 of Section 16, T. 159 N., R. 25 W. The third conductor is located south of the Manitou Rapids dike in the SW 1/4-NW 1/4 of Section 16, T. 159 N., R. 25 W. The trends of the two northern conductors compare quite well with the general stratigraphic attitudes in the area although there is no outcrop to correlate them with. The conductor south of the dike is discordant with the attitude of the stratigraphy for part of its distance and may represent a mineralized fracture zone. None of these conductors are of a nature that would interest a mining company, in the opinion of M. K. Vadis (pers. comm., 1978). The two southern conductors are confirmed by diamond drill holes drilled in 1972 which intersected semi-massive sulfides consisting mostly of pyrrhotite and pyrite with very minor chalcopyrite and sphalerite.

Other EM anomalies were found, but these were not traceable with the fixed transmitter vertical loop EM. These may represent minor lenses or pods of stratabound mineralization or mineralized fracture zones, but it is not determinable which is the case due to their lack of continuity.

Magnetometer surveys were run over the same traverses as the horizontal shootback EM and indicated that the EM conductors frequently have an associated magnetic anomaly. The magnetic response from the area indicates that the conductive zones have near vertical to steep northerly dips which corresponds reasonably well to the dips observed in outcrop.

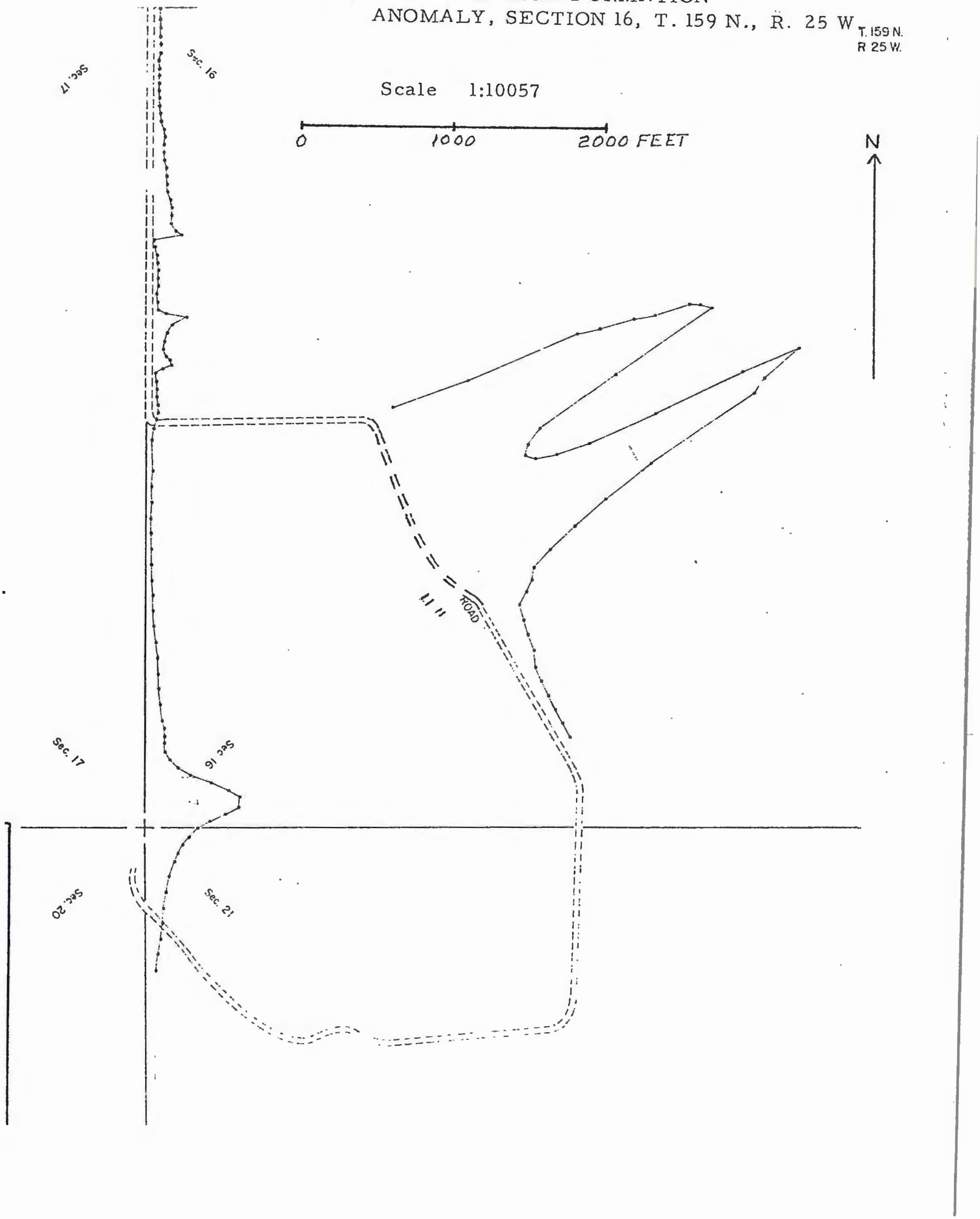
Two traverses (Figure 12) using a magnetometer only were run over a magnetic iron-formation which outcrops in the NE 1/4-SW 1/4 of Section 16, T. 159 N., R. 25 W. and has been roughly delineated by aeromagnetic surveys to extend discontinuously (Ojakangas, et. al., 1977) for about 28 miles in Minnesota and about seven miles into Ontario. These traverses indicate one magnetic peak over the iron-formation near the southwest corner of Section 16, T. 159 N., R. 25 W. and a two peak anomaly in the NE 1/4-SW 1/4 of Section 16, T. 159 N., R. 25 W. Apparently there are two lenses of iron-formation in this latter area, but further work is required to determine what the situation is.

The anomaly pattern for the eastern traverse across the iron-formation suggests that these bodies (if they are discrete bodies) may be from 100 to 150 feet wide and have from 50 to 100 feet of overburden. The anomaly on the west traverse is much weaker and may be due to a lower concentration of magnetite or to greater depth of overburden or both.

Structure

The structure in the Indus area is highly conjectural due to limited outcrop. Using outcrop data, Hurd photoquad maps and the work of Ojakangas, et. al. (1977), the structure shown in Plate 1 and Figure 13 is suggested.

FIGURE 12 . MAGNETIC IRON-FORMATION ANOMALY, SECTION 16, T. 159 N., R. 25 W



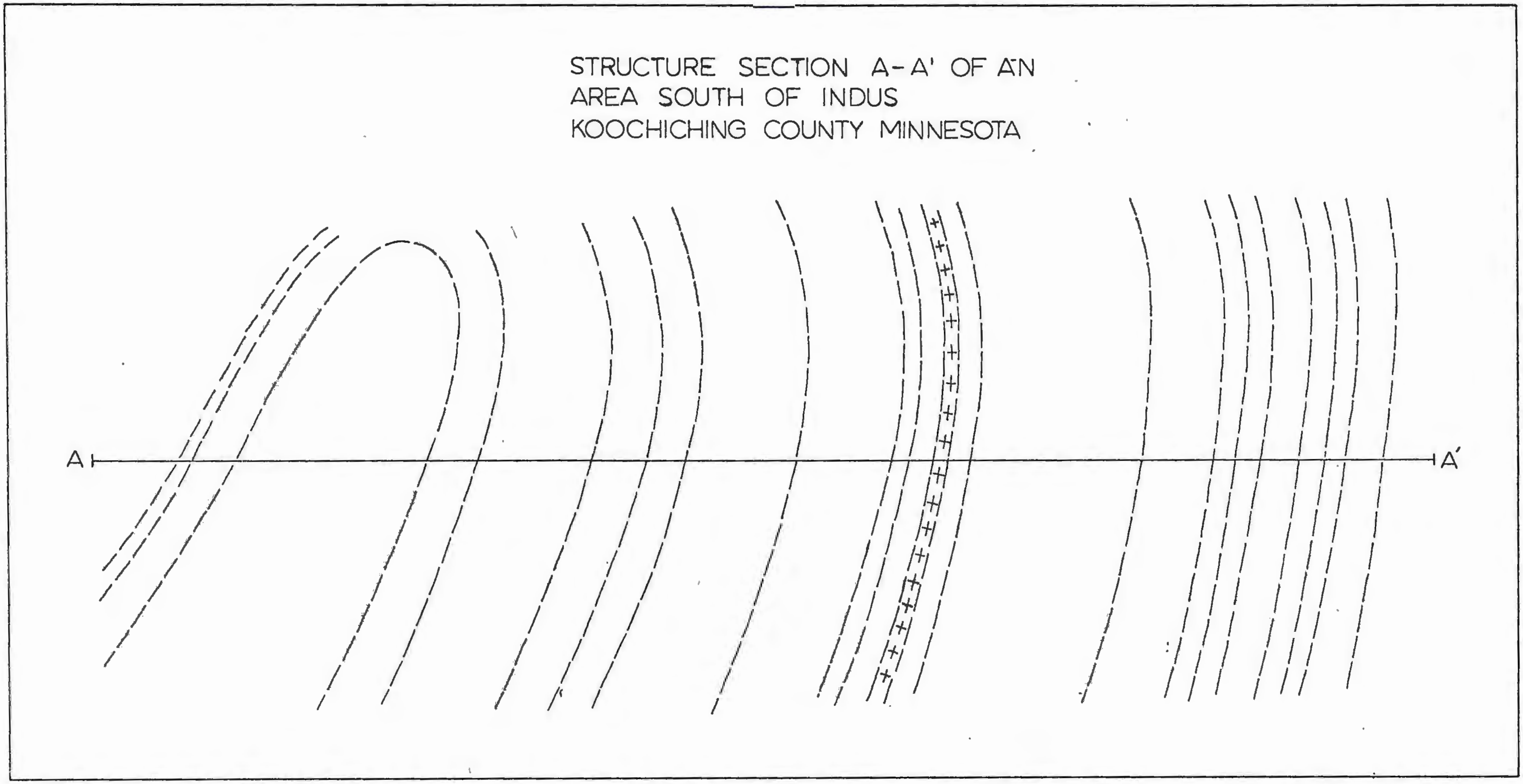


FIGURE 13 - SUGGESTED STRUCTURE SECTION OF AN AREA SOUTH OF INDUS, KOOCHICHING COUNTY, MINNESOTA.

Faults

No evidence of major faulting other than the fracture occupied by the Manitou Rapids dike was observed in outcrop. Minor shears with up to six feet of offset were observed in the Archean volcanics parallel to and adjacent to the dike but these may have been related to the fracture system occupied by the dike.

Two faults have been inferred in the NE 1/4 of Section 17 and one in the S 1/2 of Section 8, all in T. 159 N., R. 25 W. (Plate 1) based on lineaments shown in Hurd photoquad maps and apparent offset of the Manitou Rapids dike and topography as observed in topographic maps. The horizontal offset appears to be in the 200 to 500 feet range, but the vertical component, if any, is not known.

Folds

The area has been isoclinally folded about ENE plunging fold axes. The lack of outcrop in critical areas precluded the determination and location of fold structure from evidence within the area. Therefore, the structure section (Figure 13) is an adaptation from Ojakangas, et. al. (1977) as discussed in the regional geology of the area. As shown in Plate 1 and Figure 13, the folding in the area consists of an isoclinally folded anticline plunging to the northeast. Associated with this fold structure is a northeasterly plunging lineation of minerals at angles varying from 20 to 50 degrees and a foliation of minerals which is parallel or subparallel to bedding.

Two discordant dips of bedding were noted during field mapping. However, their relationships to the attitudes of other units nearby suggest that they may represent minor drag folds on the major structure. Questionable northwest facing pillow tops in the NW 1/4-NE 1/4 of Section 21, T. 159 N., R. 25 W., when considered in relation to the regional geology (Figure 2), suggest the possibility of a synclinal axis trending ENE through the northern part of Section 21. Since there is no supporting evidence, they too were considered as possibly representing just a drag fold.

Metamorphism

All rocks in the study area have been metamorphosed to a greater or lesser extent. The Archean volcanics and their related intrusions were metamorphosed during the Algoman orogeny which produced the major folds and intense shearing. The mineral assemblages and textures developed during this event are those characteristic of the greenschist-amphibolite transition facies of regional metamorphism (Turner, 1968). As a result, the rocks are almost completely recrystallized except for relict feldspar and quartz phenocrysts in the felsic units. The Middle-Precambrian Manitou Rapids dike has been uralitized, but still retains much of its original mineralogy and textures.

The mafic Archean volcanics are composed of an assemblage of amphibole and plagioclase with minor chlorite, epidote, and garnet. Some of the amphibole is actinolite, but most appears to be blue-green hornblende. The plagioclase is all very fine-grained and untwinned. The chlorites present show a wide range of optical properties varying from optically negative, iron-rich chlorite with normal interference colors to optically positive, magnesium-rich chlorite with normal interference colors. The chlorites between these extremes showed the anomalous interference colors near the optic sign change described by Albee (1962). The iron-rich chlorite is more common that the magnesium-rich type. The epidote shows a great range in crystallinity and commonly has yellowish to red-green interference colors.

The mineral assemblage in the felsic rocks consists of quartz, plagioclase, biotite, and muscovite with minor chlorite and hornblende which is consistent with this grade of metamorphism. The chlorite shows the same variation in these rocks as in the mafic rocks. Staining shows that the potassium in these rocks is contained in the micas as they contain little potassium feldspar.

Prehnite and pumpellyite associated with calcite are frequently seen in veins, especially in the mafic rocks, apparently products of a retrograde event.

The metamorphism of the Manitou Rapids dike consists chiefly of the uralitization or alteration of pyroxene to amphibole of indeterminate composition. Hanson and Malhotra (1971) attribute this alteration to burial while Ojakangas, et. al. (1977) suggested that it may be the result of deuteric alteration.

Sulfides of the Indus Area

Disseminated sulfides occur in almost all rock units of the area studied including the mafic volcanic rocks and the Manitou Rapids dike. Massive, semi-massive, and disseminated sulfides are found in outcrop and drill core in the SW 1/4-NE 1/4 of Section 16, T. 159 N., R. 25 W. (Plate 1). This zone extends for approximately 400 feet along the Manitou Rapids dike. Three shallow test pits and a test shaft, all of which were completed in the late 1950's and for which no records are available, are located here. In 1972 the Minnesota Department of Natural Resources drilled three shallow drill holes (Plate 1) which intersected zones of semi-massive and disseminated sulfides.

The sulfide zone is located in an area of felsic to intermediate metatuffs. A comparison of whole rock analyses (Table 1 , p. 61) and of thin sections from these rocks show no consistent, significant differences between the rocks in the sulfide zone and those on either side of it. The sericite content increases to 25 percent with depth in drill hole IH-10 and is consistently about 20 percent in IH-11 while in IH-12 it remains relatively constant at five to eight percent. The sericite content in samples collected from outcrop within the sulfide zone averages about 20 percent which is higher than the average for felsic rocks outside the sulfide zone although locally these reach 20 percent in the same sequence of felsic volcanics in which the sulfide zone is located. The only other difference noted was a slightly higher percentage of sphene in the sulfide zone, possibly as an alteration product of ilmenite.

Mineralogy

The sulfide minerals in order of decreasing abundance are pyrrhotite, pyrite, chalcopyrite, and sphalerite. Also noted in fractures or veins was what appears to be colloform pyrite or an intermediate phase in the pyrrhotite-pyrite transition. On an overall basis, pyrrhotite is the dominant sulfide, followed closely by pyrite. In some polished sections pyrrhotite is dominant and in others pyrite predominates. Chalcopyrite is third in abundance, occasionally constituting one percent of the sulfides; sphalerite occurs in trace amounts.

Pyrrhotite occurs in both massive and disseminated sulfide zones. Where massive it consists of aggregates of crystals, frequently with a polygonized or annealed texture (Plate 17). Numerous inclusions of gangue and occasional pyrite cubes (Plate 18) are often present in the massive pyrrhotite. Anhedral blebs of pyrrhotite are often present in inclusion rich pyrite. In zones of disseminated sulfides, the pyrrhotite occurs as fine-grained blebs frequently aligned in the foliation planes of the enclosing tuffs.

Pyrite occurs in massive and disseminated form. The massive form usually consists of intergrown anhedral grains while

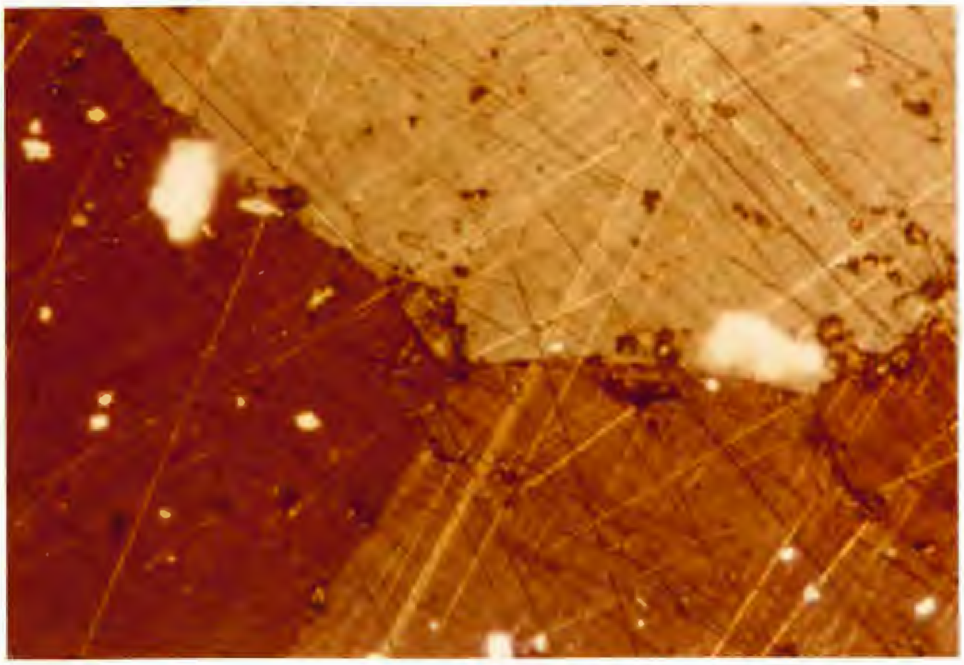


PLATE 17 - ANNEALED TEXTURE IN MASSIVE PYRRHOTITE. SAMPLE NO. IH-10-32.5. REFLECTED LIGHT, 128X, CROSSED NICOLS.

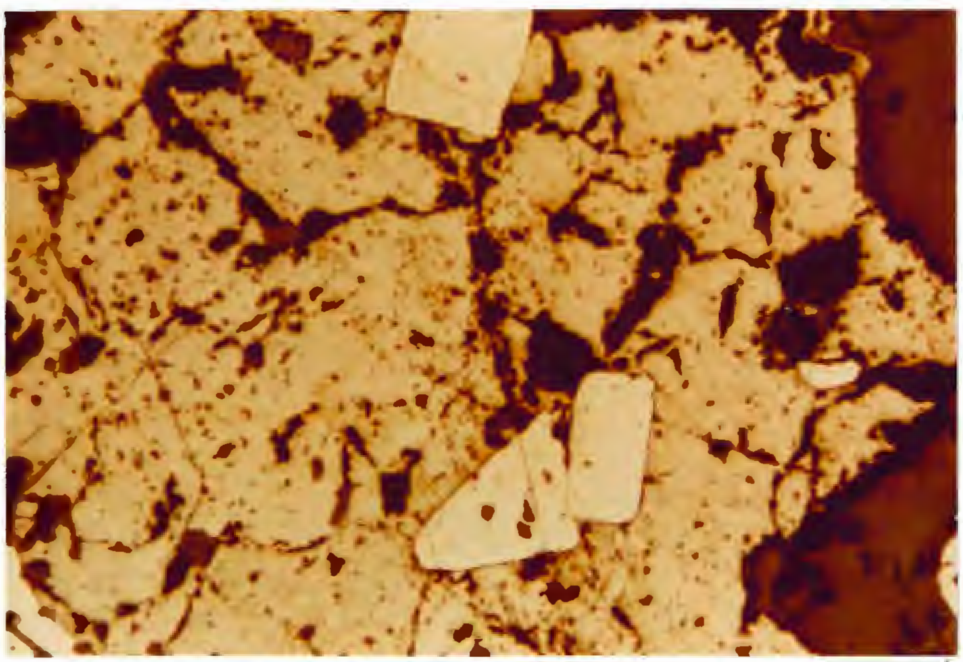


PLATE 18 - PYRITE CUBES AND GANGUE IN MASSIVE PYRRHOTITE. SAMPLE NO. IH-10-32.5. REFLECTED LIGHTS, 32X, UNCROSSED NICOLS.

the disseminated pyrite is more commonly subhedral to euhedral in form. In the more massive pyrite zones, occasional cubes of pyrite are surrounded by massive anhedral pyrite. Some pyrite is slightly anisotropic. There are two generations of pyrite. One consists of mostly euhedral pyrite cubes with a few inclusions of gangue. The other is more commonly subhedral to anhedral massive pyrite with numerous inclusions of gangue, frequent inclusions of pyrrhotite and traces of chalcopyrite and sphalerite (Plate 19).

Chalcopyrite is a minor sulfide occurring in amounts varying from a trace to one percent of the sulfides. It is found as very fine disseminated blebs, but is noted most frequently in association with pyrrhotite and as short veinlets into the pyrrhotite (Plate 20). A few very fine inclusions of chalcopyrite were noted in the late pyrite.

Sphalerite is less conspicuous than chalcopyrite and may be present in the same abundance as chalcopyrite although it is less obvious. When seen, it was usually as discreet disseminated grains, although it was occasionally noted as inclusions in the massive pyrrhotite and late pyrite.

In polished sections with massive pyrrhotite as the major sulfide, a mineral identified as colloform pyrite or a pyrrhotite-pyrite transition phase is present in minute fractures in the pyrrhotite. It may reach an abundance of ten percent of the sulfides

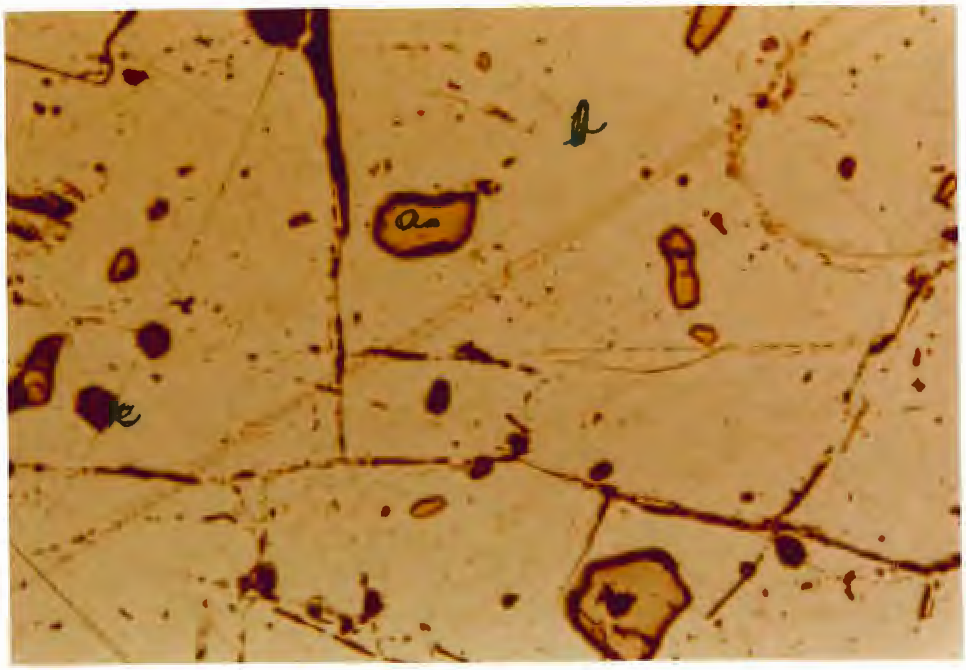


PLATE 19 - MASSIVE PYRITE WITH INCLUSIONS OF PYRRHOTITE AND GANGUE. SAMPLE NO. IH-10-32.5. REFLECTED LIGHT, 32X, UNCROSSED NICOLS. (a) PYRITE, (b) PYRRHOTITE, (c) GANGUE.

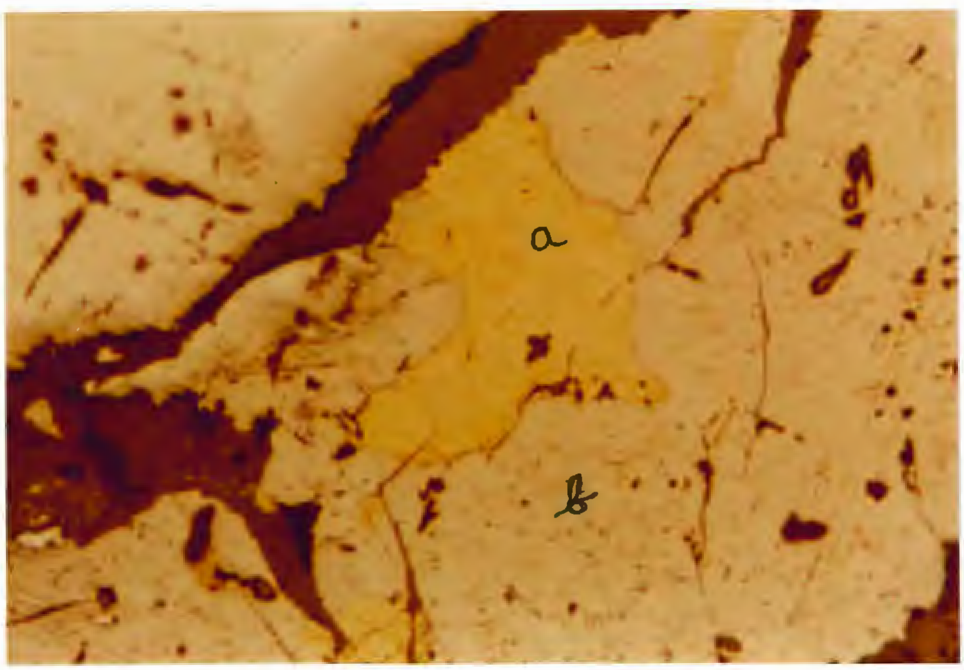


PLATE 20 - CHALCOPYRITE IN PYRRHOTITE. SAMPLE NO. IH-10-32.5, REFLECTED LIGHTS, 128X, UNCROSSED NICOLS. (a) CHALCOPYRITE, (b) PYRRHOTITE.

in some polished sections. The centers of these grains are massive with concentric rings about the center with dark areas between the rings (Plate 21). One sample contained what appears to be a subhedral pyrite grain in the center.

Massive Sulfides

Massive sulfides with a sulfide content greater than 75 percent are found chiefly in drill hole IH-10 although minor layers to a few inches in thickness are found in IH-12. Massive sulfides appear to have been present in the test shaft and in the southeast test pit, but the test shaft is full of water and what appears to be zones of massive sulfides in the test pit area are highly weathered.

Sulfides in drill hole IH-10 occur in a zone of felsic rocks that appear to be slightly agglomeratic or brecciated with the sulfides filling the intervening fractures or as a matrix of fragments or parallel to foliations in the rock. The sulfides consists predominantly of pyrite and pyrrhotite with either being locally dominant. The host rock becomes more massive with depth with a corresponding decrease in sulfide content.

Disseminated Sulfides

The most common occurrence is as disseminations with percentages present varying from three to five percent. Pyrite and pyrrhotite are frequently aligned in the foliation planes of the host rock and in minute crosscutting veinlets (Plate 22). In thin

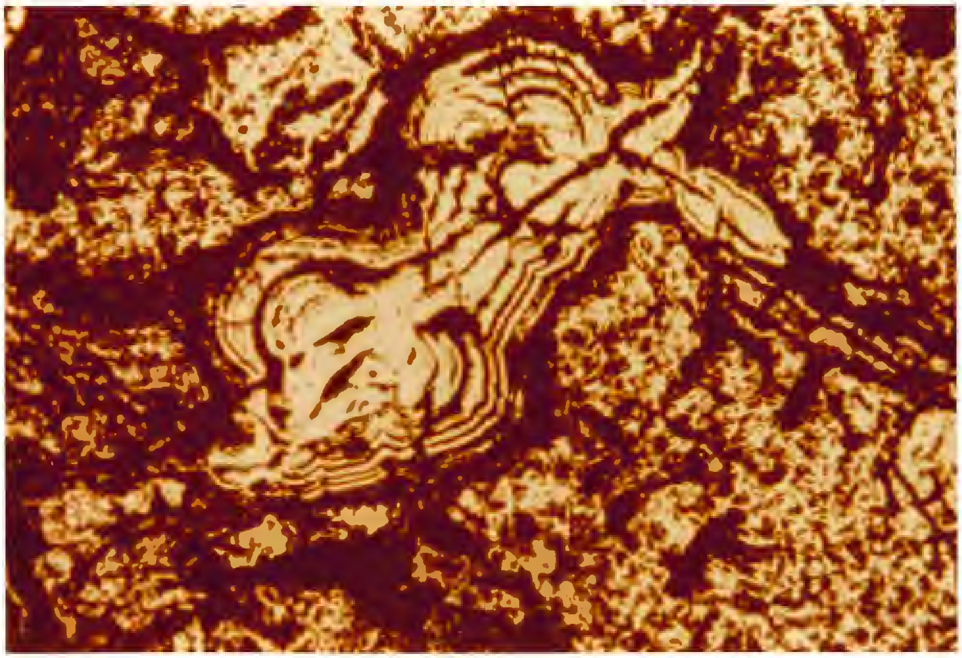


PLATE 21 - MINERAL IDENTIFIED AS EITHER COLLOFORM PYRITE IN PYRRHOTITE OR A TRANSITION PHASE BETWEEN PYRRHOTITE AND PYRITE. SAMPLE NO. S-1, REFLECTED LIGHT, 32X, UNCROSSED NICOLS.

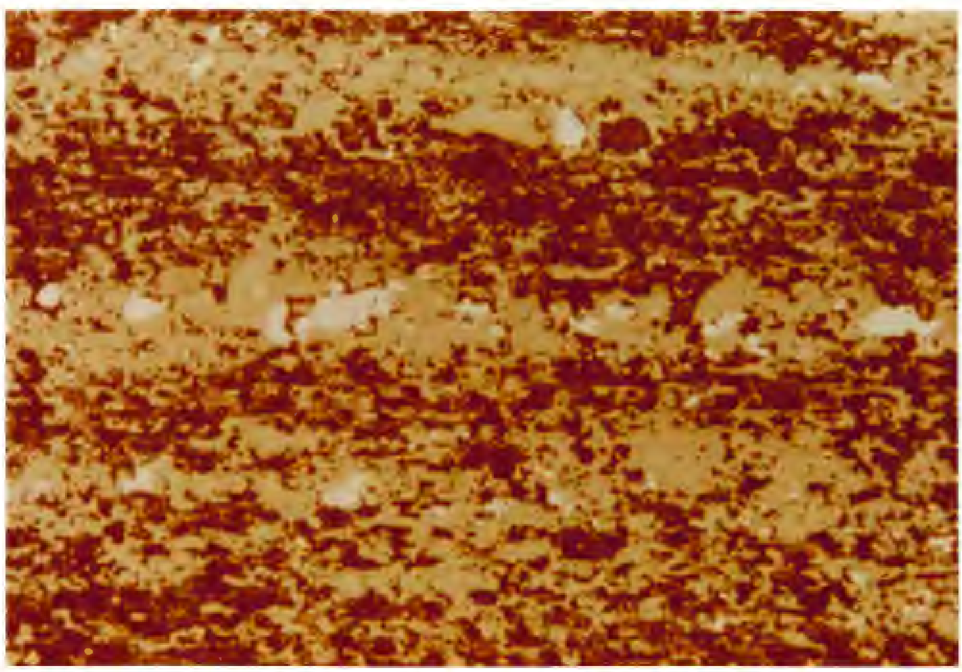


PLATE 22 - DISSEMINATED PYRITE AND PYRRHOTITE IN THE FOLIATION PLANES OF THE HOST ROCK. SAMPLE NO. TP-1, REFLECTED LIGHT, 32X, UNCROSSED NICOLS.

section, pyrite cubes are frequently seen in crosscutting relationships with the host rock. Chalcopyrite when seen is in the form of very fine disseminated grains.

Base Metal Content

Rocks from the sulfide zone have been thoroughly analyzed by the Minnesota Department of Natural Resources and from samples obtained during this investigation. Gold, silver, cobalt, and nickel as well as copper, zinc, and lead contents were determined by the atomic absorption method. In all cases, values were very low. The highest value for zinc was 1104 ppm for one analysis from drill hole IH-11 and the highest for copper was 584 ppm for a grab sample from the southeast test pit.

In this study, all rocks with noticeable sulfide contents were analyzed. No consistent relationship between the nature of the host rock and the base metal content is observed. Some felsic rocks in the sulfide zone are lower in base metals than are either felsic or mafic rocks outside the zone. A comparison of total sulfide content evident by visual inspection with the base metal content obtained by analysis shows that the content of base metals does not increase significantly with increasing sulfide content.

Sequence of Mineralization

The paragenetic sequence determined from a study of polished sections is shown in Figure 14.

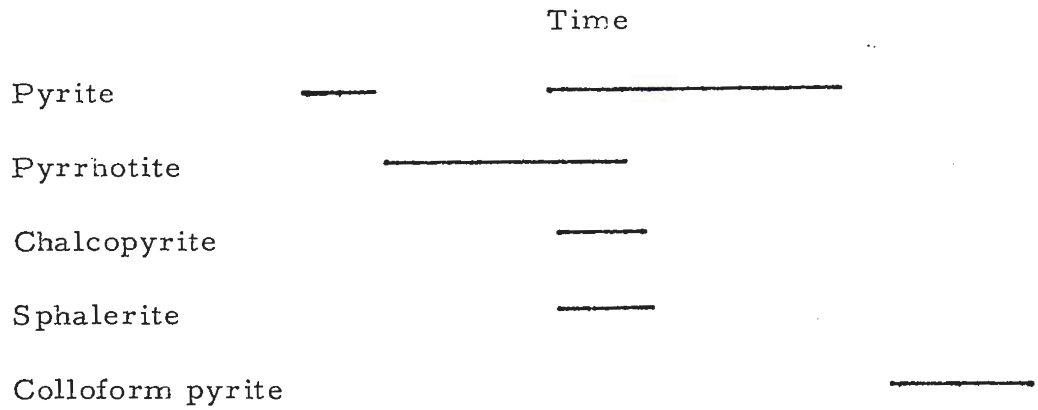


FIGURE 14 - PARAGENETIC SEQUENCE

The early pyrite is usually in the form of relatively inclusion-free disseminated cubes and blebs lying in the foliation planes of the host rock while later pyrite contains numerous inclusions of gangue and pyrrhotite. Pyrrhotite contains occasional pyrite euhedra and is locally gangue rich. The late pyrite and pyrrhotite tend to occur more frequently in massive to semi-massive forms and also occur in small veinlets crosscutting foliation and bedding. Chalcopyrite occasionally occurs as disseminated blebs, but is usually closely associated with pyrrhotite, either replacing it or along grain boundaries. The sphalerite occurs as disseminated blebs and veinlets and also as occasional inclusions in pyrrhotite and pyrite. The colloform pyrite is later than pyrrhotite.

Origin of Sulfides

The metals and sulfur are believed to be magmatic in origin and syngenetic with the enclosing volcanics as a product of volcanic exhalative processes. Sulfur isotope data that could suggest a possible origin for the sulfur is lacking (Stanton, 1972, p. 175-188). Therefore, since no graphite was observed that could indicate possible biogenic sulfur, it seems that the sulfur was most likely a volcanic product. The sulfide zone is very small in comparison to the extent of the enclosing volcanics so it would not have taken a particularly high concentration of sulfur in the magma to provide the sulfur, especially if it were concentrated later.

It is proposed that the disseminated sulfides were moved and redeposited in favorable sites by a later hydrothermal event. The evidence for this supposition is the paragenetic sequence which indicates a post lithification time for much of the sulfide deposition. The most likely period for sulfide movement and deposition would appear to be during the regional metamorphism. Based on available evidence there is no indication of an alteration zone or pipe associated with the massive sulfide zone that is typical of a direct volcanic emission origin. The sericite present in the sulfide zone could have been produced by the same fluids transporting the sulfides. Further evidence of this concept of concentration is the occurrence of the massive sulfides in agglomeratic zones which are more permeable. The mafic dike did not appear to have aided in sulfide mineralization. While it could possibly have provided some of the heat for remobilization, it was apparently lacking the necessary fluids for transporting material as no alteration was observed in the adjacent volcanics.

Trace Element Distribution

Thirty-six samples were submitted to the Minnesota Department of Natural Resources geochemical laboratory at Hibbing, Minnesota for trace element analysis to determine their base metal content. These results were used to determine the base metal ratios to see if there are discernable trends that could be correlated with the geology. A further purpose was to compare base metal contents and ratios with those determined by Listerud (1974) for the Birchdale anomaly area. Twelve samples were from the sulfide zone, 18 samples containing noticeable sulfides were from locations outside the sulfide zone along the Manitou Rapids dike and six samples were from the dike where it bordered the sulfide zone. The total sulfide content was less than five percent except in samples 24A and 24B which contained 10 to 12 percent pyrite. The samples from the dike were analyzed to see if it could have been a source for the mineralization in the sulfide zone. The results of these analyses and the associated type of rock are shown in Table 4. The trace element content and ratios are summarized by rock type in Tables 5 and 6. The relative abundances of trace elements in the earth's crust by rock type are shown in Table 7 (after Levinson, 1974). Analyses and ratios from drill cores IH-10, IH-11, and IH-12 are summarized in Tables 8 and 9. Table 10 contains trace element analyses from the Birchdale area.

The number of samples and their spatial distribution is insufficient to be a statistically valid sampling and to illustrate trends, but several differences are suggested by a comparison of trace element analyses and their ratios for both the Indus and Birchdale area.

1. Samples collected from outcrop (Table 4) are higher in copper relative to zinc while analyses from drill core (Table 8) show higher values for zinc than for copper.
2. Base metal values in zones of semi-massive to massive sulfides are little higher than for zones of disseminated sulfides (Table 11) in the Indus area. This has been noted by other workers in the region. It has been suggested by Ojakangas, et. al. (1977, p. 55) in a summary of mineralization in the Birchdale-Indus area that possibly "relatively constant amounts of zinc and copper were available, but their concentrations were diluted by the tremendous quantities of iron sulfides during times of rapid sulfide formation and deposition". Also, it is possible that iron sulfides are more easily mobilized and transported than base metal sulfides and that the base metals in massive sulfide zones have been diluted by iron sulfides which have been moved from other areas and redeposited.

3. In general, base metal values in samples collected outside the sulfide zone are similar to those collected in the sulfide zone.

4. Copper and zinc values correlated with rock type are slightly higher for rocks in the Indus area than for the average of rocks of corresponding type in the earth's crust (Tables 6 and 7), but nickel and cobalt values are distinctly higher, especially for felsic and intermediate volcanic rocks and metasediments. Their ratios (Table 5) show a corresponding relationship. Graphical representation of these values is shown in Figure 15 and illustrates how copper-zinc and nickel-cobalt vary in a parallel to sub-parallel fashion.

5. Tables 11 and 12 suggest rather distinct differences in trace element content and their ratios between the Indus area and the Birchdale area. Massive sulfide ratios in the Indus area appear to be distinctly lower for Ni/Zn, Co/Zn, Cu/Co, and Cu/An while the Cu/Ni, Co/Ni, Cu + Zu/Co, and Cu + Zn/Ni + Co ratios vary from similar to distinctly higher in the Indus samples. In contrast, the ratios in disseminated sulfides are higher in the Indus samples for Ni/Zn and Co/Zn, but lower for Cu/Co, Cu/Ni, Co/Ni, Cu/Zn, Cu + Zn/Co, and Cu + Zn/Ni + Co.

TABLE 4 - TRACE ELEMENT ANALYSES FOR ROCKS FROM THE INDUS AREA IN PPM, Au, Ag IN Oz/T.

Sample Number	Rock Type	Ag	Au	Cu	Zn	Co	Ni
1	Felsic tuff	0.2	.018	56	38	50	56
2	Felsic tuff	0.7	.006	44	70	52	60
3	Felsic tuff	1.0	.006	584	80	30	76
4	Felsic tuff	0.4	0	318	128	34	54
5B	Felsic tuff	0.3	0	48	156	38	54
7	Felsic tuff	0.9	.018	190	56	50	58
16A	Felsic tuff	0.2	0	48	92	60	74
16C	Felsic tuff	0.3	0	70	46	62	96
16D	Felsic tuff	0.2	.006	86	54	62	88
16E	Felsic tuff	0.4	0	84	216	78	74
8X	Felsic tuff	0.2	0	62	42	62	76
11D	Felsic tuff	0.1	0	50	60	42	78
11F	Felsic tuff	0.4	0	120	40	96	136
21	Metased.	0.8	.023	152	78	126	216
23	Metased.	0.8	0	206	78	118	208
24A	Metased.	0.8	0	106	98	112	132
24B	Metased.	1.0	.006	74	212	110	130
53	Felsic tuff	0.7	0	160	50	164	176
56	Mafic tuff	0.6	0	146	96	134	130
58	Mafic flow	0.6	0	84	122	124	130
59	Intermed. tuff	0.4	.012	128	86	160	168

Sample Number	Rock Type	Ag	Au	Cu	Zn	Co	Ni
60	Intermed. tuff	0.6	0	126	100	134	136
61	Mafic flow	0.8	0	250	104	150	146
63	Felsic tuff	0	0	40	38	110	110
64	Intermed. tuff	0.4	.012	64	72	148	172
75	Mafic flow	1.0	.006	192	38	140	158
76	Felsic tuff	0	0	42	62	104	94
77	Mafic flow	0.7	0	100	112	114	154
D1	Mafic dike	0.6	0	74	180	144	108
D2	Mafic dike	0.7	0	84	78	164	124
D3	Mafic dike	0.7	0	130	278	140	136
D4	Mafic dike	0.5	0	72	82	142	118
D5	Mafic dike	0.7	0	70	100	132	108
D6	Mafic dike	0.6	0	74	76	130	100

Rock Type	No. Spls.	Ni / Zn	Co / Zn	Cu / Co	Cu / Ni	Co / Ni	Cu / Zn	Cu + Zn / Co	Cu + Zn / Ni + Co
Felsic volcanics	6	2.33	2.00	0.82	0.71	0.86	1.65	1.32	0.61
Intermed. volcanics	3	1.86	1.71	0.72	0.66	0.92	1.23	1.31	0.63
Mafic volcanics	5	1.53	1.40	1.17	1.07	0.92	1.64	1.88	0.90
Metasediments	4	2.10	1.43	1.44	0.98	0.68	2.06	2.15	0.87
Mafic dike	6	0.79	0.97	0.59	0.72	1.22	0.58	1.62	0.89

TABLE 5 - AVERAGE OF TRACE ELEMENT RATIOS FROM OUTCROP SAMPLES FROM THE INDUS AREA BY ROCK TYPE. ALL DISSEMINATED SULFIDES.

Rock Type	No. Spls.	Cu	Zn	Ni	Co
Felsic volcanics	6	79	48	112	96
Intermed. volcanics	3	106	86	160	147
Mafic volcanics	5	154	94	144	13 2
Metasediments	4	169	82	172	117
Mafic dike	6	84	146	116	142

TABLE 6 - AVERAGE OF TRACE ELEMENTS ANALYSES FROM OUTCROP SAMPLES FROM THE INDUS AREA BY ROCK TYPE. ALL DISSEMINATES SULFIDES. VALUES IN PPM.

Rock Type	Cu	Zn	Ni	Co
Ultra-mafic	10	50	2000	150
Basalt	100	100	150	50
Granodiorite	30	60	20	10
Granite	10	40	0.5	1
Shale	50	100	70	20

TABLE 7 - RELATIVE ABUNDANCES OF TRACE ELEMENTS IN THE EARTH'S CRUST (IN PPM). CORRELATED TO ROCK TYPE (AFTER LEVINSON, 1974).

Hole Number	Footage	Are. pa and py content	Average Analysis in PPM Cu	Zn	Ni	Co
IH-10	21-34	40%	57	176	32	95
IH-10	34-40	15	99	207	36	39
IH-10	40-47	3	11	114	36	37
IH-11	127-197	1.5	15	250	45	39
IH-11	19.7-24.2	2	8	56	46	43
IH-12	17-20	7	15	96	390	74
IH-12	20-25	16	42	42	198	59
IH-12	25-27	5	18	152	358	70
IH-12	27-34	14	27	35	55	52
IH-12	34-43	8	22	39	88	54

TABLE 8 - SUMMARIES OF DRILL CORE ANALYSES FROM THE INDUS AREA; ALL ROCKS ARE FELSIC VOLCANICS.

Drill Hole	Frontage	Average Po + Py	Ni/Zn	Co/Zn	Cu/Co	Cu/Ni	Co/Ni	Cu/Zn	(Cu + Zn)/Co	(Cu + Zn)/(Ni + Co)
IH-10	21-34'	40%	0.21	0.61	0.69	1.71	2.92	0.34	2.77	1.94
IH-10	34-40'	15	0.21	0.24	2.53	2.81	1.13	0.58	8.03	4.11
IH-10	40-47'	3	0.97	0.32	0.30	0.31	1.03	0.10	3.38	1.71
IH-11	12.7-19.7'	1.5	0.18	0.16	0.38	0.33	0.87	0.06	6.79	3.15
IH-11	19.2-24.2'	2	0.82	0.77	0.19	0.17	0.93	0.14	1.49	0.72
IH-12	17-20'	7	4.06	0.77	0.20	0.04	0.19	0.16	1.50	0.24
IH-12	20-25'	16	4.71	1.40	0.71	0.21	0.30	1.00	1.42	0.33
IH-12	25-27'	5	2.36	0.46	0.26	0.05	0.20	0.12	2.43	0.40
IH-12	27-34'	14	1.57	1.49	0.52	0.49	0.95	0.77	1.19	0.58
IH-12	34-42'	8	2.26	1.38	0.41	0.25	0.61	0.56	1.13	0.43

TABLE 9 - TRACE ELEMENT RATIOS FROM DRILL CORE SUMMARIES FROM THE INDUS AREA.

Sample No. and Sulfide Type	In ppm Cu	Zn	Ni	Co
R-2-2-153.5, Disseminated	40	460	80	43
R-2-2-222, Disseminated	222	180	135	96
S-43-2-174, Disseminated	26	140	190	116
R-2-1-170.5, Disseminated	392	640	42	54
R-2-1-307, Disseminated	89	280	112	100
R-2-1-351, Disseminated	228	700	70	64
R-2-1-479, Disseminated	40	160	75	60
S-43-3-165.5, Massive	152	140	173	122
S-43-1-165, Massive	600	440	124	206
S-43-1-307, Massive	376	120	140	251
R-2-1A-327, Massive	240	33	322	276
R-2-1-108, Massive	376	28	184	170
R-2-1-178, Massive	154	14	223	248

TABLE 10 - TRACE ELEMENT ANALYSES FROM THE BIRCHDALE ANOMALY (AFTER LISTERUD, 1974).

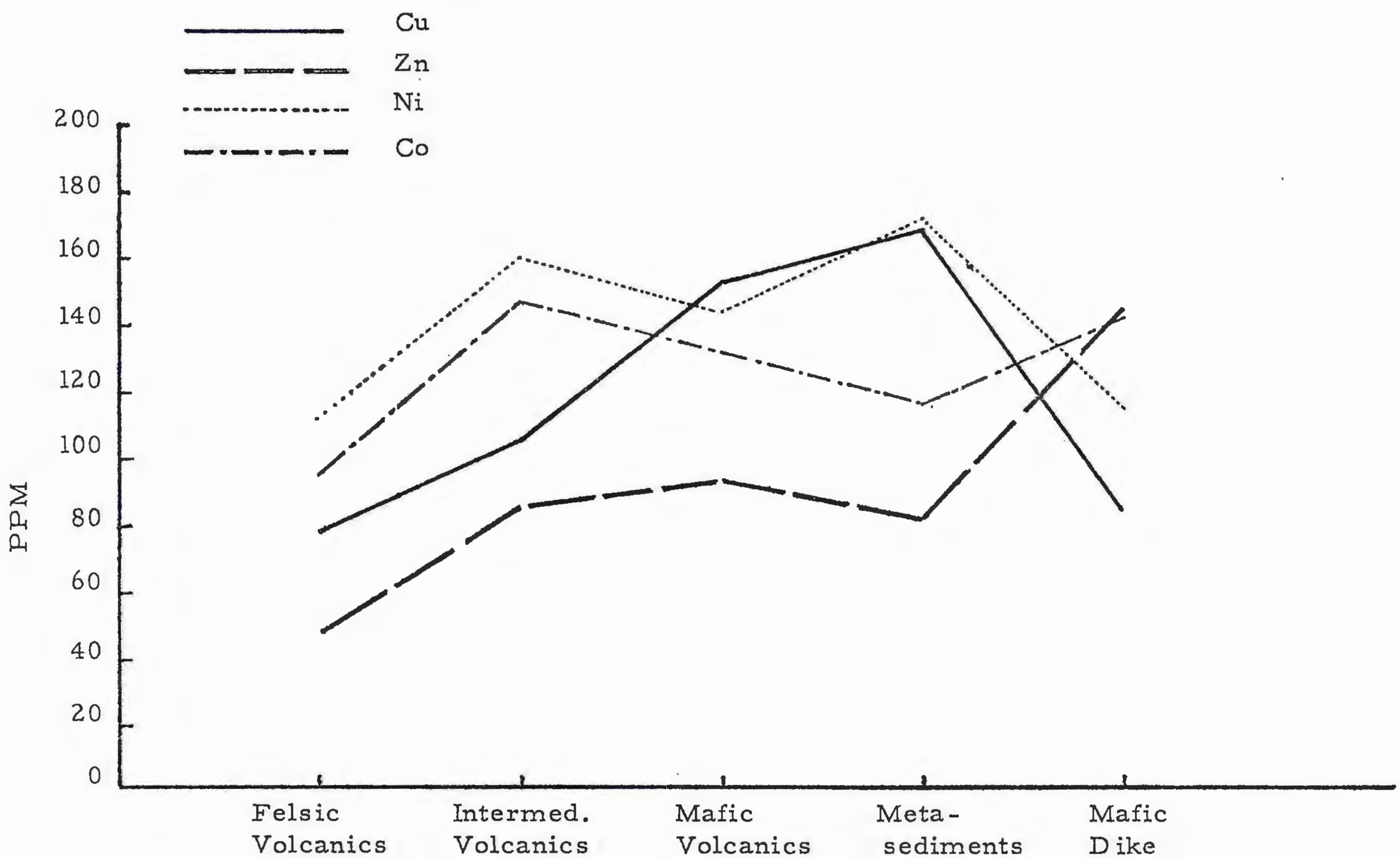
Sulfide Type	Location	Cu	Zn	Ni	Co
Massive	Indus	57	176	32	95
Massive	B-dale	316	129	194	212
Disseminated	Indus	14	118	101	47
Disseminated	B-dale	148	366	101	76

TABLE 11 - COMPARISON OF TRACE ELEMENT CONTENT IN MASSIVE AND DISSEMINATED SULFIDES IN PPM IN THE INDUS AND BIRCHDALE AREAS. BIRCHDALE VALUES AFTER LISTERUD (1974).

Sulfide Type	Location	Ni/Zn	Co/Zn	Cu/Co	Cu/Ni	Co/Ni	Cu/Zn	$\frac{Cu+Zn}{Co}$	$\frac{Cu+Zn}{Ni+Co}$
Massive	Indus	0.18	0.54	0.60	1.78	2.97	0.32	2.45	1.84
Massive	B-dale	1.50	1.64	1.49	1.63	1.09	2.45	2.10	1.10
Disseminated	Indus	0.86	0.40	0.30	0.14	0.47	0.12	2.80	0.89
Disseminated	B-dale	0.28	0.21	1.95	1.47	0.75	0.40	6.76	2.90

TABLE 12 - COMPARISON OF TRACE ELEMENT RATIOS IN MASSIVE AND DISSEMINATED SULFIDES IN THE INDUS AND BIRCHDALE AREAS.

FIGURE 15 - GRAPH OF TRACE ELEMENTS IN PPM BY ROCK TYPE FOR THE INDUS AREA.



Trace element ratios are frequently used in studies of ore bodies and their enclosing rocks. Absolute metal values may be inconsistent, but their ratios will be consistent and characteristic of ores in a district although the ratios may vary from district to district. Roscoe (1965) in a study made in the Noranda and Matagami districts in Ontario found that high Co/Ni ratios were common in ore bodies, but very low in barren sulfides. Wilson and Anderson (1959) in a study of copper-zinc ores of Canada determined that each deposit or district has its distinctive ratio. The value of the ratios determined in this study in regard to ore potential is unknown at present. When more analyses from the area and region become available, they may be useful in tracking down an ore body.

Relationship of the Sulfides to Stratigraphy

The sulfides in the Indus area appear to be stratabound bodies closely related to certain strata in the felsic volcaniclastics. The EM responses that were traceable for any distance indicated conductors that for the most part paralleled the attitudes of the enclosing rocks quite closely. The massive sulfides occurring in slightly agglomeratic units suggests stratigraphic controls in the localization of sulfides wherein the ore-bearing fluids are channelled through more permeable units by enclosing relatively impermeable units. This relationship of mineralization to felsic strata has been observed in other sulfide occurrences in the region (Ojakangas, et. al., 1977).

SUMMARY AND CONCLUSIONS

The Archean volcanics and their associated sulfides may have originated in a situation similar to a modern island arc environment. Beginning with mafic volcanism, the sequence progresses upward through intermediate and felsic volcanism with associated intrusives. Tuffaceous metasediments including iron-formation were deposited in the upper part of the volcanic pile with very minor sedimentary units in lower volcanic units. The volcanic center appears to have been located to the northwest as clast sizes in agglomeratic units increase in that direction (Ojakangas, et. al., 1977). Most deposition appears to have been subaqueous under still, deep water conditions since amygdular basalts are not notably conspicuous and bedding features characteristic of reworking are lacking in the tuffaceous volcanics.

Sulfides are common in all lithologies in the Indus area and appear to be syngenetic with the enclosing rocks as a product of volcanic exhalative processes. Both the metals and sulfur are believed to be magmatic in origin as no graphite was observed that would suggest a biogenic source for sulfur. The sulfides are present in both disseminated and massive form. Trace element analysis shows base metal values to be low in all cases.

The area was regionally metamorphosed during the Algoman orogeny to the greenschist-amphibolite transition facies. This event appears to have also served to remobilize the sulfides and concentrate them in favorable sites in the sulfide zone where their presence appears to be that of relatively small stratabound bodies.

The area was isoclinally folded about ENE trending axes during the same event that produced the metamorphism and the intense shearing of the rocks. Later, a northwesterly trending fracture developed with the intrusion of the Manitou Rapids dike. Northeasterly-trending faults are inferred from lineaments visible in aerial photos and from apparent offsets of the Manitou Rapids dike. It is not known whether these represent new faults or renewed movement along old faults.

The latest event in the geologic history of the area was Pleistocene glaciation which scoured material from the higher elevations and left a covering of glacial till and glacial lake sediments over the remainder of the area.

The potential for economic mineralization does not appear bright for the Indus sulfide deposit studied, but the region has not been thoroughly explored. The zone lies in a felsic volcanic horizon which is one that is favorable for economic mineralization so further work to either the east or the west may be profitable. Since Ojakangas, et. al. (1977) has postulated a volcanic center to the northwest for these felsic volcanics, it is possible that the felsic-intermediate zone north of the anticline in Figure 2 may be more favorable for prospecting since it is closer to the possible volcanic vent.

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APPENDIX A.

PETROGRAPHIC DESCRIPTIONS OF PHOTOMICROGRAPHS

Mafic flow (Plate 4)
Sample No. 61 from SE 1/4-NE 1/4,
Section 17, T. 159 N., R. 25 W.

Estimated mode:

Hornblende:	70	Chlorite	Tr.
Garnet	20	Epidote	Tr.
Opaques	10	Pumpellyite	Tr.

Chemical composition (K. Ramlal, 1978)

SiO_2	47.90	K_2O	0.98
Al_2O_3	13.81	H_2O (+)	(2.15
Fe_2O_3	2.86	H_2O (-)	(
FeO	13.41	CO_2	0.35
MgO	5.15	TiO_2	0.92
CaO	9.18	P_2O_5	0.11
Na_2O	2.31	MnO	0.41

Sample No. 61 is a dark, rusty, buff-gray on a weathered surface. Grain size is aphanitic to very fine-grained and the texture is massive.

This rock is composed almost entirely of felty-textured blue-green hornblende with garnet porphyroblasts. The chlorite occurs almost entirely in the garnets and the epidote and pumpellyite are found as fracture or vein fillings. The opaques are anhedral magnetite and pyrite occurring as very fine disseminations and as coarser-grained inclusions in the garnet.

Mafic flow (Plate 5)
Sample No. 41 from SE 1/4-NE 1/4,
Sec. 21, T. 159 N., R. 25 W.

Estimated mode:

Hornblende	60
Plagioclase	35
Epidote	3
Biotite	1
Opaques	Tr.

Chemical composition (K. Ramlal, 1978)

SiO_2	51.15	K_2O	0.42
Al_2O_3	13.96	H_2O (+)	(1.48
Fe_2O_3	2.94	H_2O (-)	(
FeO	7.00	CO_2	0.14
MgO	7.95	TiO_2	0.74
CaO	9.82	P_2O_5	0.42
Na_2O	3.55	MnO	0.19

Unit No. 41 is greenish-gray on a weathered surface and dark, greenish-gray on a fresh surface. The grain size is aphanitic and the rock is massive.

Very fine-grained subhedral, lineated blue-green hornblende is the major mineral in this rock. There are a few phenocrysts of hornblende to 1 mm. Very fine-grained, untwinned, plagioclase in a granoblastic texture is interstitial to the hornblende. Minor anhedral biotite and epidote and traces of anhedral magnetite are disseminated throughout.

Intermediate flow (Plate 7)
Sample No. 40 from SE 1/4-NE 1/4, Sec. 21,
T. 159 N., R. 25 W.

Estimated mode:

Plagioclase	55%	Sericite	5%
Amphibole	30	Biotite	1
Quartz	10	Opaques	2

This unit is aphanitic and massive. It is gray on a weathered surface and medium-gray on a fresh surface.

Randomly oriented, subhedral, blue-green hornblende is enclosed in a matrix of partially recrystallized plagioclase. Relict, plagioclase phenocrysts to 1 mm. show traces of albite twinning, but no plagioclase determination was possible. Some plagioclase shows considerable sericitization. Disseminated anhedral quartz, biotite, and magnetite complete the mineralogy.

Rhyodacitic lapilli tuff (Plate 11)
Sample No. 11H from SW 1/4-NW 1/4, Sec. 16,
T. 159 N., R. 25 W.

Estimated mode:

Plagioclase	45	Calcite	1
Sericite	20	Apatite	Tr.
Quartz	15	Epidote	Tr.
Chlorite	15	Tourmaline	Tr.
Biotite	4	Opaques	Tr.

Chemical Composition (K. Ramlal, 1978)

SiO_2	66.05	K_2O	3.26
Al_2O_3	17.41	H_2O (+)	(1.39
Fe_2O_3	1.22	H_2O (-)	(
FeO	1.80	CO_2	0.17
MgO	1.39	TiO_2	0.48
CaO	1.31	P_2O_5	0.11
Na_2O	5.22	MnO	0.04

This rock is buff-gray on a weathered surface and greenish-gray on a fresh surface. The grain size is aphanitic. It is well foliated with the foliations wrapping around stretched lapilli size clasts.

The very fine-grained quartz and plagioclase occurs in a granoblastic texture in tuff and lapilli size fragments. The sericite occurs both as an alteration of plagioclase and along with the other micaceous minerals and epidote in the foliation planes. Apatite is disseminated throughout while the tourmaline occurs in one band where it is almost five percent. The opaques are disseminated pyrite-pyrrhotite.

Dacitic lapilli tuff (Plate 12)
Sample No. 51 from SE 1/4-NE 1/4, Sec. 17,
T. 159 N., R. 25 W.

Estimated mode:

Plagioclase	10	Garnet	1
Quartz	10	Potassium feldsp.	Tr.
Hornblende	5	Epidote	Tr.
Biotite	4	Tourmaline	Tr.
Chlorite	4	Opaques	6

Chemical composition (K. Ramlal, 1978)

SiO_2	65.40	K_2O	0.28
Al_2O_3	15.82	H_2O (+)	(1.20
Fe_2O_3	1.26	H_2O (-)	(
FeO	3.19	CO_2	0.62
MgO	0.59	TiO_2	1.64
CaO	1.97	P_2O_5	0.18
Na_2O	7.43	MnO	0.17

This rock is rusty, gray-brown on the weathered surface and medium gray on a fresh surface. It is aphanitic and foliated.

The plagioclase and quartz are extremely fine-grained and occur in ash and lapilli size fragments. The biotite, chlorite and epidote occur chiefly in the foliation planes wrapping around the ash and lapilli while the amphibole (blue-green hornblende) is in a discrete layer. Traces of garnet, potassium feldspar and tourmaline are disseminated throughout. The opaques are very fine-grained anhedral magnetite and pyrite lying in the foliation planes.

Rhyodacitic lapilli crystal tuff
(Plate 13)
Sample No. 16D from SW 1/4-NE 1/4,
Section 16, T. 159 N., R. 25 W.

Estimated mode:

Plagioclase (phenocrysts)	5	Potassium feldspar	Tr.
Plagioclase (matrix)	50	Biotite	Tr.
Sericite	15	Sphene	Tr.
Quartz	10	Garnet	Tr.
Chlorite	4	Apatite	Tr.
Epidote	5	Opaques	6
Mafic rock fragment	Tr.		

Chemical composition (K. Ramlal, 1978)

SiO_2	65.25	K_2O	2.14
Al_2O_3	17.94	H_2O (+)	(1.21
Fe_2O_3	2.57	H_2O (-)	(
FeO	1.76	CO_2	0.69
MgO	0.90	TiO_2	0.48
CaO	1.11	P_2O_5	0.13
Na_2O	5.57	MnO	0.04

Sample 16D is rusty-brown on a weathered surface and dark gray on a fresh surface. It contains plagioclase phenocrysts to 2 mm. in an aphanitic, foliated groundmass.

Very fine-grained plagioclase and quartz form the matrix for the plagioclase phenocrysts and for ash and lapilli size fragments and as a major constituent of these fragments. The plagioclase is heavily sericitized. The biotite, chlorite, epidote and sericite occur primarily in the foliation planes, but also as disseminations. The traces of apatite, garnet, and sphene are disseminated. The opaques are secondary pyrite which crosscut the foliation planes.

Rhyodacitic intrusive (Plate 14)
Sample No. 73 from SE 1/4-SW 1/4,
Section 8, T. 159 N., R. 25 W.

Estimated mode:

Plagioclase (phenocrysts)	30	Calcite	3-4
Plagioclase (matrix)	30	Epidote	3-4
Quartz (phenocrysts)	8	Apatite	Tr.
Potassium feldspar	Tr.	Sphene	Tr.
Sericite	15	Opaques (pyrite)	1-2

Chemical composition (K. Ramlal, 1978)

SiO_2	71.05	K_2O	2.05
Al_2O_3	15.11	H_2O (+)	(0.80
Fe_2O_3	0.72	H_2O (-)	(
FeO	0.84	CO_2	0.64
MgO	0.68	TiO_2	0.21
CaO	1.86	P_2O_5	0.07
Na_2O	5.80	MnO	0.02

This rock is a light pinkish-gray on a weathered surface and greenish-gray on a fresh surface with phenocrysts of feldspar and quartz to 3 mm. in a very fine-grained to aphanitic matrix. It appears massive in hand specimen.

The heavily sericitized, sheared phenocrysts of plagioclase and quartz are enclosed in a very fine-grained matrix of granoblastic plagioclase, quartz and traces of potassium feldspar. A faint lineation is defined by calcite, chlorite, and epidote which occur as disseminated anhedral grains and as replacement and alteration of plagioclase. Accessory minerals include apatite, sphene, and pyrite in amounts varying from a trace to 1 to 2 percent.

Diabasic gabbro (Plate 16)
Sample No. 34 C from NW 1/4-NE 1/4,
Sec. 21, T. 159 N., R. 25 W.

Estimated mode:

Plagioclase	60	Biotite	Tr.
Pyroxene	30	Quartz	Tr.
Opaques	8	Apatite	Tr.

Chemical composition (K. Ramlal, 1978)

SiO_2	48.65	K_2O	0.28
Al_2O_3	13.58	H_2O (+)	(1.13
Fe_2O_3	3.83	H_2O (-)	(
FeO	11.34	CO_2	0.13
MgO	6.15	TiO_2	1.68
CaO	10.41	P_2O_5	0.13
Na_2O	2.05	MnO	0.24

Sample No. 34C is from the Manitou Rapids dike. It is gray-brown on a weathered surface and dark gray on a fresh surface. It is medium-grained and massive.

Laboradorite plagioclase and pyroxene is a diabasic texture are the major minerals. The pyroxene is clinopyroxene with minor orthopyroxene and has been highly altered to chlorite, epidote and hornblende. Apatite, biotite occur in trace amounts interstitial to the plagioclase and pyroxenes. Anhedral magnetite-ilmenite and traces of chalcopyrite and pyrite are disseminated throughout.

APPENDIX B

THE WRITER'S DRILL LOGS

DRILL HOLE IH-10 (Vertical Hole)

0-20.5 feet	Overburden
20.5-36.5	Fine-grained felsic-intermediate tuff with py and po. Occasionally appears to be either agglomeratic or brecciated with sulfides filling the fractures and lying in foliation planes. Sulfides include both semi-massive and disseminated. The average sulfide content is 40 percent.
36.5-47.1	Becomes more massive, still sligbtly agglomeratic. Sulfides decrease rapidly from 30 to one percent. The angle of the bedding planes to the core axis is approximately 35 degrees.

EOH

DRILL HOLE IH-11 (Vertical Hole)

0-8.7 feet	Overburden
8.7-11.8	Sulfide cemented felsic-intermediate metavolcanic breccia with plagioclase phenocrysts to eight mm. in a very fine-grained matrix. Sulfides have been largely weathered out leaving only a trace of pyrite.
11.8-24.2	Massive, fine- to medium-grained felsic intermediate metavolcanics. Contains disseminated pyrite and pyrrhotite to one to two percent. Pyrrhotite vein at 18.3 feet. There is a faint foliation at 60 degrees to the core axis.

EOH

DRILL HOLE IH-12 (Vertical Hole)

0-17 feet	Overburden
17-20	Fine-grained, dark, gray-green intermediate metavolcanic. Contains biotite, amphibole, plagioclase, and disseminated pyrite cubes to one percent. Calcite filled fractures.
20-24.5	Very fine-grained, light to brownish-gray felsic matevolcanic. Has veins, blebs and disseminated pyrite and pyrrhotite to 15 percent.
24.5-27.5	Fine-grained, grayish-green intermediate metavolcanic containing amphibole, biotite, and disseminated pyrite cubes to five percent.
27.5-33.5	Similar to felsic unit at 20-24.5 feet range. Contains pyrite and pyrrhotite to 15 percent.
33.5-35.8	Fine-grained to very fine-grained metatuff or metasediment. Very thinly bedded. Bedding planes at 30 degree angle to core axis. Contains pyrite to five percent.
35.8-42.0	Similar to 27.5-33.5 unit above. Contains pyrite to five-ten percent.
42.0-42.8	Fine-grained brownish gray-green metasediment with disseminated pyrite to ten percent.

EOH