THE KEWEENAWAN LAVAS IN THE CITY OF DULUTH

A THESIS
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TABLE OF CONTENTS

ABSTRACT

The area of study extends from Mesaba avenue in downtown Duluth, Minnesota, to the Lester River in the east end of the city. The bedrock consists of intrusive and extrusive igneous rocks, along with a small amount of interflow sedimentary rocks. The emphasis of this study is on the extrusive rocks. This sequence of rocks is Keweenawan in age (1100 m.y.), and occurs near the base of the North Shore Volcanic Group. The extrusive rocks are underlain (and intruded) by the Duluth Complex, and are cut by five thick sills (Messabi, Endion, Northland, Lakeside, and Lester River) with a total thickness of 1125 m, and by 36 dikes with a total thickness of 161 m. Thirteen thin (a few cm to four meters) and one thick (34.5 m) interflow sandstone beds (for a total thickness of about 50 m) form the sedimentary part of the sequence.

Extrusive rocks are clearly tholeiitic, with a higher volume of felsic rocks, a higher percentage of potassium and commonly a higher Ti and Fe content than other major tholeiitic series described in the literature. Seventy-six volcanic units were distinguished and mapped; a cross-section profile yields a thickness of 2920 m for these units. Four ignimbrites form 531 m of this thickness, and lava flows comprise the rest. Compositions of the ignimbrites range from rhyolite to icelandite, and they are characterized by a lack of bedding, poor sorting, considerable thickness and great lateral extent of units.

Lava flows of the Duluth area include felsic, intermediate and mafic rocks. Six felsic flows form 637 m of the sequence and range in composition from rhyolite to icelandite, and very commonly contain phenocrysts of feldspar, altered Fe-silicates and magnetite.

Intermediate flows are of andesitic composition and include 32 units forming a total thickness of 1032 m; phenocrysts of plagioclase are common and locally comprise up to 60% of a flow. Mafic lava flows include olivine tholeiite and quartz tholeiite. Olivine tholeiites were formed from a very fluid magma and form nineteen units, with a total thickness ranging from a minimum of 363 m to a maximum of 1086 m. Dark color, mottled appearance and columnar jointing are their field characteristics. Quartz tholeiites form 15 units with a total thickness of 345 m, and commonly have a brecciated (aa type) top. The units are commonly thicker than olivine tholeiite flows. Plagioclase phenocrysts, although not abundant, are present in the majority of quartz tholeiite flows.

The volcanic rocks in the area have undergone varying amounts of hydrothermal alteration, burial and contact metamorphism. Hydrothermal products are manifested as epidote, chlorite, calcite, quartz, feldspar and zeolites in the flows, and have filled the vesicles (now amygdules), joints and other cavities. This sequence of rocks has also been subjected to contact metamorphism of up to pyroxene-hornfels facies, and burial metamorphism (hydrothermal alteration) which locally approaches greenschist facies.

The strike (azimuth) of the volcanic units changes from 140 degrees in the southwestern part of the area to 30 degrees in the northeastern part. Dip is about 30 degrees east in the southwestern part; it changes rather irregularly, but generally decreases toward the east. This implies some subsidence of the Lake Superior basin both during and after volcanic activity, as other investigators have found. A few faults were recognized, generally showing southeast-northwest trends with a nearly vertical dip. Duplication of flows due to faulting was not observed.

ILLUSTRATIONS

PLATE

TABLES

INTRODUCTION

The study area lies within the Duluth quadrangle, the U.S. Geological Survey's 7 1/2 minute series, St. Louis County, Minnesota. The area consists of that part of Duluth underlain by the North Shore Volcanic Group (NSVG). Its southwest limit is the Duluth Gabbro Complex contact near Mesaba Avenue and Sixth Avenue West. In the northeast the boundary is set by the Lester River sill, east of the Lester River, and the northwest the limits follow the intrusive contact with the Duluth Complex. The length of the area is about ten km and the width is about four km at its widest points. The most abundant outcrops are exposed along the shore of Lake Superior, as well as along Chester Creek, Tischer Creek, Amity Creek, the Lester River and also in smaller streams throughout the area. In addition, there are many scattered outcrops and temporary exposures in excavations in other areas throughout the city of Duluth.

The rocks are extrusive rocks, intrusive rocks, and interflow sediments of Keweenawan (Late Precambrian) age, which form part of the lower part of the North Shore Volcanic Group(NSVG) of northeastern Minnesota. Keweenawan volcanism started about 1200-1225 m.y. ago, and continued intermittently, peaking at about 1100 m.y. ago (Silver and Green, 1972; Van Schmus et al., 1982). Volcanism probably occurred in different parts of the Lake Superior region in different times and formed seven or eight overlapping basalt plateaus, each one subsiding centrally (White, 1972; Green, 1977, 1979, 1982). This formed one of the largest bodies of volcanic rocks in North America, covering an area of about $100,000^2$ km.

Purpose of Study

The location of Duluth on the flank of the Lake Superior syncline, the variety of volcanic and intrusive rocks, the good rock exposures, the interflow sediments, and the relationships between these features, make this area critical and interesting. The evidence of events of more than one billion years ago have provoked the curiosity of many geologists for over a hundred years. However, only the Ely's Peak basalts, that portion of the NSVG lying beneath the Duluth Complex southwest of Duluth, has received recent detailed flow-by-flow study (Kilburg, 1972). The objectives of this study are mapping of the location and extent of the outcrops throughout the thesis area, distinction between the extrusive and intrusive igneous rocks and their petrogenetic relations, tracing of flows laterally, determination of chemical and physical characteristics and the classification of the extrusive rocks, the alteration and metamorphism of these rocks, and interpretation of the data. The outcome provides a better understanding of the magmatic and tectonic processes that were operating in this part of the Mid-Continent Rift.

Methods

The field investigations were carried out in the summer of 1979 for nine weeks, plus occasional checking and observation during late 1979 and through 1980. Air photos with the scale of 1/24,000 and 1/4800, and topographic maps with a scale of 1/24,000 were used for location. The outcrops throughout the area were found and mapped precisely, except for the Lester River sill, for which outcrops were mapped by photo geology. Samples were taken from each outcrop, and available field data were recorded. Flow-by-flow mapping, attitude measurement, thickness measurement by the Jacob Staff method, and detailed field descriptions along the shore of Lake Superior, the rivers and other outcrops throughout the area were recorded. Due to the scarcity of outcrops in the eastern part of the area, especially in the Lakeside area of Duluth, a magnetometer was used in an attempt to distinguish individual flow units and to determine the extent of the Northland and Lakeside sills. Hundreds of magnetic measurements were recorded, but they yielded poor results, which was probably due to roughly equal amounts of magnetite in both the extrusive and diabase and, also, the abundance of pipes and electrical wires in this urban area. A paleomagnetic survey at the top and base of the Duluth Complex and the surrounding flows was carried out, and the remanent magnetization as well as secondary magnetization at the contact were studied.

A total of 460 samples of flows and associated rocks were collected, from which one hundred sixty thin sections were made.

In addition, thirty thin sections were made available by Dr. John C. Green. The composition of plagioclase phenocrysts was measured by the Michel Levy method. A Picker X-ray diffractometer was occasionally utilized to identify some obscure minerals. Whole-rock major element analyses (14 elements) were obtained for fifteen samples, representing the various volcanic units in the area. This information combined with other rock analyses available from previous work in the area provide an excellent coverage for the composition of the lava flows and associated rocks.

Previous Work

The earliest geological study of this region was reported in 1852 in an article by Norwood on the geology of the Minnesota coast of the Lake Superior. In 1871, Kloos made a survey in Duluth and vicinity and described different rocks in the region. In 1881, and 1882, N.H. Winchell in two different papers made minor contributions to the geological study of the area. In 1883, Irving reported on the northwest coast of Lake Superior from west of Duluth to Pigeon Point. He described the petrographic character of the rocks in a rather detailed manner, and divided them into six groups:

1) The St. Louis River group
2) The Duluth group
3) The Lester River group
4) The Agate Bay group
5) The Beaver Bay group
6) The Temperance River group

He estimated a total thickness of 6000 meters for all six groups along the shore of Lake Superior. In 1898, Elftman mentioned the possibility of a series of fault belts near the Lake Superior coast and divided rocks exposed in the west coast into the Gabbro member, the Beaver Bay diabase member, the Red Rock member, the Temperance River member, and the Later Diabase member. In 1899, Winchell in Final Report Volume Four devoted a chapter to the rocks of the Duluth area.

At the turn of the century and the early twentieth century, many geologists worked in and wrote about this area. Sandberg (1938) for the first time measured the thickness of intrusives, extrusives and the interflow sediments and then illustrated them in strip maps from Duluth to Two Harbors. His study was informative, but limited to the rocks exposed along the shore of Lake Superior. He described intrusive rocks and interflow sediments, divided the volcanic rocks into ophite, porphyrite, melaphyre and felsic flows, and inferred a westward movement direction for flows in this area. Schwartz (1949), in his book "Geology of Duluth Metropolitan Area", basically represented the ideas and mapping of Sandberg in discussing the flows. In 1963, Taylor published a geological map of Duluth and vicinity at a scale of 1:24,000 which partly covers the area which is the subject of this study, but his report is principally concerned with the Duluth Complex. J.C. Green has been studying the North Shore Volcanic Group since 1965. His work includes reconnaissance in the Duluth area and is published in various articles and guidebooks. In his 1971-1972 publications, he used olivine basalt to roughly replace the previous term of "ophite"; quartz tholeiite, andesitic basalt or trachybasalt rather than "melaphyre";

andesite (trachyandesite and intermediate quartz latite) rather than "porphyrite"; and felsic lava (quartz latite and rhyolite) instead of felsite or acidic lavas. He illustrated and briefly described the lavas of various composition and provided many new analyses of NSVG lavas as well as compiling earlier published analyses. The "Environmental Geology of the North Shore" (Green et al., 1977) contains brief explanations of the origin, rock units, structure and economic geology of the North Shore with maps of the bedrock geology except for the built-up area of Duluth. In another article, (1977), he suggested the existence of seven basalt plateaus in the Lake Superior District. Recently, he has compared different large pre-Tertiary basalt plateaus of the world and surveyed their general characteristics (Green, 1981) including more geochemical and petrologic data on the NSVG.

Currently, Joyce Brannon of Washington University is studying the detailed geochemical stratigraphy of the flow sequence above those of this study, between the Lester River Sill and Two Harbors. Green (1983a) has compiled a regional map of northeastern Minnesota which includes most of the Keweenawan intrusive and volcanic units (Two Harbors 1:250,000 map, Minnesota Geological Survey). Kilburg (1972 Master's thesis, Univ. of Minn.-Duluth) studied in detail the Ely's Peak basalt flows occurring southwest of this study area, around Nopeming. He distinguished and mapped 20 individual flows with a total thickness of 360 m. Jirsa (1980 Master's thesis, Univ. of Minn.-Duluth) has studied the interflow sediments occurring between volcanic rocks of the North Shore Volcanic Group and provides new information regarding this type of rocks and their tectonic interpretation. Green (1982) presented an updated overview of the Keweenawan lavas, and in another paper (1983b), he elaborated on the geological and geochemical evidence for the nature and development of the Keweenawan Midcontinent Rift. Van Schmus et al. (1982) published an article concerning the geochronology of Keweenawan rocks in the Lake Superior region.

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REGIONAL GEOLOGICAL SETTING

The Upper Precambrian (Middle Proterozic) rocks of the Lake Superior district overlie uncomformably the metasedimentary rocks of Middle Precambrian age (Lower Proterozoic). Since this sequence of rock types was first recognized and studied on the Keweenaw Peninsula of Michigan, they are called Keweenawan rocks. The Keweenawan series is composed of three distinct lithologic sequences.

(1) The older rocks of Early Keweenawan age consist of a sedimentary sequence which had been deposited before Keweenawan volcanic activity began. This sequence is found only in a few scattered localities around Lake Superior, where it overlies uncomformably to disconformably the Middle Precambrian (Lower Proterozoic) rocks. Localities include the Nopeming Sandstone west of Duluth, the Bessemer Quartzite in northern Wisconsin and Michigan, the Puckwunge Sandstone in northeastern Minnesota, and perhaps part of the lower Osler Group in northwestern Ontario ; these sedimentary rocks are lithologically equivalent, but this correlation does not imply an exact age equivalence (Ojakangas and Morey, 1982a). They all are quartzite strata with similar structural, lithological and textural characteristics. These sedimentary rocks are composed of red to white, cross-bedded,

relatively mature, sand-sized quartzite with relatively abundant zircon grains. The exact age and precise correlation of these units is still a controversial matter. The time interval between the Middle Precambrian rocks and deposition of these quartzites is hundreds of millions of years in which little is known about geological events in the region.

(2) Overlying the quartzites, or unconformably on Archean rocks elsewhere, are volcanic rocks, their associated intrusions and dike swarms, and minor amounts of interflow sediments. The volcanic sequence is composed of several hundred lava flows. The majority of flows are basalts of various kinds with lesser amounts of andesite and felsite. The volcanic sequence forms a discontinuous rim around Lake Superior and its thickness may locally exceed 10,000 m (Tyler et al. 1940; White, 1960).

(3) The Upper Keweenawan sequence contains the youngest rocks of the Lake Superior basin, consisting of the sedimentary Oronto Group and Bayfield Group and their equivalents (Ojakangas and Morey, 1982b). These rocks are mainly unfossiliferous red feldspathic, lithic, and quartzose sandstone, with minor conglomerate and siltstone. The Oronto Group occurs in northern Wisconsin, western upper Michigan and Isle Royale, consisting of the Copper Harbor Conglomerate, Nonesuch Shale, and the Freda Sandstone (Daniels, 1982).

The Bayfield Group is present in Wisconsin, overlying the Oronto Group, and consists of the Orienta Sandstone, the Devils Island Sandstone, and the Chequamegon Sandstone.

The Upper Keweenawan rocks in eastern Minnesota consist of the Solor Church Formation (equivalent of Oronto Group), the Fond du Lac Formation (equivalent of Orienta Sandstone), and the Hinckley sandstone (equivalent of Devils Island Sandstone) (Ojakangas and Morey, 1982b; Morey and Ojakangas, 1982).

The Jacobsville Sandstone occurs on Keweenaw Bay, Michigan and also at the east end of Lake Superior and beneath Lake Superior, and is considered Upper Keweenawan in age; its relationship to other Upper Keweenawan units is unclear, but is likely to be equivalent of the Bayfield Group (Kalliokoski, 1982).

The Lake Superior basin occupies a syncline which developed during and after volcanism on the Mid-Continent Rift Zone which has been traced from eastern Lake Superior to southeastern Michigan, and from western Lake Superior southwest to southern Minnesota, Iowa, Nebraska and Kansas (White, 1972; Craddock, 1972; Green, 1983b) (Fig. 1). The most conspicuous geophysical feature of the Lake Superior basin is the Mid-Continent Gravity High which is the highest in the United States. The Mid-Continent Gravity High is closely associated with the Mid-Continent Rift and is caused largely by the thick sequences of dense mafic rocks associated with the rift and derived from the mantle.

Recent studies concerning the volcanic rocks of the Lake Superior basin suggest seven, possibly eight separate, but overlapping accumulations, ranging in thickness from 2.5 to over 7 km, and in areal extent from 130 to 250 km in diameter (White, 1972; Green, 1977; 1979; 1982). They were fed by fissures and

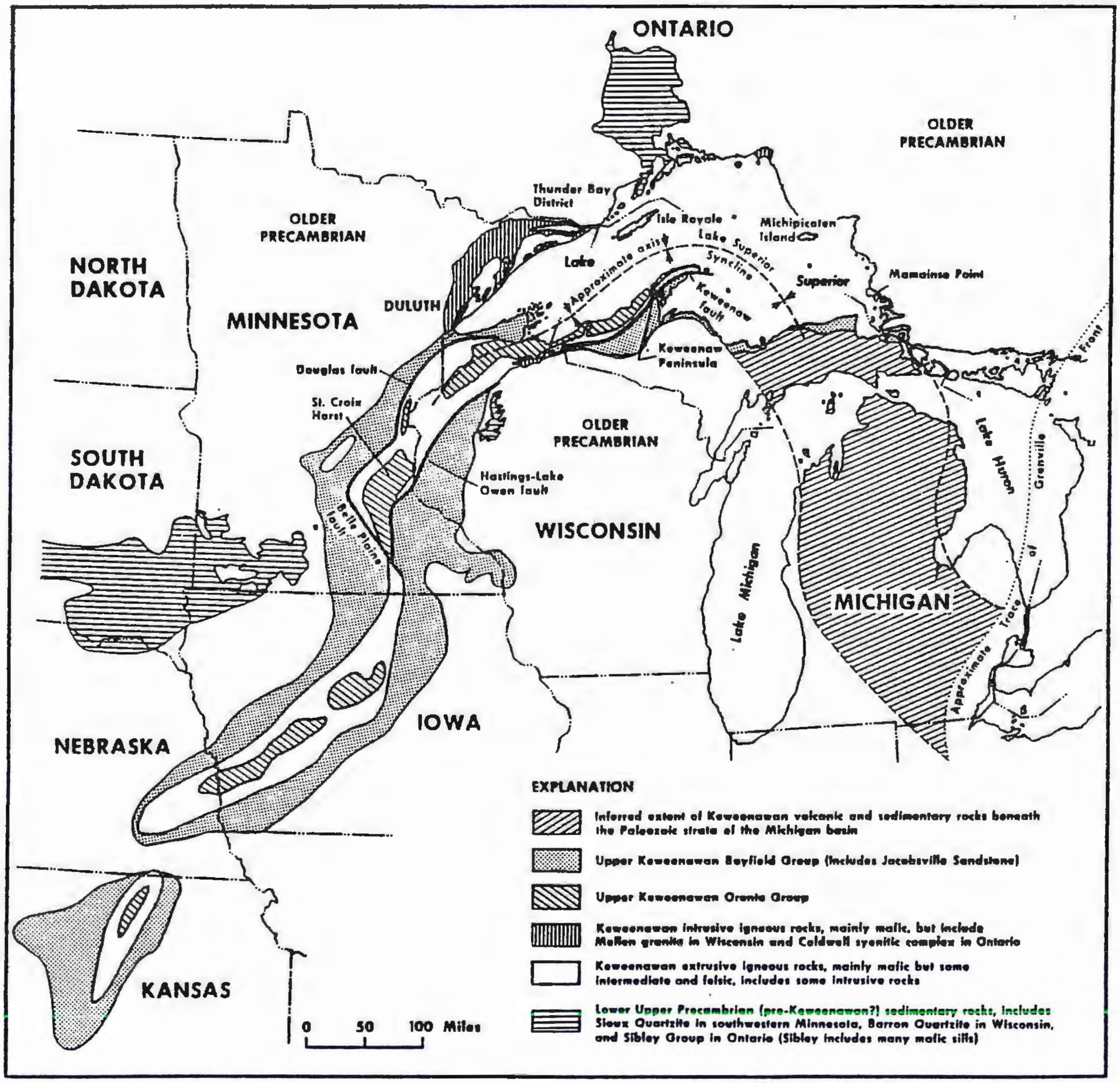


Fig. 1 The inferred extent and generalized geology of Upper Precambrian rocks in the Mid-continent region. From Craddock, 1972

show central subsidence during and after eruption. The accumulations are referred to as plateaus and each consists of hundreds of individual flows. Pillow lavas occur only at the base of some plateaus and almost all the lavas were subaerial (Green, 1972a; 1983b). The thickness of flows varies from less than one meter to more than 400 meters.

Various igneous intrusions including dike swarms, sills, plugs, and large stratiform bodies cut through the volcanic sequence of these accumulations. The composition of the intrusions is mostly mafic, particularly diabase, but some have felsic or intermediate composition. Many dikes show a strike parallel to the axis of the Lake Superior syncline (Green, 1977). The thicker intrusions commonly have metamorphosed the adjacent rocks.

The lava plateaus were partially eroded during intervals between volcanic activity. The eroded material, possibly along with minor sediments from outside of the basin were carried toward the subsiding center by streams, forming interflow sediments (Jirsa, 1980). The interflow sediments are commonly red or buff, rarely gray, and consist primarily of immature sandstone and rarely conglomerate or siltstone. They are typically lenticular in shape with a thickness ranging from a few centimeters to a few meters. A few units up to 80 meters or more thick are present.

In an attempt to more accurately define periods of volcanic activity in this region, radiometric dating has been carried out by several investigators. Although not completely successful, nevertheless, it has shed light on some of the problems. Goldich et al. (1961) determined an age of 1.0 to 1.2 b.y. by applying the K-Ar and Rb-Sr methods to the Duluth Complex in Minnesota. Faure, et al. (1969) determined the ages of 1.115 b.y. for Duluth Complex and 1.092 b.y. for the Endion sill by the Rb-Sr method. Silver and Green (1972) utilizing U-Pb dating of zircon, indicate that both the volcanic and intrusive rocks are 1.12-1.14 b.y. old. Hanson (1975) defined an age of 1.15-1.17 b.y. for the Logan sills by the A_{40}-A_{39} spectrum method. Van Schmus et al. (1982) elaborated on the previous data on the geochronology of Keweenawan rocks, and by considering the paleomagnetic pole position, concluded that Keweenawan volcanic activity started 1.2-1.225 b.y. ago, peaked at 1.11 b.y. ago, and stopped rather abruptly afterward. Other geologists with different methods came up with similar and younger ages for the volcanic rocks and period of volcanic activity. Since Rb-Sr and K-Ar systems can be affected by hydrothermal alteration and low grade metamorphism (Van Schmus et al., 1982), the age obtained by these latter methods should be considered a minimum age.

NORTH SHORE VOLCANIC GROUP AND ASSOCIATED ROCKS

The Keweenawan rocks of the Lake Superior region include a major volume in the northeastern part of Minnesota. They form a rim around the west side of the lake from Duluth to Grand Portage Bay, and extend inland from a few up to 35 km. The volcanic rocks are called the North Shore Volcanic Group (NSVG) (Goldich,et al., 1961). The North Shore Volcanic Group is divided into the southwest limb and the northeast limb.

The southwest limb starts west of Duluth and continues to Tofte in Cook County (Fig. 2). The oldest flows in this limb show a reversed polarity and are exposed at Nopeming ("Ely's Peak basalts"). They conformably overlie the thin quartzite of the Nopeming sandstone, which in turn uncomformably overlies the Middle Precambrian (Lower Proterozoic) Thomson Formation. These flows have a northerly strike and a dip of 10 to 25 degrees to the east. They consist of 20 flow units with a total thickness of 370 meters (Kilburg, 1972). The volcanic rocks above the Duluth Complex become successively younger northeastward toward Tofte. Flows with normal magnetic polarity form all of this part of the limb. The strike (azimuth) of these flows changes northeastward from 140 to 40 degrees and the dip changes from 30 to 12 degrees to the east-southeast with a general decrease in younger flows.

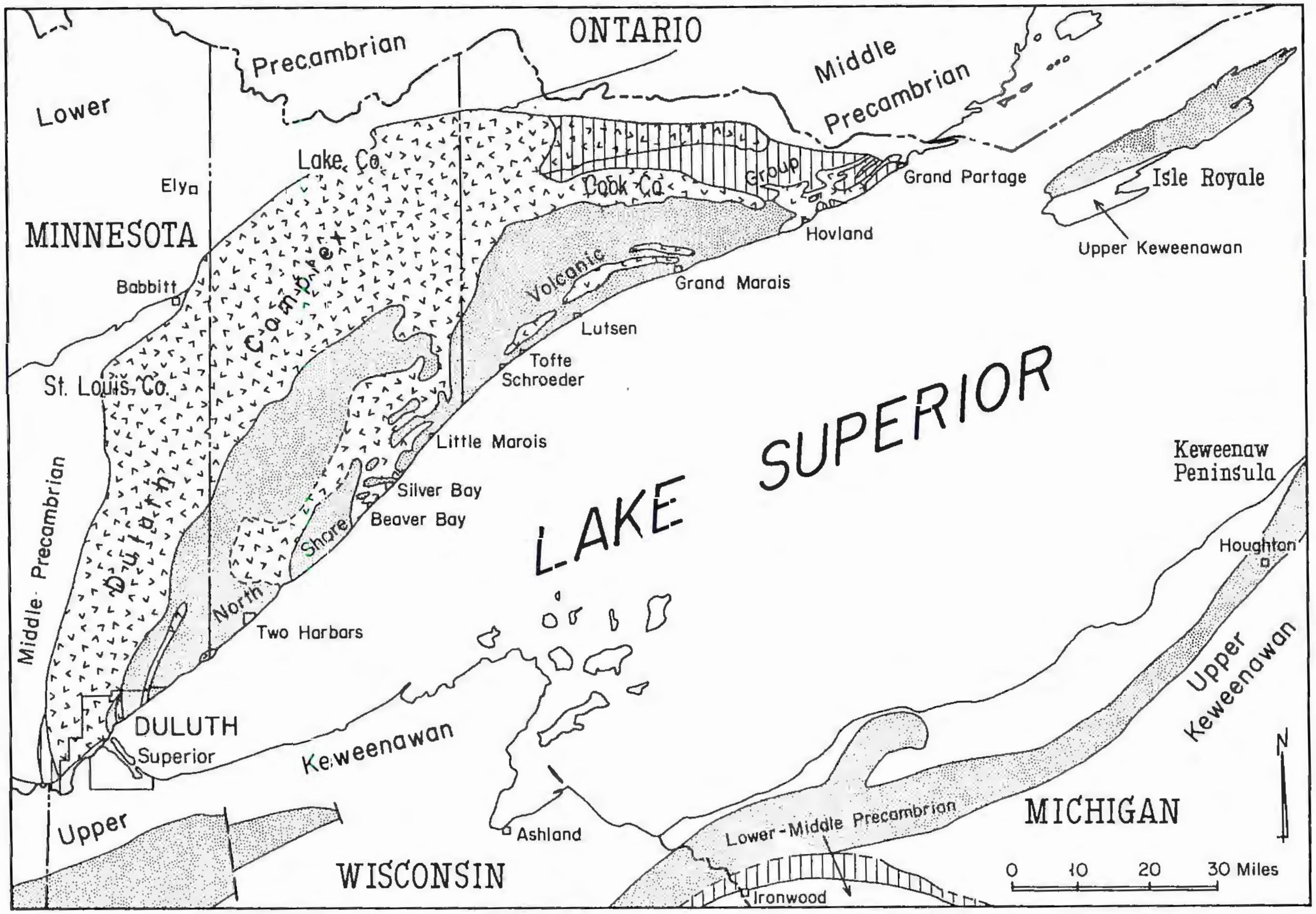


Fig. 2 Generalized geological map of west part of Lake Superior, illustrating the North Shore Volcanic Group and adjacent rocks. Check pattern, intrusive rocks; vertical rule, Lower Keweenawan rocks(magnetically normal and reversed); stipple, Middle Keweenawan lavas(magnetically normal). From Green, 1972a

The northeast limb (Green, 1980) consists of the flows between Lutsen and Grand Portage in Cook County (Fig. 2). The youngest flows in this limb occur near Lutsen, with a strike parallel to the lake shore. The oldest flows are exposed in the Grand Portage-Hovland area and have reversed magnetic polarity. These flows, which form the lower half of the flows in this limb, have a general easterly strike, a dip of about 10 degrees south, and a total thickness of 2.7 to 3 km. The basal flows overlie disconformably the quartzite of the Puckwunge Formation, which itself disconformably lies on top of the Middle Precambrian (Lower Proterozoic) Rove Formation.

The youngest lava on the shore of Lake Superior crops out between the two limbs from Tofte to Lutsen, with a strike parallel to the shore and a dip of about 12 degrees southeast (Fig. 2). According to Green (1977) the basal lavas with reversed polarity exposed on both ends of the section, are part of the "Ironwood - Grand Portage - Nopeming" plateau. The flows with normal magnetic polarity form part of the "North Shore Normal" plateau (Fig. 3). The contact between the two plateaus in Minnesota appears to be occupied by intrusive rocks.

Extrusive Rocks

In early studies only mafic lavas and felsic flows had been described, and intermediate lavas were thought to be lacking (Sandberg, 1938). Later, with more detailed observations and rock analyses of samples from different flows in the area,

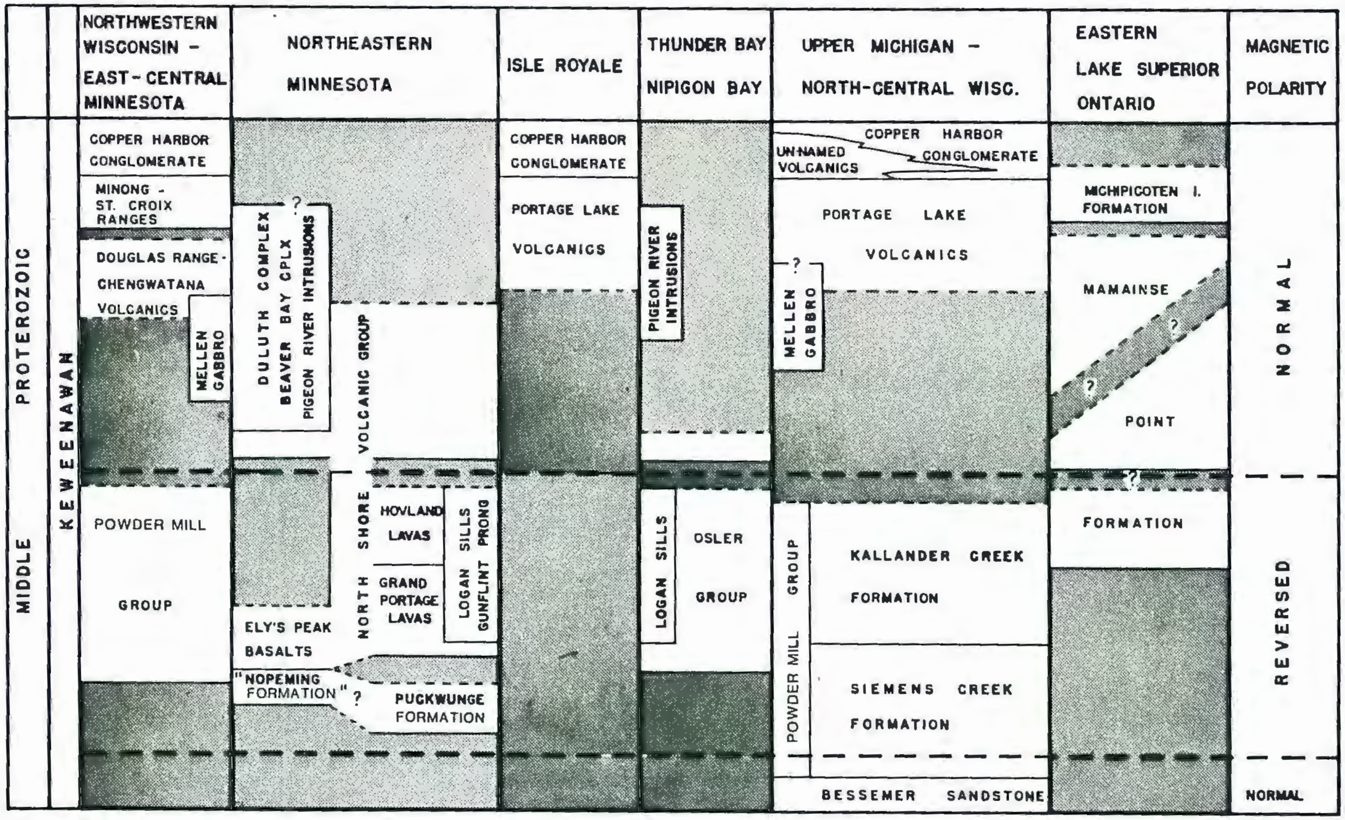


Fig. 3 Proposed stratigraphic correlation of Keweenawan igneous rocks of the Lake Superior. From Green, 1982

existence of intermediate flows, in addition to a complete series of mafic and felsic flows was indicated (e.g. Green, 1972a; 1972b; 1982). The following generalized descriptions are derived from Green (1972a).

Mafic lavas include olivine tholeiite, transitional basalt, and quartz tholeiite with a SiO_2 content ranging from 46 to 52 %, an Al_2O_3 content of 14 to 18.5% and MgO content of 4 to 9%. They are mostly holocrystalline and commonly ophitic or intergranular, and only rarely show porphyritic texture. Their thickness varies from less than one meter to more than 100 meters. The olivine tholeiites commonly have ropy or flat and smooth tops which suggests a very fluid lava. Columnar jointing exists in many of the ophitic basalts. Quartz tholeiites may show rubbly or aa tops.

Intermediate lavas vary in composition from basaltic andesite to trachyandesite. The phenocrysts are plagioclase, augite, magnetite and rarely olivine. The SiO_2 content ranges from 52 to 58%, the Al_2O_3 content is 10.6 to 16.6%, and the MgO content varies from 0.8 to 4.5%. The thickness of individual flows ranges from 15 to 170 m, typically with a scoriaceous top and a gray to dark brown color.

Felsic rocks range from dacite and icelandite, through quartz latite to rhyolite, and include felsic lava flows and ignimbrite. Felsic rocks are anomalously abundant and form about 25% of the sequence in the northeastern limb (Green, 1972b), and in the Duluth area (this study). They form thicker flows than the intermediate and mafic lavas. The thicknesses range from 15 to 400 meters, with a vesicular, banded or wrinkled surface, abundant jointing, and pink to brown color. Most felsic rocks are porphyritic, with phenocrysts of feldspar and/or quartz. The felsic rocks are composed of 62 to 78% SiO_2, 11.0 to 12.8% Al_2O_3, and 0.1 to 0.7% MgO. Some of these felsic rocks show considerable lateral extent: one unit near Grand Marais, Cook County, has been traced over 36 km (Green, 1972a).

Intrusive Rocks

The Duluth Complex is the largest intrusive body in the Lake Superior region. It forms a belt from Duluth nearly to Grand Portage and was intruded mostly along the uncomformity between the Middle and Upper Precambrian rocks. Locally it is found between the reversed and normal polarity Keweenawan extrusive rocks. It shows normal magnetic polarity, except in the northeastern part in the Gunflint prong which has a reversed polarity. The other large intrusive complex in the area is the Beaver Bay Complex, intruded into the younger flows in a higher level of the sequence (Fig. 2).

There are also many sills and dikes in the southwest and northeast limbs. The Messabi sill, Endion sill, Northland sill, Lakeside sill, Lester River sill, Stony Point-Knife Island sill, the Silver Creek Cliff sill, and Lafayette Bluff sill are all in the southwest limb with a combined thickness of 1750 m. Between Tofte and Lutsen there is one large sill (Leveaux porphyry) and an assemblage of several small sills. The Grand Marais intrusion, the Hovland diabase, the diabases of the Cook County Complex, the Reservation River diabase, and the Grand Portage dike swarm are the major intrusives in the northeastern limb (Green, 1972a).

Whether or not all these intrusions are related to the Duluth Complex is still obscure. Grout (1918) in an analysis of the Duluth Gabbro, the diabase sills and their associated red rocks found that the Duluth Gabbro had less silica than the diabase sills and that the red rock in the gabbro had more silica than that of the red rock of the sills. He concluded that the sills are not offshoots of the Duluth Complex, but are later intrusives of a less differentiated magma which crystallized faster due to their lesser thickness. There are also many smaller dikes a few cm to 50 m thick (Green, 1972a; 1972b; 1977; this study) cutting through the flows, commonly with a steep dip and a strike parallel to the regional trend of the base of the Duluth Complex.

Red Rock

The "red rocks", granitic rock or granophyres, are brick red, massive, fine to medium-grained, commonly porphyritic, and granitic in composition. They have been found in various provinces of the Keweenawan sequence, and similar rocks are also known in many other places around the world (Wager and Brown, 1967; Ernst, 1960; Leighton, 1954; Grout et al. 1959; Taylor, 1964). The close association of red rock and diabase or gabbroic rock has been noticed in most exposures.

Interflow Sedimentary Rocks:

The interflow sediments have a combined thickness that is 91.5m thick on the southwest limb and 152.5m on the northeast limb (Sandberg, 1938; Schwartz, 1949; Jirsa, 1980; Merk and Jirsa, 1982). They make up one to three percent of the rocks of the North Shore Volcanic Group (Green, 1972a; 1972b). They commonly form lenticular bodies a few centimeters to a few meters thick, but some were found to have thicknesses of five to ten meters. Three large units of interflow sediments possess thicknesses of 30.5, 34.5, and 85 meters (Jirsa, 1980; this study). These rocks are red to brown, relatively soft, and consist of lithic arkose or feldspathic lithic arenite. Tabular and trough crossbedding, planar bedding, and ripple marks are common sedimentary structures. Grain size varies between 1/4 and one mm in diameter in the sandy beds. The grains are predominantly plagioclase and volcanic rock fragments. The opaque minerals are a minor constituent, and quartz, pyroxene, and shale fragments are locally present as clasts. The source of the interflow sediments is predominantly Keweenawan extrusive rocks, but some of the Middle Precambrian rocks possibly contributed a minor portion. The vast majority of the sediments were deposited in a fluvial environment, and paleocurrent data (Jirsa, 1980) show a direction of movement toward the present basin of Lake Superior (Fig.4).

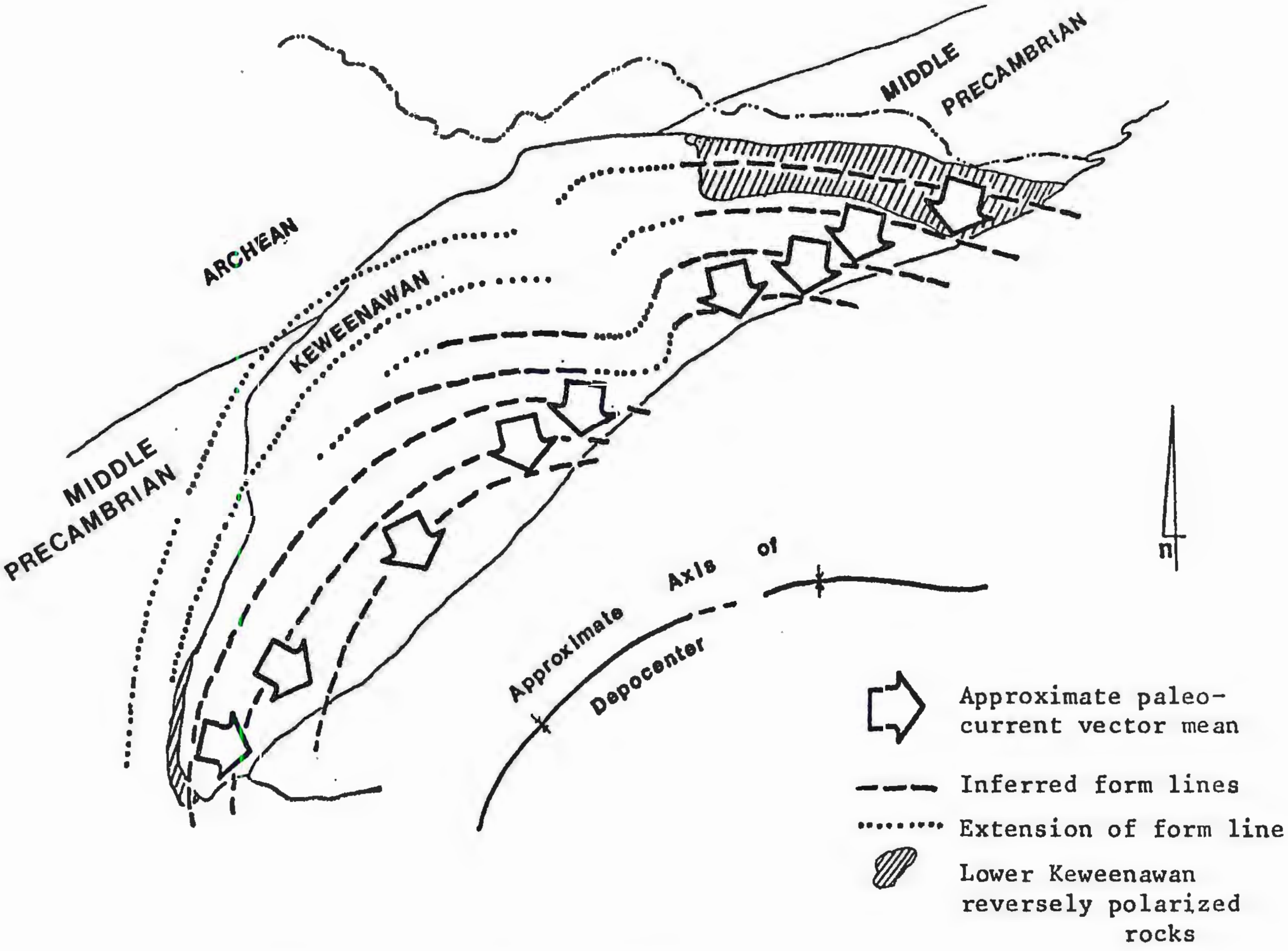


Fig. 4 The source regions, direction of transport, and basin form of the interflow sediments in the North Shore Volcanics of Lake Superior. From Jirsa, 1980

FIELD RELATIONS AND PETROLOGY

Introduction

The rocks mapped in the Duluth area occur stratigraphically in the lower part of the North Shore Volcanic Group consisting of the "Leif Erickson Park lavas" and "Lakeside lavas" of Green 1972a; 1972b. They include lava flows, sills, dikes, and a small amount of interflow sedimentary rocks. In this study this sequence of rocks, particularly the extrusives, is the subject of petrological, mineralogical and chemical investigation. The texture of the rocks is described and ignimbrites and lava flows are classified according to various methods suggested or used by different workers in recent years. Furthermore, the composition and characteristics of the flows in the study area are compared with other flows of the Lake Superior district as well as some other lava plateaus throughout the world.

The extrusives, particularly felsic flows, have been considerably altered, and lavas adjacent to the Duluth Complex have been metamorphosed. These phenomena and the intensity of their effects on the flows of the area are discussed and illustrated.

Composition and Classification of Rock Types

The chemical compositions of 15 representative flows of the study area were obtained and are shown in Table 1, along with chemical compositions of five other rocks of this area found in the literature. They represent a wide range of composition. The CIPW norms of these rocks appear in Table 2. The method of classification of volcanic rocks and the criteria used for this purpose differ from one author to another. In recent years classification of igneous rocks, particularly extrusives, has been based on modal mineralogy, various aspects of the chemical composition, geological environment of rock formation, or a combination of some or all of these. In general, although features such as color, texture, and mineralogy of volcanic rocks are sporadically used as criteria, the classification of volcanic rocks based solely on their chemical composition is found to be more accurate and useful, and has been in general use, particularly during the last three decades. In this study, an effort has been made to classify the flows based principally on their chemical composition, but also considering the texture and mineralogy of these rocks.

The chemical classification guide for the common volcanic rocks proposed by Irvine and Baragar (1971), referred to below as I&B, is the most applicable to the sequence of volcanic rocks of the study area, but it has some limitations and shortcomings. For example, the Na_2O and CaO, which are the main factors in classifying rocks based on their normative plagioclase composition, as well as K_2O which is one of the essential oxides in I&B's scheme all are susceptible to metasomatism in burial-metamorphosed rocks like these. In fact, they are the most mobile major components. Church (1975) and Jensen (1976) refer to some other problems involved with the I&B method. They point out

Table 1 : Chemical Analyses of Volcanic Rocks in the Duluth Area

Listed in Order of Increasing SiO_2

A - Major Elements (Weight%)

OXIDE	LEP-36*	LEP-5	LEP-34	LEP-2	LS-19	D-9a	LS-28	LEP-25	LEP-43	D-30	LS-2	LS-9	D-28	LS-10	M-4600	LS-6	LS-12	LS-1	LS-7	S&S-1-7
SiO_2	45.50	46.50	47.10	47.30	47.40	48.95	49.10	49.80	50.30	50.40	53.60	56.50	63.45	64.70	64.95	65.80	66.10	72.90	73.60	75.48
TiO_2	3.59	0.95	1.71	2.91	2.90	3.48	3.51	4.23	2.37	2.92	2.26	1.97	0.69	0.77	0.82	0.67	0.61	0.35	0.21	0.21
Al_2O_3	14.30	15.80	14.70	13.30	14.70	12.14	12.70	12.70	13.70	15.01	15.20	12.50	12.80	11.90	12.58	12.30	12.00	12.30	11.70	12.30
Fe_2O_3 ---- FeO	15.50@	11.30	12.10	15.30	12.30	7.02 ---- 7.88	14.50	15.60	13.40	6.33 ---- 6.92	10.10	10.40	3.75 ---- 7.40	7.55	4.70 ---- 4.83	6.98	6.67	2.64	3.71	2.54 ---- 0.36
MnO	0.22	0.18	0.19	0.22	0.18	0.18	0.22	0.26	0.27	0.20	0.23	0.18	0.18	0.13	0.16	0.09	0.10	0.04	0.01	0.02
MgO	5.20	7.83	7.13	5.33	5.20	5.15	4.79	3.76	5.38	4.11	3.66	1.87	1.48	0.21	0.93	0.26	0.05	0.10	0.07	0.001
CaO	8.97	9.64	8.84	9.83	8.50	5.92	4.75	3.70	5.64	4.20	3.14	4.22	1.79	3.05	2.07	1.88	2.54	0.49	0.29	0.14
Na_2O	2.59	3.14	3.07	2.48	2.74	3.20	3.27	3.10	3.28	4.36	3.79	2.74	3.22	2.16	3.46	2.59	3.46	3.06	2.08	3.43
K_2O	1.12	0.42	1.06	0.66	1.23	2.19	2.33	2.52	2.01	2.08	3.06	3.41	3.94	4.49	4.21	5.48	4.53	5.86	5.78	5.17
P_2O_5	0.50	0.10	0.14	0.34	0.54	0.69	0.84	0.64	0.32	0.51	0.38	0.71	0.15	0.12	0.15	0.08	0.08	0.03	0.01	0.02
L.O.I. H_2O ---- CO_2	1.00	2.92	3.15	0.38	2.54	2.88 ---- 0.21	2.92	2.23	2.31	2.77 ---- 0.15	3.31	4.77	0.81 ---- 0.00	3.77	0.86 ---- 0.03	2.38	2.46	0.92	0.92	0.28 ---- 0.0
TOTAL	98.49	98.78	99.19	98.05	98.23	99.89	98.93	98.54	98.98	99.96	98.73	99.27	99.66	98.85	99.75	98.51	98.60	98.69	98.38	99.95
Mg' = MgO/[MgO +0.9(FeO +2Fe₂O₃)] Mol.	0.40	0.58	0.54	0.41	0.46	0.42	0.40	0.32	0.44	0.39	0.42	0.26	0.21	0.05	0.17	0.07	0.01	0.07	0.04	0.0

B - Trace Elements (Data in P.P.M.)

	LEP-36*	LEP-5	LEP-34	LEP-2	LS-19	D-9a	LS-28	LEP-25	LEP-43	D-30	LS-2	LS-9	D-28	LS-10	M-4600	LS-6	LS-12	LS-1	LS-7	S&S-1-7
Cr_2O_3	90	230	270	140	140	-	60	40	110	-	50	<10	-	10	-	<10	<10	<10	<10	-
Zr	250	50	100	200	300	-	440	340	180	-	430	640	-	1080	-	880	1000	440	410	-
Sr	200	220	470	250	230	-	250	260	250	-	300	100	-	70	-	70	50	30	20	-
Rb	30	<10	10	20	50	-	70	80	50	-	120	110	-	150	-	190	140	240	220	-

- Blank = not detected
- - = data not available
- @ = total iron content is reported as FeO
- * : Explanation of Samples Follows:

Table 1 continued**

1 - Sample LEP-36: Olivine Tholeiite, about 1 km N.W. of center a of section of 11, T.50N., R.14W.; Hartley Park, Duluth

2 - Sample LEP-5: Olivine Tholeiite, 8th St. and 2nd Ave. E., Duluth

3 - Sample LEP-34: Olivine Tholeiite, the shore of Lake Superior, below the stage of Leif Erickson Park

4 - Sample LEP-2: Olivine Tholeiite, Central Entrance and Clearwood Drive, N.E. of Central High School, Duluth

5 - Sample LS-19: Olivine Tholeiite, Amity Creek and 50 m S.E. of continuation of Avondale St., Duluth

6 - Sample D-9a: Quartz Tholeiite, 900 m north of shore of Lake Superior in Lester River, Duluth;
(J.C. Green, unpublished data, K. Ramlal analyst, 1972)

7 - Sample LS-28: Quartz Tholeiite, Lester River, 100 m S.E. of rail road bridge, Duluth

8 - Sample LEP-25: Quartz Tholeiite, the shore of Lake Superior, between 7th and 8th Ave. E., Duluth

9 - Sample LEP-43: Quartz Tholeiite, the shore of Lake Superior, between 14th and 15th Ave. E., Duluth

10 - Sample D-30: Porphyritic Quartz Tholeiite, 1st St. and 6th Ave. E., below Miller Hospital, Duluth;
(J.C. Green, unpublished data, K. Ramlal analyst, 1972)
11 - Sample LS-2: Andesite, the shore of Lake Superior between continuation of 33rd and 34th Ave. E., Duluth

12 - Sample LS-9: Trachyandesite, the shore of Lake Superior and foot of 45th Ave. E., Duluth

13 - Sample D-28: Icelandite or Quartz Latite, 8th St. and 3rd Ave. W., Duluth (same location as sample M-4600)
(Green, 1972a, Table V-3C, K. Ohta analyst)
14 - Sample LS-10: Icelandite, the shore of Lake Superior, between 46th and 47th Ave. E., Duluth

15 - Sample M-4600: Icelandite (Quartz Latite or Dellenite), 8th St. and 3rd Ave. W., Duluth;
(average of two closely agreeing analyses, Taylor, 1964, Table 17, p.54; Smith and Goldich analysts)

16 - Sample LS-6: Icelandite or Quartz Latite, The shore of Lake Superior, 100 m west of foot of 40th Ave. E., Duluth

17 - Sample LS-12: Quartz Latite, the shore of Lake Superior, 50 m east of continuation of 50th Ave E., Duluth

18 - Sample LS-1: Rhyolite (Quartz Latite), the shore of Lake Superior and foot of 26th Ave. E., Duluth

19 - Sample LS-7: Rhyolite, the shore of Lake Superior and foot of 43rd Ave. E., Duluth

20 - Sample S&S-1-7: Rhyolite, Tischer Creek, near 2nd St., Duluth;
(Schwartz and Sandberg, 1940, Table 1, no 7; S.S. Goldich analyst)

** - analyses 1, 2, 3, 4, 5, 7, 8, 9, 11, 12, 14, 16, 17, 18, and 19 are the rock samples analysed
for this study by X-Ray Assay Laboratories Limited, Don Mills, Ontario, 1980.

Table 2 : CIPW norms of Volcanic Rocks in the Duluth Area

in Order of Increasing SiO_2 (H_2O and CO_2 are excluded)

		LEP-36	LEP-5	LEP-34	LEP-2	LS-19	D-9A	LS-28	LS-1	LEP-43	D-30	LS-2	LS-9	D-28	LS-10	M-4600	LS-6	LS-12	LS-1	LS-7	S&S-1-7
QUARTZ		-	-	-	0.34	0.20	0.32	1.18	4.49	-	-	4.42	14.58	18.25	26.84	19.43	23.47	22.45	30.92	37.61	34.20
ORTHOCLASE		6.79	2.59	6.52	3.99	7.60	13.37	14.34	15.46	12.29	12.29	18.95	21.39	23.56	27.91	25.14	33.69	27.85	35.42	35.05	30.65
ALBITE		22.49	26.49	27.05	21.49	24.23	27.97	28.82	27.24	28.71	38.02	33.61	24.53	27.56	19.22	29.59	22.80	30.45	29.48	18.06	29.12
ANORTHITE		24.71	28.98	24.16	23.76	25.27	12.70	13.64	13.81	17.30	15.71	13.98	12.39	8.09	10.01	6.43	5.98	3.99	2.31	1.42	0.58
CORUNDUM		-	-	-	-	-	-	-	-	-	-	0.80	-	0.31	-	-	-	-	0.10	1.56	0.85
NEPHELINE		-	0.66	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DIOPSIDE	EN	3.47	4.82	4.78	4.64	3.35	2.76	1.13	0.23	1.96	0.51	-	0.71	-	0.14	0.20	0.11	0.06	-	-	-
	FS	3.87	3.29	3.52	5.34	2.94	2.76	1.25	0.33	2.02	0.59	-	1.60	-	2.27	0.91	1.38	4.01	-	-	-
	WO	7.42	8.48	8.62	10.07	6.46	5.62	2.41	0.56	4.05	1.12	-	2.23	-	2.16	1.03	1.35	3.60	-	-	-
HYPERSTHENE	EN	5.52	-	0.99	8.95	10.18	10.49	11.30	9.49	11.84	7.18	9.55	4.21	3.73	0.41	2,14	0.56	0.07	0.25	0.18	0.0
	FS	6.14	-	0.73	10.30	8.93	10.50	12.55	13.74	12.21	8.26	10.40	9.46	13.20	6.85	9.79	6.97	4.06	2.96	4.56	3.10
OLIVINE	FO	3.01	10.87	8.91	-	-	-	-	-	0.04	2.00	-	-	-	-	-	-	-	-	-	-
	FA	3.68	8.17	7.24	-	-	-	-	-	0.05	2.53	-	-	-	-	-	-	-	-	-	-
MAGNETITE		5.13	3.80	4.06	5.05	4.14	4.73	4.87	5.22	4.47	4.19	3.41	3.55	3.51	2.56	2.95	2.34	2.24	0.87	1.23	0.86
ILMENITE		7.00	1.88	3.38	5.66	5.76	6.83	6.94	8.34	4.66	5.71	4.50	3.96	1.33	1.54	1.57	1.32	1.21	0.68	0.41	0.40
APATITE		1.12	0.23	0.32	0.76	1.23	1.56	1.91	1.45	0.72	1.15	0.87	1.64	0.33	0.28	0.55	0.18	0.18	0.07	0.02	0.04
TOTAL		100.36	100.26	100.28	100.35	100.29	99.60	100.34	100.36	100.31	99.64	100.24	100.25	99.86	100.18	99.73	100.16	100.16	100.06	100.08	99.80

that, since the I&B classification is primarily based on the alkali, silica and calcium content of rocks, which show only minor change in a wide variety of mafic rocks, this method cannot be very discriminating among such rocks. Also, the fact that a small error in Na_2O and CaO is magnified in the final results, makes this method less reliable.

In this study, the Irvine and Baragar classification method (1971) has been widely used. However, due to the above deficiencies, in some instances other methods are found to be more suitable or as suitable. These methods are also discussed, and flows are categorized accordingly. The following classification methods are considered in final assignment of flows in the thesis area:

- Color Index
- Saturation in SiO_2 and Al_2O_3
- Subalkaline vs. Alkaline rocks

Color Index

Color index refers to relative abundance of mafic (ferromagnesian) rock forming minerals. Following Irvine and Baragar (1971) the amount of anorthite and apatite are excluded from the norm, and the remaining minerals are brought up to 100%. The color index is obtained by subtracting the percentage of the salic minerals (qz, ab, or, lc, ne, tks) in each sample from the adjusted total, and represents the percentage of mafic minerals. Color index of flows based on their norms is listed in Table 3.

Table 3: Color index of volcanic rocks in the Duluth area

Sample Number	Color Index	Sample Number	Color Index
LEP-2	66	LS-2	33
LEP-36	61	LS-9	29
LEP-5	58	D-28	24
LS-19	57	M-4600	20
LEP-34	56	LS-10	18
D-9a	51	LS-12	16
LEP-43	50	LS-6	15
LS-28	48	LS-7	8
LEP-25	45	LS-1	5
D-30	39	S&S-1-7	5

Saturation of SiO_2 and Al_2O_3

Classification of igneous rocks based on their saturation in SiO_2 and Al_2O_3 has been used by many geologists. Five of the flows in the thesis area for which analyses were obtained are presently peraluminous by molecular proportions. The amount of their Al_2O_3 exceeds the total amount of ($CaO + Na_2O + K_2O$), and corundum appears in their norms. It is probable that their original compositions have been subjected to some alteration, for example partial alteration of feldspars to clay minerals, particularly kaolinite, which can be seen in thin sections. The loss of alkalis relative to alumina associated with such alteration leads to a spurious peraluminous effect.

The ratios of Fe_2O_3/FeO can appreciably affect the norm, and may also be critical in classification of the rocks (Irvine and Baragar, 1971, p. 526). In case of oxidation Fe_2O_3/FeO ratios increase, and as a result, the analyses yield a more silica-saturated norm. Since oxidation is more common than reduction, a variable upper limit for the amount of Fe_2O_3 in various rocks has been set by some geologists. Chayes (1966), for example, rejected analyses with Fe_2O_3/FeO ratios greater than 0.60. Irvine and Baragar (1971), (considering that in unaltered volcanic rocks, Fe_2O_3 and TiO_2 generally have similar trends) used the equation ($\% Fe_2O_3 = \% TiO_2 + 1.5$) to set the upper limit of Fe_2O_3. If the amount was greater than this, the "excess" was converted to FeO.

In the new analyses for this study the total iron content is reported as FeO. After determination of molecular proportion this total iron was apportioned to Fe_2O_3 and FeO, using the following equations:

$$\text{Mol. Prop.}\quad Fe_2O_3 = 0.1\ (2Fe_2O_3 + FeO)$$
$$FeO = 0.8\ (2Fe_2O_3 + FeO)$$

Furthermore, the use of the Jensen ternary cation plot in this study, as a means of classification, which involves Al_2O_3, MgO, and combined $FeO + Fe_2O_3 + TiO_2$, will minimize any error in classification due to possible change in Fe_2O_3/FeO ratios.

Silica-oversaturated rocks show quartz in their norm (Table 2). As can be seen from the table the majority of flows are over saturated in silica. In silica-saturated rocks neither quartz nor unsaturated minerals (e.g. leucite, nepheline, or olivine) are present in the norm. Although none of the samples are actually in this class, samples D-9a, LS-19, LEP-2, and LEP-43 are very close to the boundary line. Undersaturated rocks contain normative olivine and hypersthene, and in critically undersaturated rocks a feldspathoid mineral appears in the norm along with olivine. Although sample LEP-5 falls in this category, the amount of normative Ne (0.66%) is so small that it may result from analytical error or alteration. No modal nepheline has been identified petrographically.

Subalkaline Vs. Alkaline Rocks

For dividing the flows into the two subdivisions of subalkaline and alkaline rocks, the following method was chosen:

A tetrahedron system (Cpx-Ol-Ne-Q) which is based on the minerals present in the norm. This diagram was used by Yoder and Tilley (1962) and has been commonly applied to volcanic rocks, particularly the basaltic rocks. Contents of the tetrahedron are projected from Cpx onto the basal triangle Ol'-Ne'-Q'. The dividing plane between two fields is called "The Critical Plane of Silica Undersaturation" and separates the rocks with nepheline (alkaline rocks) from the rocks with orthopyroxene in the norm (subalkaline or tholeiitic). The divide is an internal plane of clinopyroxene (Cpx), olivine (Ol), and albite (Ab) and coincides roughly with a low-pressure liquidus thermal divide that separates the subalkaline from alkaline lavas. Poldervaart (1964), by considering the positions of major volcanic suites on the diagram, stated that the proper dividing plane of these two fields should be slightly on the Opx normative side of Yoder and Tilley's plane. He suggested that a better divide would pass from the Cpx - Ol edge of the tetrahedron, to the opposite side at nepheline (Ne)47, Quartz (Q)53. I&B (1971) proposed a dividing plane which started at Ne45, Q55 at the bottom of the

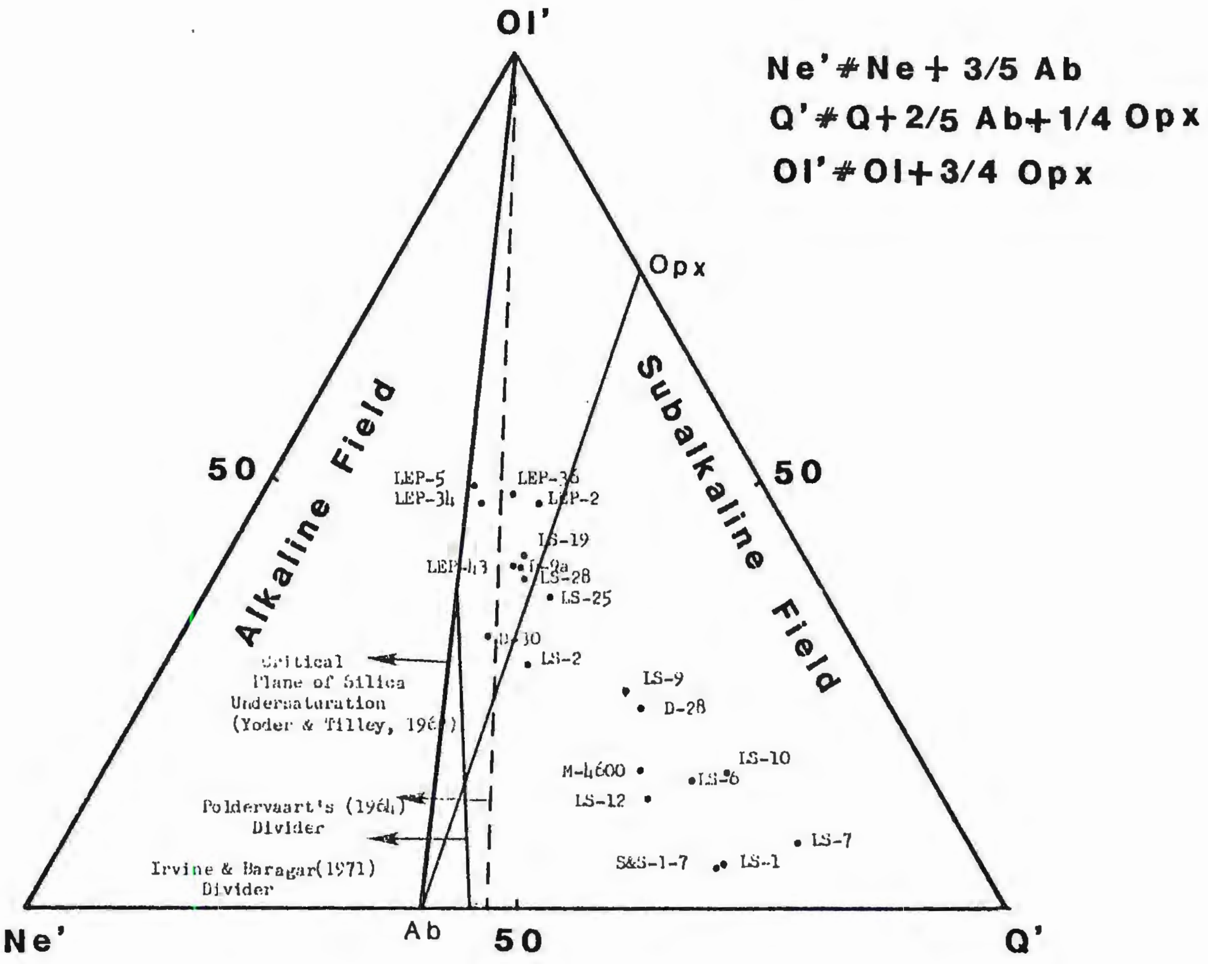


Figure 5: Proposed Dividing Planes Between Alkaline and Subalkaline Fields on a Tetrahedron System based on CIPW Norms of Rocks. Contents of Tetrahedron are Projected from Cpx on to the Basal Triangle Ol'-Ne'-Q'

tetrahedron and joins the Yoder and Tilley dividing line at about 63% Ol (Fig. 5). As illustrated in the figure, the dividing plane separates the critically undersaturated rocks with Ne in their norm, the silica undersaturated rocks (with Opx and Ol), and the silica oversaturated rocks which show (Opx and Q) in their norms. Samples of lava flows of the Duluth area all fall in the subalkaline field of the tetrahedron in Fig. 5 (I&B,1971 divider).

Classification of Subalkaline Volcanic Rocks

Within the subalkaline group, an AFM diagram can be employed to separate calc-alkaline and tholeiitic rocks, (according to I&B, 1971; Jensen, 1976). The positions of samples of the study area appear in Figure 6.

Irvine and Baragar (1971) also chose a different method in classifying subalkaline extrusives. Considering the chemical composition of several major volcanic suites throughout the world, the calc-alkaline series appeared to be generally richer in Al_2O_3 than the tholeiitic series (16 to 20% vs. 12 to 16%). Irvine and Baragar used the percent of Al_2O_3 of rocks vs. their normative plagioclase compositions. The categorization of flows in the study area based on this method is shown in Figure 7. In the felsic rocks ($SiO_2 > 62\%$), this method is imprecise and use of the AFM diagram is recommended. However in separation of rhyolitic rocks both methods fail to precisely discriminate.

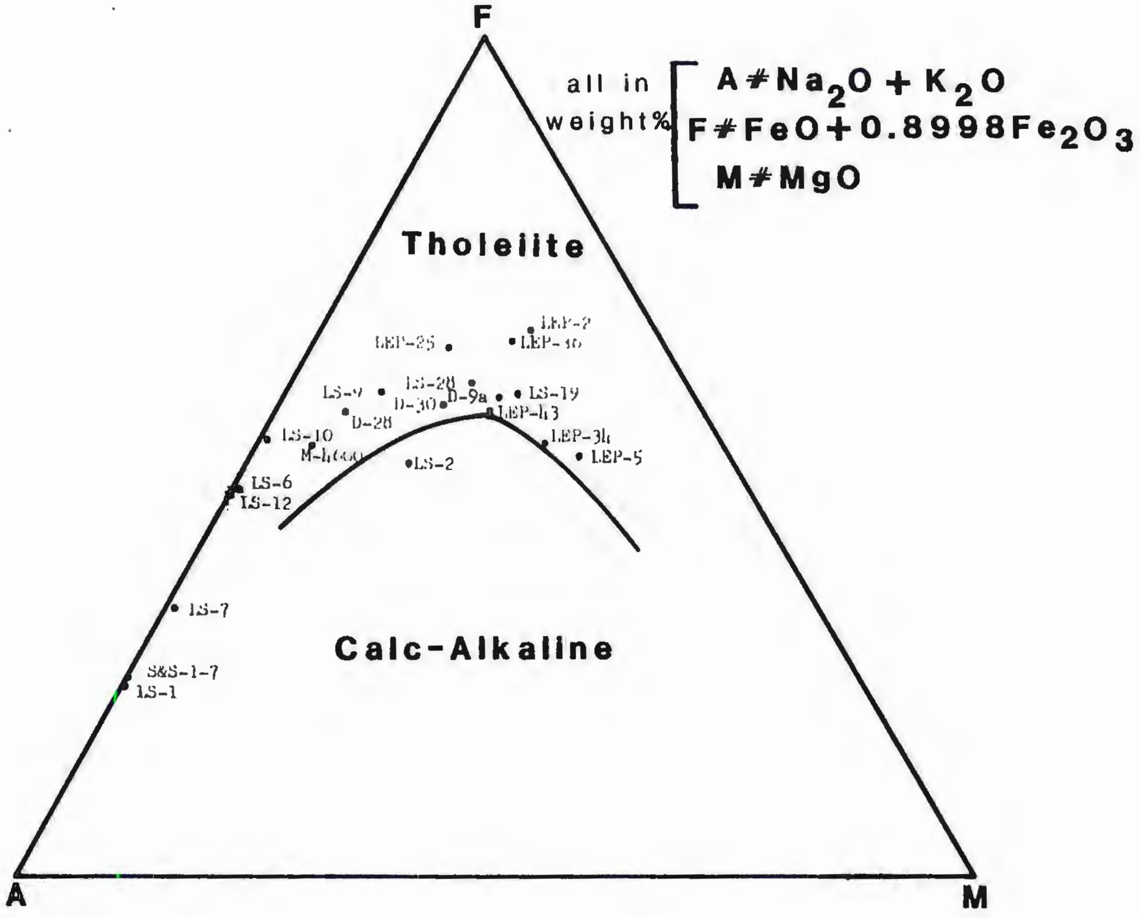


Figure 6: AFM Diagram and Tholeiite VS. Calc-alkaline Fields, showing compositions of the analyzed samples from the Duluth area.

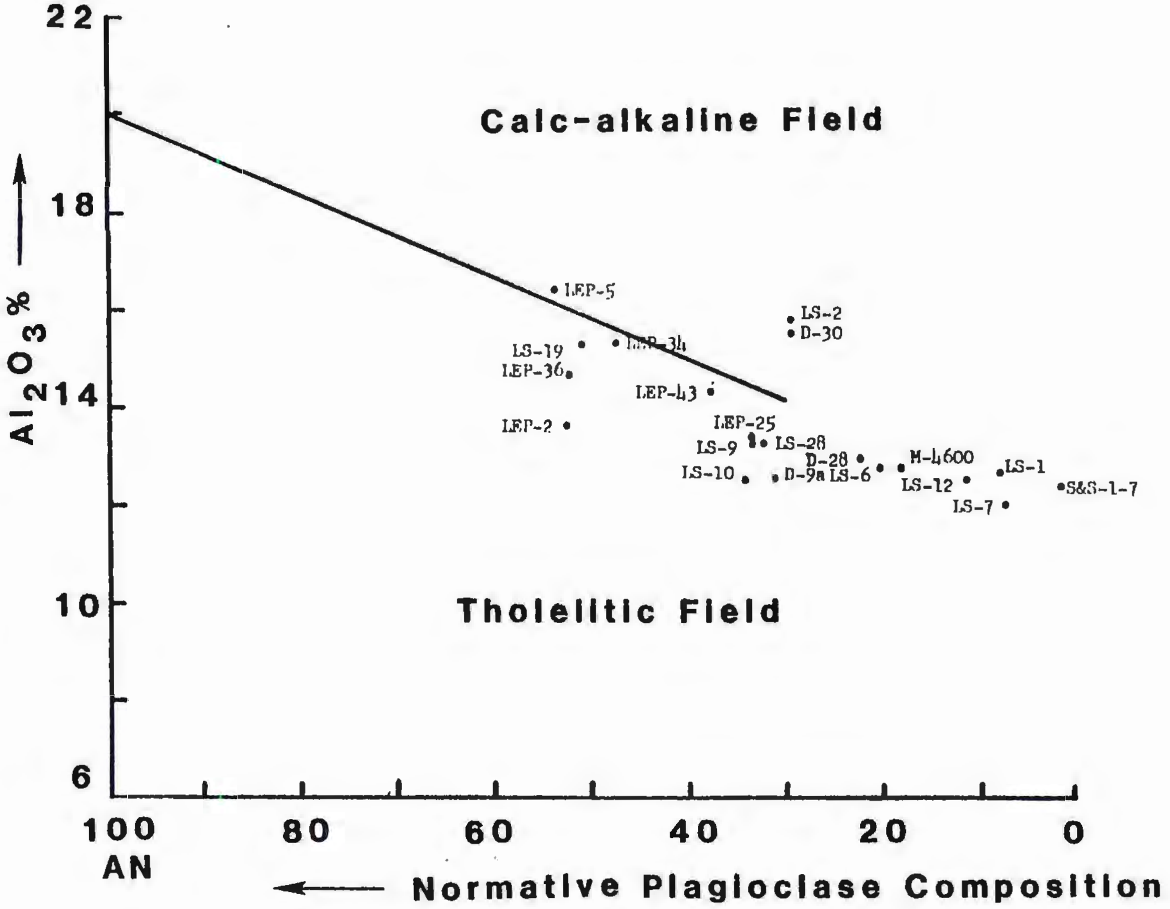


Figure 7: Tholeiitic and Calc-alkaline Fields According to Irvine and Baragar, 1971, showing compositions of analyzed samples from the Duluth area.

Tholeiitic Basalt series Subdivisions

In this study the classification proposed by Jensen (1976) is accepted as a suitable method not only for tholeiitic basalt series classification, but also for dividing sub-alkaline rocks into tholeiitic series and calc-alkaline series. In order to help differentiate the tholeiitic series from calc-alkaline rocks, Jensen introduced a ternary AlFM diagram with Al_2O_3, (FeO + Fe_2O_3 + TiO_2) and MgO at its apexes. According to Jensen, the basis for this is the greater stability of Al_2O_3 than alkalies in alteration processes, as well as roughly similar amounts of this component in subalkaline volcanic rocks. The classification of the samples according to this method is represented on Figure 8. As can be seen the samples occur in the tholeiitic field.

System Used in This Study for Naming Rocks

The extrusive rocks in the Duluth area, as indicated above, are tholeiitic with a complete gradation in their chemical compositions from basaltic to rhyolitic. The tectonic setting of these rocks also suggests a tholeiitic character for them. In this study the above system of I&B is used for mafic rocks, with intermediate and felsic rocks named with a modified version of divisions established by Williams et al. (1955) and Green, (1972b). Williams et al. (1955) refer to rocks with more than 66% SiO_2 as acidic; the rocks which contain betwen 52 and 66% SiO_2 as intermediate; and those which contain between 45 and 52% silica as mafic. Green (1972b) used a combination of SiO_2, K_2O, and MgO in describing the major lava types of the North Shore Volcanic

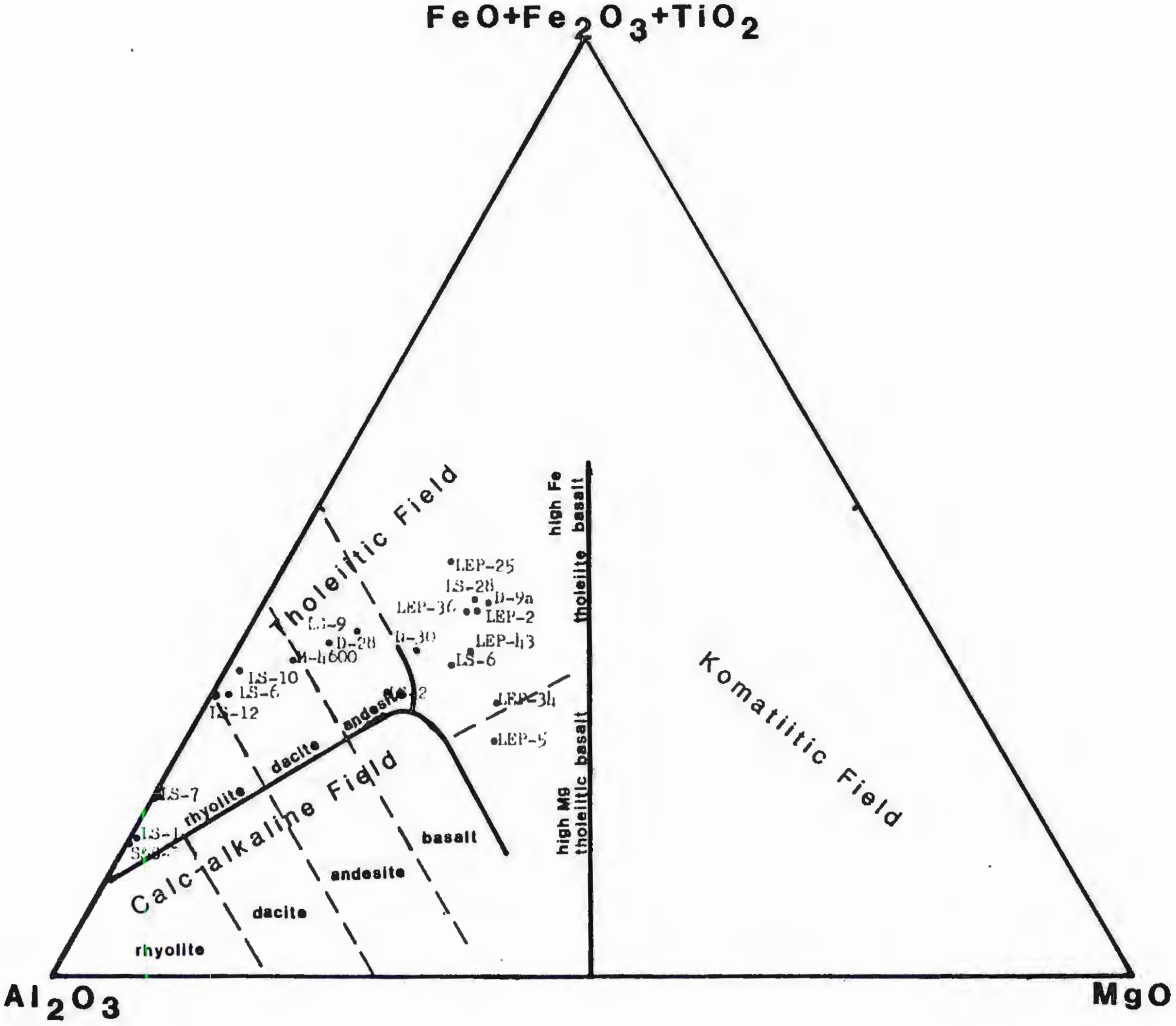


Figure 8: Jensen Cation Plot (1976), Showing compositions of analyzed samples from the Duluth area.

Group. The volcanic rocks in this study are classified according to a modified form of the above methods, and are shown in Table 4. As is discussed in the alteration section, K_2O is a mobile constituent in the rocks of the study area, and its use for classification seems inadviseable. However, here, use of this oxide as a criterion for classifying volcanic rocks is found to be acceptable and indicative. This classification not only is the simplest, but is also found to be consistent with the other methods discussed in the previous pages. For example, this method gives almost all the samples of the study area the same names as the Jensen method. This coincidence seems rather interesting since the oxides used in one classification are completely different from those used in the other method.

Table 4: Classification of Volcanic Rock Samples in Duluth Area According to Their SiO_2, K_2O, and MgO Content. (CO_2 & H_2O excluded)

Tholeiitic Volcanic Rocks

	Mafic Flows		Intermediate Flows	Felsic Flows	
	olivine tholeiite	quartz tholeiite	andesite trachyandesite	icelandite	Qtz latite rhyolite
SiO_2%	45-50	50-52	52-58	62-68	72-78
K_2O %	0.1-2	2-3	3-4	4-5	5-6
MgO%	9-5.34	5.33-3.90	3.90-1.90	1.90-0.05	0.10-0.0
	LEP-2	D-30	LS-2	M-4600	S&S-1-7
	LEP-5	LEP-25	LS-9	D-28	LS-1
	LEP-34	LEP-43		LS-6	LS-7
	LEP-36	D-9a		LS-10	
	LS-19	LS-28		LS-12	

Field Characteristics and Petrography of the Volcanic Rocks

Forty flow units are mapped along the shore of Lake Superior and another thirty-six flows are distinguished in the rivers and as scattered outcrops in the Duluth area. The distinction between flows is primarily based on exposures of their tops and/or bottoms and also their distinct compositional and/or textural differences. The flows along the lake shore and along the rivers, although nearly continuously exposed, are sporadically covered by Pleistocene or Recent deposits; this fact suggests the existence of a greater number of flows than were actually counted. The thinnest flow unit is about one meter thick and the thickest flow is a felsic unit 400 meters thick. The cross-section profiles of the volcanic sequence in the study area yield a thickness of 2920 meters, including the thickness of covered flows, assuming they have the same dip and strike as the adjacent exposed units.

The most explicit criteria for distinguishing successive units are the existence of interflow sediments, accumulation of amygdules in the top and to a lesser extent in the bottom of flows, rubbly tops, and ropy surfaces. Lithological and textural changes are used to distinguish flows only where flows are partly covered, the bottom of a flow or the top of the underlying unit is not exposed, and/or adjacent outcrops demonstrate conspicuous lithological and/or textural differences.

Petrography of the extrusive rocks of the Duluth area is described in three parts based on their composition: 1)-mafic; 2)-intermediate; 3)-felsic.

1 -Mafic Flows As specified in the previous section the mafic flows include olivine tholeiite and quartz tholeiite lavas.

a - Olivine tholeiite

A minimum of 19 olivine tholeiite flows occur in the study area with a total maximum thickness of 1086 meters. The thickness of individual flows ranges from less than one meter to more than twenty meters in the units for which their true thickness can be measured. The locations of all the outcrops are shown on the enclosed geological map. The lava was very fluid, and has formed relatively thin and extensive flows with smooth or ropy tops. The amygdules in this flow type are commonly spherical, and are concentrated in the top and a thin zone at the base of flows. The characteristics of olivine tholeiite in the field include their fine grain size; dark gray, greenish gray, or brownish gray color; mottled appearance (ophi-mottling); and crude columnar jointing.

In thin sections the olivine tholeiites appear to be slightly to moderately altered. Their textures vary from intersertal (now devitrified) to holocrystalline. More than half of the flows are porphyritic, and the vast majority are ophitic or subophitic. Phenocrysts in the major part are plagioclase, which form from less than one percent to ten percent of the rock. Plagioclase phenocrysts in some flows are large, approaching 5 mm in length, and commonly appear tabular. Twinning is very common, but zoning is rather rare. Both albite and Carlsbad twinning are present. The plagioclase phenocrysts are slightly to considerably altered to kaolinite, epidote, and chlorite. Plagioclase phenocrysts are in some flows accompanied by olivine and/or magnetite phenocrysts. Olivine phenocrysts are all altered, and are best recognized under reflected light. Secondary magnetite appears in the rims and along the fractures of altered olivine crystals, and chlorite, with or without iddingsite and serpentine has replaced the rest of the crystal. Olivine phenocrysts are about one millimeter in length, and are present in about 1/3 of the flows. They commonly form about 0.5% of the flow, but locally may comprise up to 5%. Magnetite phenocrysts are 1 to 2 mm across, subhedral to anhedral, and are found in only a small number of flows, where they comprise up to 2% of the rock.

Augite is the only pyroxene identified in the flows of the Duluth area, except along the contact zone of lava flows with the Duluth Complex, where the exsolution of augite in hypersthene (inverted pigeonite) is observed. Poikilitic augite with ophitic or subophitic texture is abundant in the basalts. The ophitic augite, with a 2V of about 50 degrees, may reach 3 mm in diameter, and occasionally contains plates of ilmenite, and/or euhedral grains of magnetite as inclusions (Fig. 9). In some of the flows, ophitic augite is partially or totally altered to calcite, actinolite, and to a lesser extent chlorite. In some cases where augite is totally replaced, the primary ophitic texture is preserved. Total replacement of augite by actinolite has taken place in the vicinity of intrusions, where the effect of contact metamorphism was rather intense.

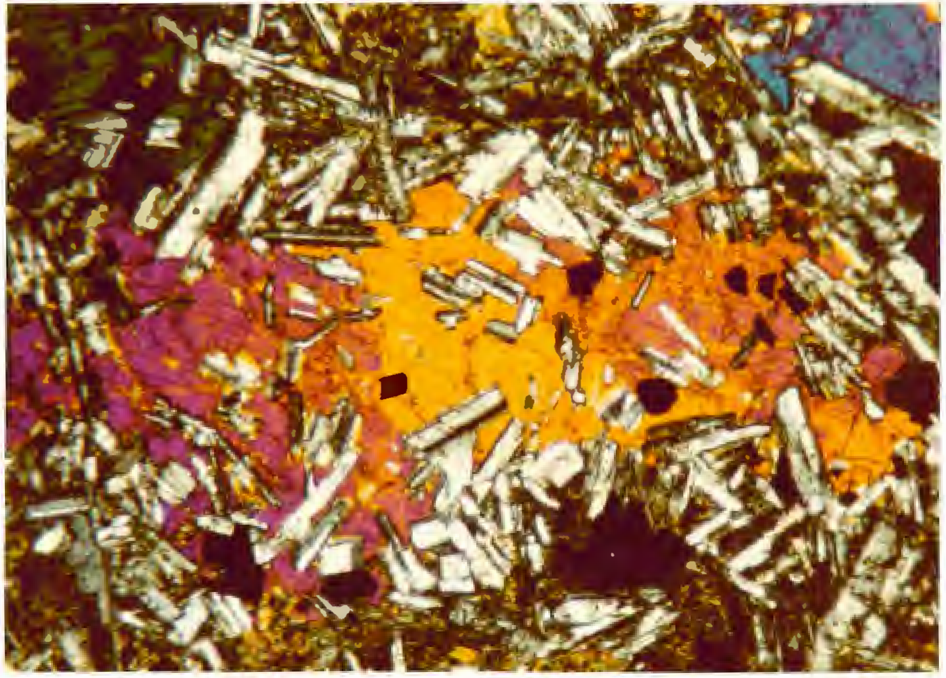


Figure 9: Ophitic augite surrounding numerous laths of plagioclase and several grains of magnetite in olivine tholeiite flow. Unit LEP-36 (Crossed nicols, field of view 5 mm)

The groundmass of the flows is composed of devitrified glass and very fine-grained crystals, and appears to be more altered than the phenocrysts. Altered glass with intersertal texture appears in a majority of the lavas. It locally may form up to 15% of the flows, but generally forms less. The crystalline part of the groundmass is composed mainly of plagioclase, with a lesser amount of pyroxene, olivine, magnetite, and commonly a small percentage of apatite plus or minus ilmenite and pyrite. The plagioclase grains in the groundmass form between 25 to 70% of flows, with an average of about 50%. They are commonly subhedral, very fine-grained and with a lath shape. Clinopyroxene grains are very fine-grained, and form anhedral intergranular crystals. In some of the flows the gradual change from intersertal to intergranular texture can be observed. The intersertal or intergranular texture is predominant at the top and base of flows, and changes to subophitic and ophitic toward the inner part of the flow. The amount of clinopyroxene in the groundmass ranges from 10% to as high as 50% of olivine tholeiite flows with an average of 23%.

Olivine appears in the groundmass of a great majority of flows as very fine-grained, anhedral, completely altered grains. They commonly form a few percent of the groundmass, but locally may comprise about 10% of the flows. Olivine grains in the groundmass show the same characteristics as olivine phenocrysts.

Magnetite is by far the most abundant opaque mineral. Some flows may contain as much as 15% magnetite in their groundmass, but the average is about 8%. Magnetite crystals in the groundmass are very fine grained, subhedral or blocky and locally are accompanied by ilmenite and/or pyrite. Apatite appears as an accessory mineral in many of the olivine tholeiite flows. The amount of apatite locally approaches two percent. Apatite forms a relatively high percentage for rocks with such a mafic composition. Apatite grains appear generally as six-sided prisms, and less commonly in needle-shaped crystals up to 2 mm long. Secondary minerals present in the olivine tholeiite flows are mainly epidote and chlorite and commonly a small amount of kaolinite, sericite, serpentine, iddingsite, and hematite. Epidote locally forms 50% of some metasomatized rocks, and chlorite may comprise up to 30%.

b - Quartz Tholeiite

Fifteen lava flows in the Duluth area are identified by chemistry or texture as quartz tholeiite with a total thickness of 345 meters. The thickness of individual flows varies from 10 to more than 40 m, and generally they appear to be thicker than olivine tholeiite flows. The flows are fine-grained and brownish gray. Amygdules are spherical or ovoid and are filled with one or a combination of a few secondary minerals including quartz, calcite, chlorite, epidote and opaques. Although amygdules are concentrated mainly in the top and base of flows, they may occasionally be seen in the inner part as well.

In thin sections, quartz tholeiite appears to be slightly porphyritic or aphyric, hypocrystalline and intersertal (devitrified) or less frequently holocrystalline. Some show pilotaxitic texture. Phenocrysts of augite are rare (Fig. 10), but subophitic, ophitic, and intergranular texture are locally present. Ophitic augite locally reaches one millimeter in size. Most of the flows have been moderately altered. Phenocrysts are exclusively plagioclase and occur in small amount in a majority of flows. The phenocrysts locally form up to eight percent of rocks, but commonly comprise between 0.5 to 3% (average 2%).

The groundmass of quartz tholeiites is mostly composed of feldspar, mainly plagioclase. The feldspar in the groundmass occurs in two forms: 1) Subhedral laths of plagioclase crystals, which form the major portions of the groundmass, and 2) a minor intersertal part, which is composed of a mixture of plagioclase,

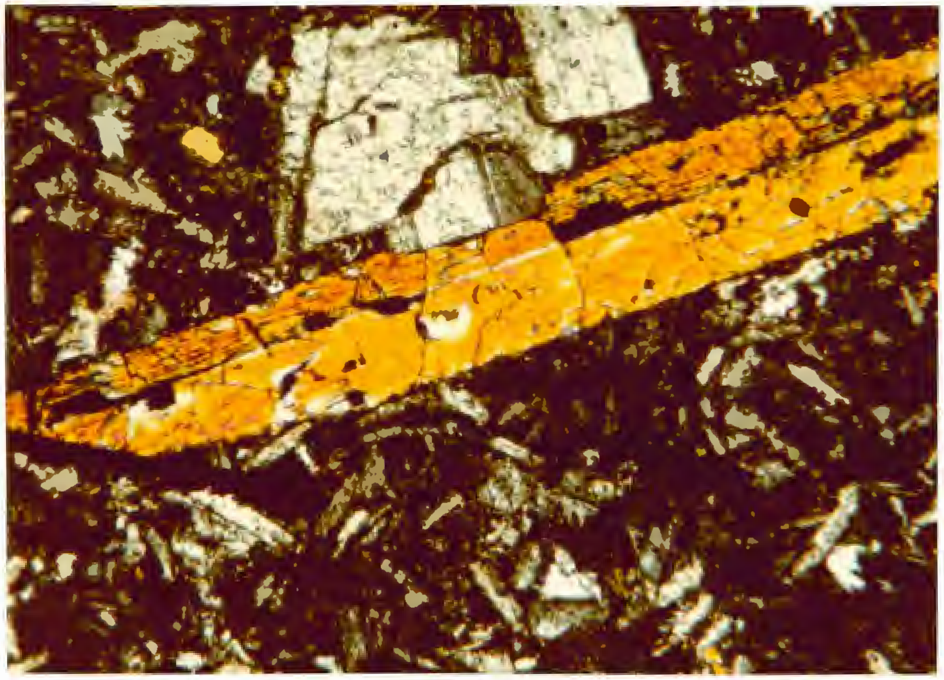


Figure 10: Phenocryst of augite with twinning in quartz tholeiite. Unit LS-13 (Crossed nicols, field of view 5 mm)

orthoclase, and magnetite with a small amount of pyroxene. The intersertal portion in many instances appears to have formed from devitrification of primary glass. Quartz locally appears interstitially in the groundmass of quartz tholeiites and may be primary or secondary quartz.

The total feldspar (as phenocrysts and in groundmass) in quartz tholeiite flows ranges from 50% to over 80%, with an average of 70%. Magnetite plus or minus ilmenite are the next most abundant primary minerals and form ten percent of quartz tholeiite on average (range 6-20%). Magnetite grains are anhedral, fine-grained and are slightly altered to hematite. The ilmenite is commonly subhedral and platy and up to one mm in length. Clinopyroxenes are present ranging in amount from a trace amount up to 15% of these rocks. Olivine exists only in 1/3 of the flows and forms four percent of these rocks on average. The olivine grains are small, anhedral or subhedral, and all are altered. Apatite is found in about half of the flows, in which it constitutes an average of 1.3%. Apatite grains of needle shape (prism) are common and rarely are more than two mm in length.

Alteration products include epidote, chlorite, and calcite. Epidote is found in a limited number of quartz tholeiites, but it locally may constitute up to 20% of a flow. Epidote is fine grained, and anhedral to subhedral. Chlorite is common, making up 3 to 15% of these rocks with an average of 9%. Calcite is found only in a few flows and may form up to 15% of the rock. In some instances, it has replaced plagioclase or pyroxene grains, but in some other cases the altered mineral cannot be identified.

2 - Intermediate Lavas

The intermediate flows are andesite. This group contains thirty-two flows with a total thickness of 1032 meters (see geological map for their distributions). The flows range in thickness from a few to about 90 meters. In the field, the andesites range from dark gray to brownish and a majority of them contain some phenocrysts.

Amygdules are commonly less than one cm in diameter and are filled with epidote, chlorite, calcite, and minor amounts of quartz, feldspar, and opaque minerals. In some units amygdules are filled with plagioclase or chalcopyrite and pyrite (Figs. 28 and 29).

Phenocrysts are plagioclase with occasional magnetite, olivine and ilmenite. Plagioclase phenocrysts comprise from less than 1% to about 60% of andesite with an average of 12 percent. The crystals are 1 mm up to 4 cm in length, subhedral, and tabular with common albite and/or Carlsbad twinning and rare zoning (Fig. 11). Plagioclase phenocrysts are slightly to highly altered. Due to the alteration of plagioclase phenocrysts, determination of composition by extinction angles was found to be inconclusive. Alteration minerals in order of decreasing abundance are epidote, chlorite, kaolinite, sericite and calcite. Magnetite, olivine, and ilmenite phenocrysts form less than two percent of the flows in which they appear. Magnetite phenocrysts are anhedral or subhedral and blocky; olivine phenocrysts are subhedral and altered, and ilmenite phenocrysts are thin and platy (Fig. 12).

In the groundmass feldspar is predominant. The feldspar is composed mainly of fine-grained plagioclase laths, locally accompanied by small amounts of orthoclase. Feldspar in the groundmass comprises between 25 and 75% of the andesite flows, with an average of 60 percent. Quartz is commonly present in the groundmass, in minor amount. Magnetite plus or minus ilmenite is found to be relatively abundant and these oxides vary from six to 20% with an average of 12 percent of the rock (Fig. 13). Relict pyroxene grains with granular texture are occasionally present and form up to ten percent of the rock. Andesites contain from a trace up to 3% of apatite. Altered olivine crystals are rather rare. In general, magnetite appears to be more abundant in

Figure 11: Large, subhedral plagioclase phenocrysts in andesite. Hematite dust gives a reddish color to plagioclase crystals. (Unit LS-2)

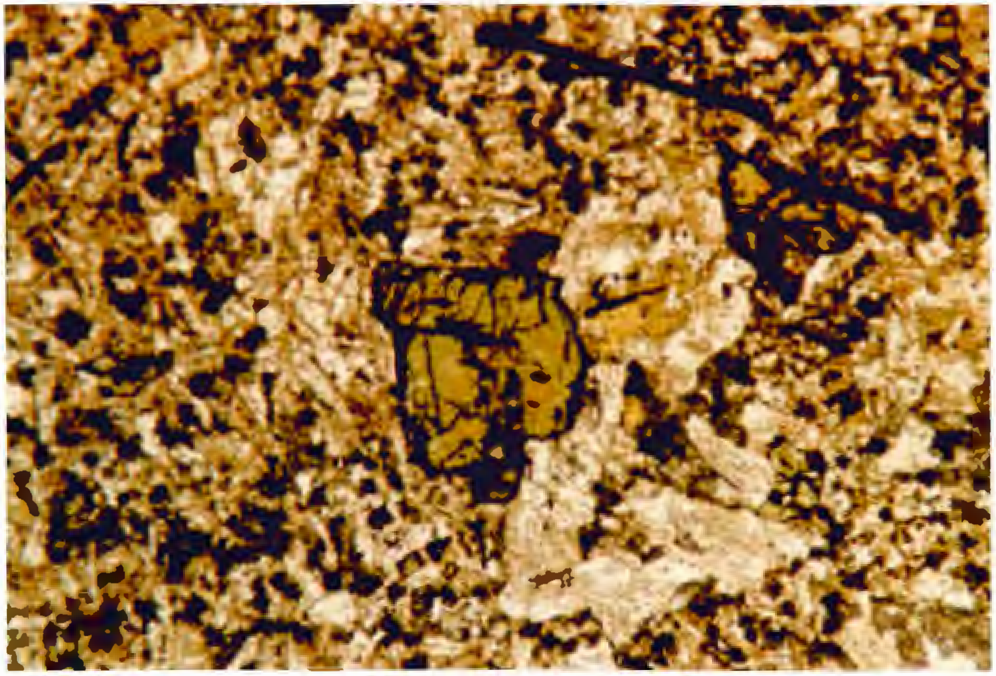


Figure 12: Altered olivine phenocrysts in andesite. Magnetite appears in the rim and fractures of phenocrysts and chlorite has replaced the olivine. Ilmenite plates appear in lower left corner of picture. Unit LS-12, location 228E (Uncrossed nicols, field of view 4mm)

andesite than in any other flow type. Although the total feldspar of andesite is comparable with the basalts, the phenocrysts in andesite form a considerably higher proportion than in any other rock type in the Duluth area. The amount of K feldspar and of apatite increases relative to mafic flows and olivine becomes relatively scarce.

Alteration minerals include epidote, chlorite, calcite, pyrite and sphene. Epidote is a rather abundant secondary mineral; 2/3 of andesites contain epidote which varies from two to over 30% of the rock with an average of ten percent. Representative epidote grains are fine-grained, interstitial and anhedral. Chlorite shows interstitial texture and occurs in half of the andesites with an average amount of about six percent. Calcite is a rather rare secondary mineral and only partially replaces some of the primary minerals. Pyrite grains are fine-grained, show cubic habit and occur in a few flows where locally they may comprise three percent of rock. Sphene is present only in a couple of flows and is a metamorphic product.

3 - Felsic Rocks

The felsic volcanic rocks include two rock types according to their mode of eruption: felsic lava flows and ignimbrites (see plate 1 for the flow distributions). Although a complete range of rock compositions between icelandite and rhyolite do exist, precise field distinction between these compositional types was found to be difficult. So, the lava flows with a compositional range from icelandite to rhyolite are called felsic flows, and together with ignimbrites are referred to as felsic rocks.

The felsic rocks in the Duluth area include ten units with a total thickness of 1170 m. Based on physical characteristics, four of these units are identified as ignimbrites. It should be clarified here that in some units in the study area the difference between felsic lava flows and ignimbrite is vague, and further investigations may indicate that some of the units which are here considered as lava flows are indeed ignimbrites. The major problem in distinguishing between the two is the existence of banded (laminated) felsic rocks in the area. Some of banded units are tens of meters thick. Individual bands are a few mm thick, and are commonly parallel to the base of banded units. Some units contain collapsed pumices, which are flattened due to high temperature and compaction; they form discontinuous bands of a few cm long, and give a banded appearance to the units. This type of band reveals the ignimbritic origin of the the unit. However, in some banded units, individual bands are rather continuous and extend laterally for several meters (Fig. 14). Whether these units are lava flows or ignimbrites remains an open question. The assumption that these units have an ash-flow origin and the individual continuous bands are pumices which are flattened to such an extent seems unwarranted. On the other hand, the pyroclastic basal portion of one ignimbrite unit (LS-7) changes to a banded portion with continuous bands with no apparent time interval between the two portions. Another ignimbrite unit (LS-1) reveals discontinuous banding in some part of its thickness and continuous banding in some other part.

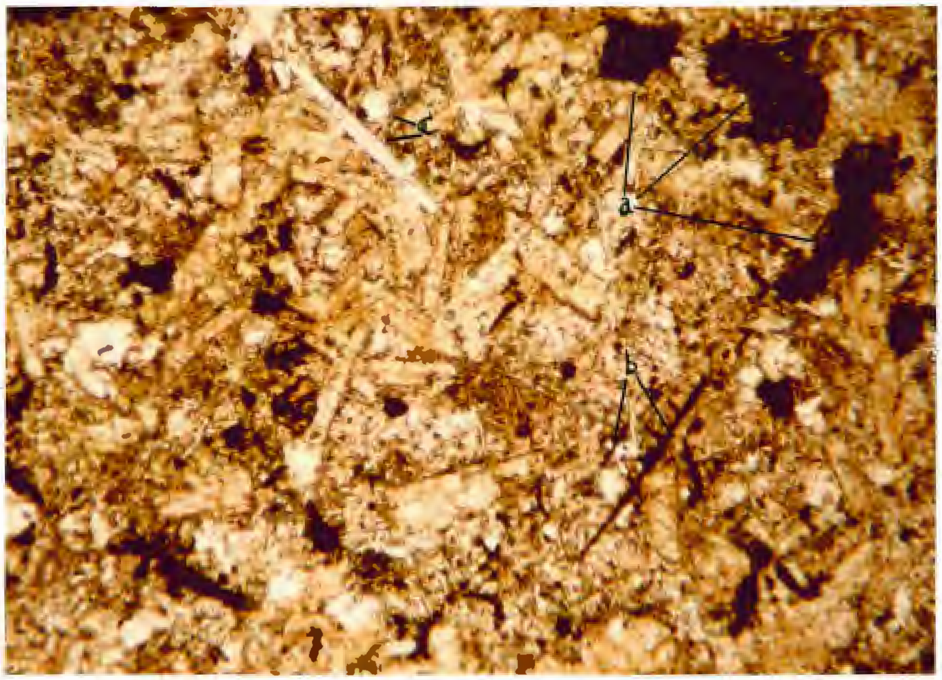


Figure 13: Magnetite, ilmenite and apatite crystals in groundmass of andesite. Unit LS-9, location 209C
a = magnetite, b = ilmenite, c = apatite
(Uncrossed nicols; field of view 4mm)

Figure 14: Continuous banding in felsic rock, bending around the rock fragments. (Unit LS-1)

These observations may suggest that banded felsic rocks both with discontinuous and continuous bands are ignimbrites. Whether the banded portion is indeed a part of an ignimbrite unit or is itself a lava flow could not be determined. The high temperature of the basal part, though it was consolidated, may have caused the overlying hot ash-rich deposit to flow, forming the continuous banded portion. It is also possible that the ignimbrite has changed to a lava flow through a gradual lateral transition as is reported from other localities (e.g. Sakhno (1961), p.138-145). In order to positively identify the type of eruption of each felsic unit in the area further field and thin section investigations are required.

In this study felsic volcanic rocks are assumed to be lava flows, except where evidence indicates ignimbrite characteristics for them. In this section felsic lava flows are described, followed by a consideration of ignimbrite units.

a - Felsic Lava Flows

The felsic lava flows in the Duluth area include six units with a total thickness of 637m. The thickness of the flows ranges from seven to 260m. The outcrops are well exposed along the shore of Lake Superior, where they form the bays and appear as cliffs, due to their lower resistance to wave erosion which in turn seems to be the result of their abundant, closely spaced jointing.

The color of the felsic lava flows varies from grayish brown to brownish red to pink. All the units contain some phenocrysts, and some rock fragments are typicaly present. The rock fragments may appear to be flattened which indicates that they were not quite solid at the time of incorporation.

Amygdules are rounded, almond shaped or more elongated. The shape and distribution of amygdules in felsic flows are more irregular than in the more mafic flows. Amygdules are filled principally with calcite and quartz; epidote, chlorite, zeolites, fluorite and opaque minerals locally fill a small portion.

The texture of felsic flows in thin section is holocrystalline but devitrified. The rocks are aphanitic to fine-grained, porphyritic, and allotriomorphic to hypidiomorphic. Recrystallization is very common and intensity of alteration ranges from moderate to high.

Phenocrysts of feldspar and magnetite are very common in felsic flows. The phenocrysts form from less than one percent to more than 15% of the rocks. Broken phenocrysts of feldspar are found in some units. Plagioclase phenocrysts are subhedral to euhedral, tabular, typically twinned and zoned, and up to 3 mm in size. Orthoclase phenocrysts are commonly seen together with plagioclase phenocrysts. They are euhedral to subhedral, may be rectangular, eight-sided or rhomboid in shape and may reach a few mm in diameter. Magnetite phenocrysts are less common and only are observed in a limited number of flows, where they are <1 mm, sub-anhedral crystals. A small amount of altered mafic silicates and a trace amount of apatite and zircon micro-phenocrysts may be present.

The major part of the groundmass of the felsic flows is composed of a very fine-grained intergrowth of plagioclase, orthoclase, and quartz with a minor amount of magnetite plus or minus ilmenite. Apatite is locally present in very small amounts, and zircon is occasionally observed in trace amounts. Quartz also occurs as long, platy crystals which are believed to have originally formed as tridymite and have inverted to quartz during cooling or burial metamorphism. The secondary minerals include epidote, chlorite, and occasionally calcite, garnet (andradite), and pyrite.

b - Ignimbrites

The term ignimbrite was originally used by Marshall (1935) for naming the rocks formed by nue'e ardente eruptions of fissure type. In later publications ignimbrite, ash-flow tuff, pumice flow, pyroclastic flow, and pumice-and-ash deposit have been used almost synonymously (Smith 1960a; 1960b; Ross and Smith, 1961; Williams and McBirney, 1979; Wright et al., 1980).

The major distinguishing characteristics of ignimbrites are their fragmental texture, poor sorting, lack of stratification, and great areal distribution. The ignimbrites in the study area include four units, forming a total thickness of 531m. They have a rhyolite to icelandite composition, lack stratification and the fragments are poorly sorted. One unit can be traced for a distance of 4 km along strike, and one has a thickness of 400 m.

Welding in some ignimbrite units is rather intense, with almost zero porosity, and the flattened pumices give a foliated fabric (banding) to these rocks.

One of the ignimbrites in Duluth is the 60m thick unit LS-7, which crops out on the lake shore and foot of 42nd Avenue East. This unit consists of pumice, scoria and accidental rock fragments enclosed in a glassy dust, since devitrified. The pumices and rock fragments form the major portion of the basal part (Fig. 15) and decrease toward the upper part. A change from the pyroclastic basal part to the banded upper part of this unit takes place in a few meters, through a narrow transitional zone. (In unit LS-1, the transitional zone is wider and the banded portion changes to pyroclastic rock again toward top of the unit.) A vague and discontinuous banding may locally be present in the pyroclastic part. The magmatic ejecta range in size from fine grains to blocks of up to 50cm in size, and range in composition from mafic to felsic. Sorting is poor, but the smaller ejecta show a decrease in amount upward and become scarce or hard to recognize in the top of this portion. Many ejecta have a lighter colored outer part as a shell or halo around them (Fig. 16). In thin section the lighter part shows a different texture in comparison to the darker part of the ejecta. The lighter part may have been formed by alteration processes after eruption. On the other hand, the ejecta may have been immersed in rhyolitic magma of the upper magma chamber before eruption, and the lighter color shells would be the remnants of rhyolitic magma on their outer parts.

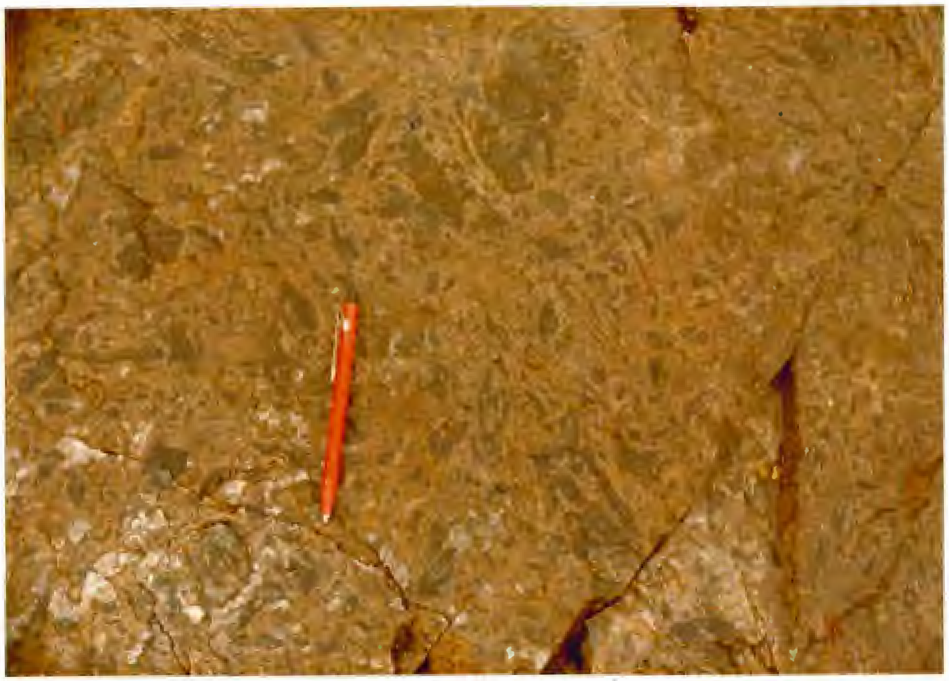


Figure 15: Pumice fragments in an ignimbrite. Pumice fragments are enclosed in a fine recrystallized ash, and form the major part of the pyroclastic units. Unit LS-7, Lake Superior shore.

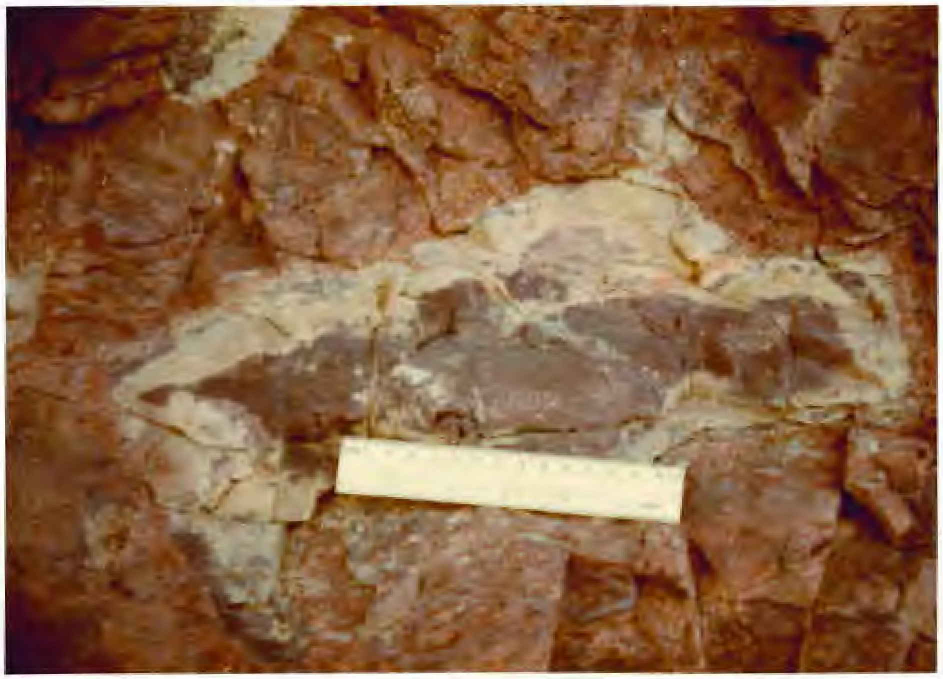


Figure 16: Magmatic ejecta surrounded by a halo of lighter color in ignimbrite. Unit LS-7, Lake Superior shore.

The ignimbrite units show shades of brown and pink in an irregular fashion, but with sharp contrasts probably from alteration by pneumatolytic/fumarolic activity (Fig. 17). Amygdules in ignimbrites are filled mostly with calcite and minor amounts of zeolites and fluorite. Amygdules vary in size from a few mm to vugs about 1 m across, and are rather scattered throughout the units. The vast majority of pumices are flattened, elongated and/or bent (Fig. 18), but the accidental fragments are commonly angular. Considerable numbers of lapilli not only are flattened, but are divided into two branches at one end. Most of the rock fragments, particularly larger ones, are more mafic than the host rock itself. They appear darker and in thin sections contain many small laths of plagioclase. The pumices, scoria and rock fragments are cemented by fine particles of ash. The lithification is caused by the high initial temperature and by the weight of the overlying load which caused compaction, followed by burial metamorphism.

Microscopic study of the banded rocks reveals a devitrified poikilitic texture. Poikilitic crystals are quartz which are elongated in the banding direction , and some reach several millimeters in length (Fig. 19). The poikilitic quartz surrounds fine-grained, euhedral or subhedral orthoclase and locally magnetite grains. The orthoclase forms up to 45% of the whole poikilitic grain and generally contains hematite and kaolinite dust. In coarse poikilitic quartz crystals in the bands, the inclusions are scarce in the central part of crystals and are restricted to the border zone. These quartz grains have probably

Figure 17: The abrupt and irregular change in color in ignimbrite unit which is probably caused by post-eruption pneumatolytic/fumarolic alteration. (Unit LS-7), Lake Superior shore.

Figure 18: Elongated and bent pumice fragments in ignimbrite. (Unit LS-7), Lake Superior shore.

formed with the assistance of SiO_2 - mobilizing fluids traveling along the more permeable laminae as the eruptive unit cooled off.

The existence of quartz after tridymite in the banded portions indicates that the temperature had remained high (over 870° C) for some time after deposition (Fig. 20). Quartz grains may show a gradual change in size and shape from very fine-grained, intersertal to the fine-to medium-grained platy shape, and to poikilitic crystals in one thin section.

Phenocrysts are observed in some ignimbrite units. They are mainly plagioclase and some appear to be broken. The bands are bent around the rock fragments and less frequently around crystals.

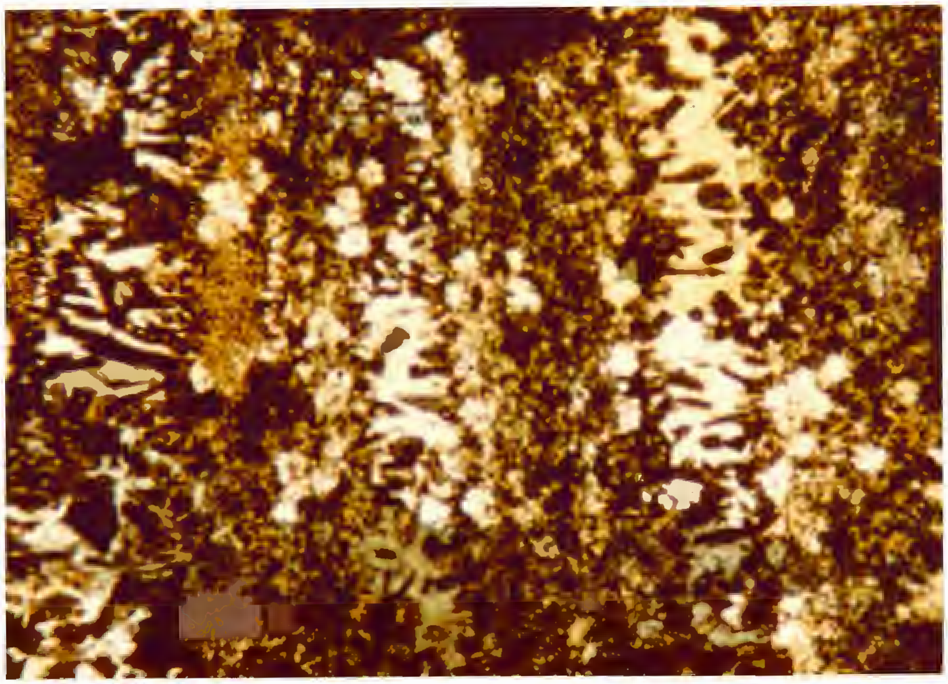


Figure 19: Poikilitic quartz crystals surrounding fine-grained orthoclase grains in banded felsic rock. UnitLS-1, location 199E (Crossed nicols, field of view 4mm)

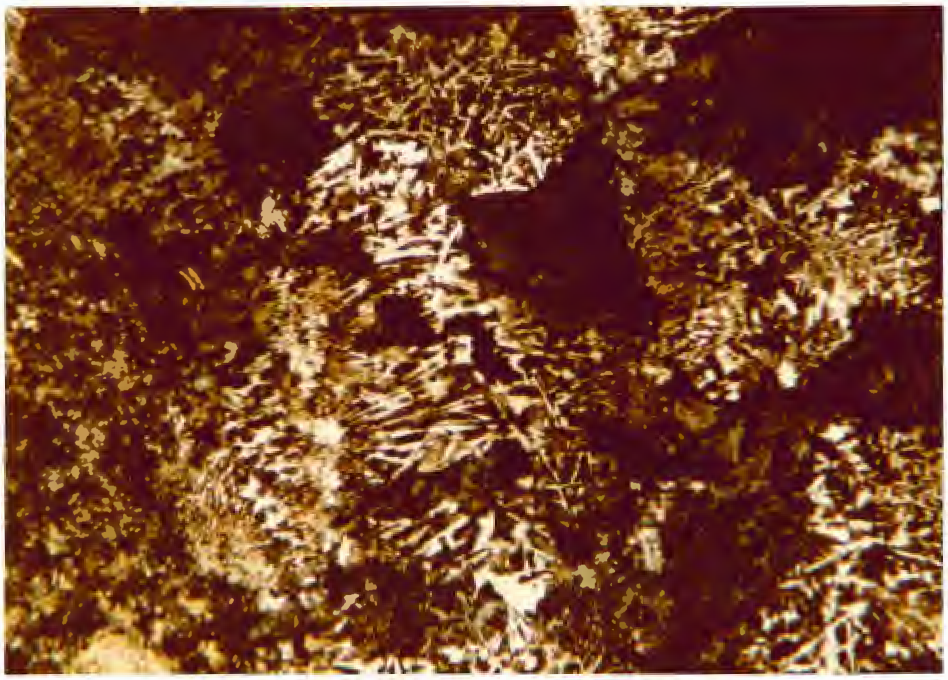


Figure 20: Thin platy crystals of quartz in felsic rock, which initially may have formed as tridymite. Unit LS-1, location 199E (Crossed nicols, field of view 4mm)

Petrogenesis

Much evidence suggests that fractional crystallization is responsible for different flow compositions in various volcanic provinces. In studies of the Keweenawan extrusive rocks, the composition of the more primitive olivine tholeiites has been found to resemble oceanic ridge tholeiite (MORB) and has been considered to be very similar to partial melts of upper mantle peridotite (Green, 1981; 1982). The REE distribution pattern for this rock type does not show depletion in incompatible elements by previous melting events (Green, 1981), and strontium isotope data show little or no indication of older-crustal contamination for these rocks (Van Schmus et al. 1982). The major-element compositional range of rocks from olivine tholeiite to transitional basalt is similar to that produced by fractional crystallization (Phinney, 1970; Green, 1981; 1982), but Brannon et al. (1981) find that trace elements do not fit this model. However, in the Duluth area **the more potassic nature** of the extrusive rocks and **the high volume of felsic rocks** are very conspicuous in comparison to other lava plateaus of the world; and since these anomalies cannot be justified by fractional crystallization alone, they are problematic.

The **more potassic nature** of the extrusive rocks in the study area is a feature not only of felsic rocks, but of basalts and the associated intrusions as well. The high potassium content can be attributed to assimilation or contamination; it also may be attributed to a local geochemical feature of mantle. No isotopic studies have yet been done on these flows in Duluth. Various hypotheses have been advanced to explain high- potassium magmas; among these, zone refining (Harris, 1957), eclogite fractionation (O'Hara and Yoder, 1967), and the degree of partial melting (Gast, 1968; O'Hara, 1968) are more popular. Jamieson and Clark (1970, P. 196-199), on the other hand, have investigated and discussed the level of this element in tholeiites, and have concluded that crustal contamination has little importance. Cox (1972) also, in a study of the Karroo volcanic rocks, attribbuted the high content of potassium in northern Karroo basalts to the mantle composition rather than a result of fractional crystallization or crustal contamination. Other basalts from higher in the NSVG section contain relatively low values of potassium (Green, 1981). It is possible that the high K content in the Duluth area may be a metasomatic feature related to burial metamorphism.

As Carmichael (1964) has stated, only 10% of felsic material can be produced by extreme fractional crystallization of a basalt parent. The excess volume of felsic flows in the Duluth area (about 1/3 the thickness of the volcanic sequence) may be a limiting factor for the hypothetical derivation of felsic rocks by fractional crystallization, unless the volume of this rock type is related to the volume of the large parent magma body which formed both the extrusive and the intrusive rocks in the region. In such a case, numerous small and large, high-level magma chambers responsible for the formation of the NSVG

(Green,1981), may have been connected to a larger and deeper magma body (chamber), and felsic magma, concentrated at the top of this magma body, worked its way to higher level magma chambers and erupted preferentially.

The composition range of the volcanic rocks and the abundance of plagioclase, olivine and magnetite phenocrysts suggest at least some crystal fractionation. Since volcanism in the area is related to rifting (or resulted from rifting), potentially fusible crustal layers may have subsided into regions of sufficiently high temperature to cause melting. This process and/or wallrock reaction in feeder channels (Brannon et al., 1981) together with crystal fractionation may explain the range in composition of this sequence of rocks, the high potassic content of flows, and also to some extent the high volume of felsic rocks. Isotopic studies are needed to help solve this problem.

Characteristics of the Continental Tholeiitic Rocks, and Comparison of the Flow Sequence in Duluth with other Tholeiitic Series

Continental tholeiitic rocks commonly occur as fissure-fed, plateau basalts which erupted as horizontal or subhorizontal flood-lavas and extend over large distances (White, 1972; Green, 1977; 1981). They range in age from Late Precambrian to Recent. Plateau basalts exist in almost all the continents of the earth. The Deccan Plateau(India); Columbia River Plateau (U.S.A.); Parana Basin (Brazil); Karroo Province (South Africa); Siberian Platform (USSR); and Lake Superior Basin (North America) are among the best known tholeiitic plateau basalts. However, some flows in these plateaus demonstrate chemical characteristics similar to weakly alkaline basalt (e.g. Karroo, Parana, Lake Superior Basin).

Tholeiitic rocks are by no means confined to plateau basalts, but are also characteristic of island arcs, intra-plate oceanic islands, and especially mid-ocean ridges.

The tholeiitic plateau lavas are very commonly associated with intrusive bodies in the form of sills and dikes. Basalt plateaus range up to and in some cases even exceed 2,000,000 km2 in area, with a thickness which locally reaches more than seven km (Green, 1977). Presently, a large portion of many of the plateaus has eroded away and the center of the majority of them occur below sea level, indicating substantial subsidence during and/or after eruption (Green, 1981).

The amount of SiO_2 in different plateaus varies widely. Some appear to have a narrow range of variation of a few percent with an average silica content of around 50% (e.g. the Siberian Platform basalts) whereas some others appear to be more siliceous and show a wide range of silica content (e.g. Keweenwan Plateau with a range in SiO_2 content from 45 to more than 75%). The Al_2O_3 content of plateau basalts commonly ranges between 13 and 16%, although some may contain up to 18% Al_2O_3. Alkali (Na_2O + K_2O) and magnesia (MgO) show a considerable variation from one plateau to the other. (Na_2O + K_2O) show averages from 2.2% (Siberian Platform) to more than 5% (Keweenawan Plateau). The average MgO of published analyses shows a range of 5% (Parana Traps) to 7.98% (Karroo Lavas). The tholeiitic rocks, in general, show a stronger iron and titanium enrichment than the calc-alkaline rocks.

As far as mineralogy is concerned, all the tholeiite plateaus appear to be similar (Green, 1981). Basalt forms the major portion of all sequences and contains plagioclase as the predominant mineral both as phenocrysts and in the groundmass, followed by clinopyroxene (commonly augite with local appearance of pigeonite). Olivine is common and magnetite plus or minus ilmenite are everywhere present in various proportions. Basalts are generally olivine tholeiite or quartz tholeiite and are hypersthene-normative.

In order to compare the lava flows of Duluth with the flows in other parts of the Lake Superior basin, other plateau basalts in the world, and volcanic rocks in the greenstone belts and

Table 5: Analyse of Basalts (Tholeiites)

A - Major elements, Wt%

	1*	2	3	4	5	6	7	8	9	10	11
SiO_2	49.75	50.78	52.24	52.08	49.10	51.12	50.04	50.51	51.12	51.75	49.97
TiO_2	1.75	1.41	1.05	1.22	3.02	2.59	1.51	2.39	0.82	0.80	2.97
Al_2O_3	16.25	15.43	15.67	14.86	13.66	14.65	17.29	12.77	16.85	15.97	14.41
Fe_2O_3	5.17	3.45	2.73	2.95	5.53	}12.88	}8.73	2.56	3.01	2.75	}14.17
FeO	6.84	7.58	9.25	9.74	8.65			8.89	6.42	7.06	
MnO	0.18	0.19	-	0.23	0.20	0.20	0.17	0.18	0.18	0.17	0.21
MgO	6.72	7.61	6.62	6.51	5.23	5.23	7.30	9.46	7.25	6.75	5.59
CaO	9.59	10.10	9.88	9.43	10.66	8.98	11.88	10.29	11.44	11.78	7.25
Na_2O	2.83	2.47	2.21	2.45	2.82	2.65	2.77	2.24	2.21	2.42	3.23
K_2O	0.74	0.88	0.36	0.35	0.50	1.12	0.16	0.46	0.38	0.44	1.72
P_2O_5	0.19	0.11		0.18	0.40	0.57	0.16	0.26	0.31	0.11	0.48
TOTAL@	100.01	100.01	100.01	100.00	99.99	99.99	100.01	100.01	99.99	100.00	100.00

B - Trace Element Values in P.P.M.

	1*	2	3	4	5	6	7	8	9	10	11
Cr				256				494		125	102
Zr				108				164		30	233
Sr				149				362	338	355	260
Rb								11	5	5	39

- Blank=Analyses Not Available
- nd = Not Detected
- @ = H_2O and CO_2 are excluded, and the rest readjusted to 100 %
- * Explanation of Numbers Follows:

Table 5 continued

1 - Representative Chemical Composition of Mafic Keweenawan Lavas ($SiO_2<52\%$); an Example of Pre-Tertiary Continental Flood Basalts. Average of 25 representative Samples; Green, J.C. 1981, Basaltic Volcanism Study Project, Table 1.2.2.19

2 - Chemical Composition of Basalt of Siberian Platform; an Example of Triassic Continental Flood Basalts. Average of 219 Representative Samples; Nesterenko et al., 1964

3 - Average Chemical Composition of Moderately K-rich Archean Tholeiites; Condie, 1976; Condie and Moore, 1977

4 - Average Chemical Composition of 487 Archean Tholeiite Basalts of Superior Province, Canada; Goodwin, A.M. 1977, Table V

5 - Average Chemical Composition of Six Tholeiite Basalts of Reydarfjordur Area, Eastern Iceland; an Example of Tertiary Continental Flood Basalt; Walker, G.P.L., 1963, Table 2

6 - Average Chemical Composition of 472 Samples of Basalts from the Columbia River Province ($48\%<SiO_2<52\%$); an Example of Tertiary Continental Flood Basalts; Swanson and Wright, 1981

7 - Average Chemical Composition of Atlantic and Pacific Ocean Tholeiites; Example of Ocean-Floor Basaltic Volcanism; Engel et al., 1965

8 - Average Chemical Composition of 17 Samples of Tholeiite Basalts from MaunaLoa and Kilauea Volcanos, Hawaii; an Example of Oceanic Intraplate Volcanism; Basaltic Volcanism Study Project, 1981, Tables 1.2.6.2. and 1.2.6.3.
Note: Trace Elements Represent Average of only Ten of These Samples from Kilauea Tholeiites.

9 - Average Chemical Composition of 12 Samples from New Britain, Central Papua, New Guinea; an Example of Island Arc Basalts; Basaltic Volcanism Study Project, 1981, Tables 1.2.7.3.&1.2.7.4.

10 - Chemical Composition of a Representative Basalt from Talasea Volcanic Field, New Britain; Lowder and Carmichael, 1970

11 - Average Chemical Composition of Ten Tholeiitic Basalts from Duluth, Minnesota; This Study

Table 6: Analyses of Andesites

A - Major Elements, Wt%

	1*	2	3	4	5	6	7	8
SiO_2	60.00	62.38	58.93	55.64	59.98	59.46	58.33	57.95
TiO_2	1.04	0.83	1.25	1.98	1.58	0.63	1.18	2.24
Al_2O_3	16.00	16.41	15.20	14.40	13.51	17.02	16.29	14.58
Fe_2O_3	1.89	1.47	2.60	6.25	4.18	2.74	2.55	}10.79
FeO	6.20	4.28	7.55	5.72	6.15	4.55	4.31	
MnO	0.16	-	0.19	0.20	0.22	0.16	0.11	0.22
MgO	3.90	3.56	3.63	3.73	2.22	2.95	4.10	2.91
CaO	5.87	3.76	6.16	6.00	5.58	6.93	5.99	3.88
Na_2O	3.85	5.65	3.30	3.77	4.09	3.72	3.96	3.44
K_2O	0.87	1.67	0.88	1.90	1.93	1.65	2.67	3.41
P_2O_5	0.23		0.32	0.42	0.55	0.20	0.53	0.58
TOTAL@	100.01	100.01	100.01	100.01	99.99	100.01	100.02	100.00

B - Trace Element Values in P.P.M.

Cr			88			nd	127	19
Zr			216			70	197	535
Sr			206			525	950	200
Rb						20	36	115

- Blank=Data Not Available
- nd = Not Detected
- @ = H_2O and CO_2 are excluded, and the rest readjusted to 100 %

1 - Average Andesite from Four Archean Belts; Baragar and Goodwin, 1969, Table III

2 - Average Chemical Composition of Moderately K-rich Archean Andesite; Condie, 1976; Condie and Moore, 1977

3 - Average Chemical Composition of 131 Archean Andesites from Tholeiitic Volcanic Rocks in Superior Province, Canada; Goodwin, A.M. 1977, Table V

4 - Average Chemical Composition of 12 Representative Samples from Keweenawan Lavas ($52\%<SiO_2<58\%$); an Example of Pre-Tertiary Continental Flood Lavas; Green, J.C. 1981, Basaltic Volcanism Study Project, Tables 1.2.2.8. & 1.2.2.19

5 - Average of Six tholeiitic Andesite Lavas, Breiddalur Volcano, Eastern Iceland; an Example of Tertiary Continental Flood Lava; Thomas, R. 1963

6 - Chemical Composition of a Representative Andesite from Talasea Volcanic Field, New Britain; an Example of Island Arc Andesite; Lowder and Carmichael, 1970

7 - Average Chemical Composition of Two Representative Andesites (TP-17 and TP-21) from the Taos Plateau; an Example of Continental Rift Volcanism; Basaltic Volcanism Study Project, 1981, Tables 1.2.4.1. and 1.2.4.2.

8 - Average Chemical Composition of Two Andesites from Duluth, Minnesota; This Study

Table 7: Analyses of Dacites and Icelandites

A - Major Elements, Wt%

	1*	2	3	4	5
SiO_2	63.94	71.66	65.17	70.06	67.12
TiO_2	0.64	0.58	0.79	0.36	0.73
Al_2O_3	16.76	13.65	14.71	15.29	12.72
Fe_2O_3	2.25	1.52	4.19	1.09	}8.49
FeO	3.02	4.28	3.27	1.91	
MnO	0.11	0.12	0.16	0.04	0.13
MgO	2.13	0.93	0.70	0.91	0.61
CaO	5.56	2.28	3.82	2.71	2.35
Na_2O	4.00	3.59	4.47	4.49	3.07
K_2O	1.41	1.28	2.49	3.03	4.67
P_2O_5	0.17	0.10	0.33	0.10	0.12
TOTAL@	99.99	99.99	100.01	99.99	100.01

B - Trace Element Values in P.P.M.

Cr		11			<10
Zr		339			987
Sr		128			63
Rb		nd			160

- Blank=Data Not Available
- nd = Not Detected
- @ = H_2O and CO_2 are excluded, and the rest readjusted to 100 %

1 - Average Chemical Composition Dacites; Nockolds, 1954

2 - Average Chemical Composition of 40 Archean Dacites from Superior Province, Canada; Goodwin, A.M. 1977, Table V

3 - Average Chemical Composition of Two Icelandites from Thingmuli Volcano, Eastern Iceland; Average of Samples 15 and 17 by Carmichael, 1964, Table 9; H_2O and CO_2 Excluded

4 - Average Dacite, Cascade Volcanoes, Carmichael, 1964, Table 8

5 - Average Chemical Composition of Five Icelandites from Duluth, Minnesota; This Study

Table 8: Analyses of Rhyolites

A - Major Elements, Wt%

	1*	2	3	4	5	6	7
SiO_2	74.25	73.83	76.91	72.72	75.53	73.95	75.33
TiO_2	0.22	0.43	0.32	0.33	0.28	0.24	0.26
Al_2O_3	13.55	13.47	11.37	12.71	12.72	14.17	12.32
Fe_2O_3	1.26	1.53	}3.66	3.17	1.58	0.06	}3.05
FeO	0.75	3.26		1.13	0.63	1.72	
MnO	0.03	0.08	0.11	0.05	0.04	0.02	0.02
MgO	0.32	0.69	0.79	0.58	0.02	0.35	0.06
CaO	1.14	1.15	2.08	2.09	0.98	1.33	0.31
Na_2O	3.01	3.83	3.88	3.48	4.80	3.99	2.91
K_2O	5.39	1.59	0.85	3.73	3.39	4.12	5.70
P_2O_5	0.07	0.15	0.03	0.02	0.04	0.05	0.02
TOTAL@	99.99	100.01	100.00	100.01	100.01	100.00	98.98

B - Trace Element Values in P.P.M.

	1*	2	3	4	5	6	7
Cr	5	10					<10
Zr	160	340					425
Sr	245	116					25
Rb	60	nd					230

- Blank = Data Not Available
- nd = Not Detected
- @ = H_2O and CO_2 are excluded, and the rest readjusted to 100 %

1 - Average Chemical Composition of Rhyolite; Nockolds, 1954

2 - Average Chemical Composition of 23 Archean Rhyolites in Superior Province, Canada; Goodwin, A.M. 1977, Table V

3 - Average Chemical Composition of 38 Archean Rhyolites from Noranda, Quebec; Provost, 1978; Spence de Rosen, 1976

4 - Representative Rhyolite from the Talasea Volcanic Field, New Britain; an Example of Island Arc Rhyolite; Lowder and Carmichael, 1970

5 - Average Chemical Composition of Three Rhyolites from Thingmuli Volcano, Eastern Iceland; Carmichael, 1964, Table 9, Samples no. 20, 21 and 22

6 - Average Rhyolite, Cascade Volcanoes; Carmichael, 1964, Table 8

7 - Average Chemical Composition of Three Rhyolites from Duluth, Minnesota; This Study

mobile volcanic belts, their chemical compositions are shown in Tables 5, 6, 7 and 8. Although similarities exist, the following differences are apparent:

I - The most prominent difference is the higher percentage of K_2O in the flows of the study area than flows from other represented areas.

II - The amount of Na_2O in the flows of the Duluth area is lower in felsic and intermediate rocks and higher in basaltic lavas in comparison with other rocks in the tables (except for Archean andesite).

III - Although the amount of Al_2O_3 in the Duluth samples commonly occurs within the range of other representative samples, it appears to be on the lower side of the range.

IV - Ca contents of all the flow types in the Duluth area are generally considerably lower than representatives in other areas.

V - Ti and Fe content in flows of the study area are commonly higher than in the similar rock types in the tables from other environments, especially for the andesites and icelandites.

The basaltic rocks in the study area appear to be very similar to the Columbia Plateau basalts. Green (1972a; 1981) also noted the similarity between North Shore Volcanic Group and Iceland plateau lavas. As is shown in the tables, this similarity is striking and exists for majority of constituent oxides and for the full range of flow composition (Tables 5,6,7,and 8).

INTRUSIVE IGNEOUS ROCKS

Intrusive rocks in the city of Duluth include the Duluth Complex, five diabase sills and 36 dikes. The five sills are the Messabi, Endion, Northland, Lakeside, and Lester River sills. Except for the Lakeside sill which consists only of diabasic rocks, the other sills are composed of a diabasic part in the lower portion, and a granophyre (granitic) facies in the upper portion, commonly with a relatively small amount of a transitional intermediate rock. The diabases are dark-colored and have a basaltic composition. The Duluth Complex and Lester River sill cut off the base and top respectively of the flows of the study area. Detailed descriptions of these intrusions are given by several geologists (e.g. Taylor, 1964, and Faure et al., 1969, for the Duluth Complex; Sandberg, 1938; Newberry, 1972; and Luhr, 1975 for the Lester River sill). The Endion and Northland sills were also studied by Ernst (1960), and by Schwartz and Sandberg (1940). These intrusions will not be discussed any further in this chapter. The Messabi and Lakeside sills, however, are named and described in this study for the first time.

The remaining intrusions are basalt dikes that occur along the shore of Lake Superior, in the river valleys, and inland in the Duluth area and are mapped and described briefly. The majority of the dikes along the shore of Lake Superior in Duluth are shown in a strip map by Sandberg (1938). The sills generally, and Messabi and Endion sills, particularly, are not offshoots of the Duluth Complex, but were formed later and cut both the lava flows and the Duluth Complex. As none of the dikes were seen to cut the Duluth Complex, their age relations are ambiguous. Some of the intrusions are very similar to some mafic lavas in the contact zone and could be mistaken for them. The following criteria have been followed in order to distinguish the lava flows from adjacent intrusions (see also Grout, 1933, p.32 and Sandberg, 1938, p. 812-813):

1) - Intrusions are less altered and look fresher in hand specimens.

2) - Thick intrusions show coarser texture than lavas.

3) - Phenocrysts are relatively rare in the intrusive rocks.

4) - Amygdules are characteristic of flows, but not common in intrusions.

5) - Intrusive rocks commonly exhibit chilled margins.

6) - Calcite, epidote, and less frequently quartz veins, are common around intrusions, particularly dikes.

7) - Dikes and sills are more resistant to erosion than flows. Dikes form points and sills form smooth rocky ledges along the shore of Lake Superior.

8) - Granophyre appears exclusively in the upper portion of sills.

9) - Sills generally show a dip of twenty degrees to the east, parallel to the flows, and dikes commonly dip seventy to eighty-five degrees to the west.

Messabi Sill

Schwartz (1949) encountered a diabasic sill in the trunk sewer tunnel along First Street, between 2nd and 3rd Avenue West. The sill is reported to be 37.5 m thick, with granitic rock in its upper portion beneath 2nd Avenue West. In later studies, this sill was traced northward for a very short distance, and was assumed to be a continuation of the dike which cut the Duluth Complex between Enger Tower and Twin Lakes (Taylor, 1956 and 1964). This sill was exposed again in excavation along Michigan Street and 2nd Ave. West in 1982. This sill is here named Messabi for its occurrence beneath the Messabi (formerly Wolvin) Building on 1st Street, between 2nd and 3rd Ave. W., Duluth.

In the course of field work for this study, several other occurrences of diabasic outcrops were recorded (e.g. in Grant School playground, 11th Street between 9th and 10th Avenue East; at the northeast corner of Kenwood Avenue and Arrowhead Road; a contact of diabase and Duluth Complex at the west corner of Humes Avenue and Buffalo Street). These outcrops together demonstrate almost the same strike as other sills in the Duluth area, and reveal the existence of a continuous but mostly covered diabasic sill in this part of the city. Additional evidence including the occurrence of granitic rock along the strike of this sill in Kenwood Avenue Quarry (near Chester Creek); existence of granitic and intermediate rocks at Cleveland Street (between Humes and Center Avenue); and slight metamorphism observed in the lava along the general strike of this intrusion all support the existence of the sill (see Plate 1). Whether this sill and the one reported by Schwartz are one and the same, or there are two different sills in this part of the city could not be determined because of the lack of outcrops. However, in this study, they are considered one sill until evidence indicates otherwise.

The sill is dark, medium-to coarse-grained, with a diabasic texture. Plagioclase, pyroxene, and titanomagnetite are present, with small amounts of olivine. Large pyroxene grains are common and reach 7 mm in length. Due to lack of outcrop in the northern part, none of the granitic rock exposures could be related to the sill with certainty, but granitic stringers a couple of cm wide are present within the diabase. Intermediate rocks with a grayish red color are observed locally. The texture of intermediate rocks appears to be very similar to the diabasic portion, and they contain abundant elongated pyroxene crystals, some up to a few cm long and a few mm wide. Plagioclase with or without K feldspar composes the main portion of the intermediate rocks.

Lakeside Sill

The base of this sill emerges at the foot of 47th Avenue East and the shore of Lake Superior and continues along, and almost parallel to the shore to 49th Avenue East. It trends northeast and reappears at Amity Creek near Woodlawn Street, where a limited exposure is found; it cannot be followed much farther due to a thick cover of Quaternary lake clay. The sill crops out in three other places inland (see Plate 1). The sill is here named for the Lakeside district of Duluth where it occurs.

In its exposure along the shore of Lake Superior, the Lakeside sill has a thickness of 50 m, and shows a dip of 18 degrees E. A chilled zone appears at both the top and the base of the sill for a few meters where it gradually changes to a medium-grained, slightly porphyritic diabase toward the inner part of the sill. Veins of calcite with disseminated pyrite and chalcopyrite are visible in the upper part of the intrusion. In the very top, curves and features of the base of the overlying intermediate flow, against which the sill intruded are perfectly exposed along the shore of Lake Superior. Two types of inclusions are apparent in the top part of the sill: boulder-sized pieces of the overlying lava flow and cobble-to boulder-sized, ghost-like remnants of coarse-grained igneous rocks. The latter inclusions might have been carried for a considerable distance. The upper contact is almost parallel to the lake shore and can be followed for a few hundred meters. Granitic rocks do not exist in the upper part of this sill. An icelandite flow with a sharp contact occurs at the base. No signs of metamorphism are detected in the flows. In the vicinity of the sill at Amity Creek, a vertical dike 50 m thick cuts the flows and may be an off-shoot or feeder of the sill (dike M', Fig. 22).

Plagioclase forms about 60% of the sill. Crystals are medium to coarse-grained, lathy or tabular in shape, subhedral, with common albite twinning. Local Carlsbad twinning and zoning are present. Augite is commonly coarse-grained, subophitic to ophitic and forms 20% of the rock. The augite crystals are moderately altered at the margins. Olivine is altered and forms a few percent of the rock. Magnetite and ilmenite together form about 6% and are equally abundant. Apatite appears as an accessory mineral and forms about 2% of the sill.

Basalt Dikes

Dike swarms are widely known as evidence for tensional stress relations in continental provinces. These dikes are intruded into intrusive and extrusive rocks. They generally have a dark gray to black color, are fine-grained, exhibit chilled borders, and typically have a north-south strike with a steep dip to the west. Thicknesses of individual dikes in the area range from about 5 cm to more than 20 m; most are between 1 and 4 m thick. A dike occurring in Amity Creek along the extension of Ivanhoe Street shows an abnormal thickness of fifty meters and seems to be an off-shoot (feeder) of the Lakeside sill. Although in a few locations, dikes cut through sills (e.g. A" and B" in Northland Sill), no general statement with regard to the relative age of sills and dikes can be made.

Twenty-one dikes with a total thickness of 35.9 meters cut through the flows on the lake shore. Another seventeen dikes with a total thickness of 118.5 meters were found along the rivers and creeks in the city, and two dikes four and three meters thick are recorded at other locations inland. No correlation between any of the dikes occuring along the lake shore and the dikes in the rivers, creeks and inland could be made. They commonly form small points along the shore, and locally show subhorizontal columnar jointing perpendicular to their contacts. Thin veins of calcite and epidote with or without pyrite and chlorite commonly exist in joints along the walls of the dikes. Considering the number of dikes recorded in the NSVG from Duluth to Two Harbors (Sandberg, 1938), they seem to be highly concentrated in the Duluth area, especially near the Duluth Complex. They occur more abundantly in the lava flows than in the intrusions. All the dikes in the area seem to have a very similar petrography and composition (basaltic composition; see Taylor, 1964 P. 63, Table 14).

Plagioclase, pyroxene, and opaque minerals with minor olivine are the main components and microgabbroic texture is predominant. The thicknesses, dips and strikes of individual dikes are given in Table 9, and their locations are shown in Figs. 21 and 22. the dikes which cut the flows along the shore are designated by A, B, C, ...; the dikes along the rivers by A', B', C', ...; and the inland dikes by A", B".

Table 9: Basaltic Dikes Cutting the Flows of the Duluth Area

	location of dikes (see Figs. 21&22)	sample No.	number of dikes	thickness (meters)	strike	dip
Lake Shore	A	133B	2	1.5	160°	80° W
				0.3	160°	80° W
	B	136B	1	1.0	105°	80° E
	C	138B	2	0.6	150°	~vertical
				2.5	150°	~vertical
	D	139B	1	1.0	150°	70° W
	E	143B	3	0.3	variable	variable
				0.1	variable	variable
				0.05	variable	variable
	F	144B	2	2.2	190°	80° W
				1.0	190°	80° W
	G	145B	1	0.4	90°	80° S
	H	147B	1	0.5	-	-
	I	150C	1	4.7	190°	77° W
	J	165	3	3.0	190°	55° W
				3.0	190°	55° W
				4.0	190°	55° W
	K	219B	1	0.75	180°	70° W
	L	220B	1	4.0	165°	67° W
	M	223E	1	4.0	205°	80° W
	N	223F	1	1.0	190°	70° W
		TOTAL THICKNESS		35.9 m		
Inland Streams	A'	167B	1	1.5	70°	~vertical
	B'	168B	1	1.5	180°	~vertical
	C'	172B	2	1.0	195°	80° W
				1.5	195°	80° W
	D'	173B	1	12.0	90°?	80° S
	E'	182B	1	4.5	180°	70° W
	F'	183D	1	4.0	80°	~vertical
	G'	208E	1	2.0	185°	75° W
	H'	208F	1	6.0	200°	75° W
	I'	226A	1	2.0	180°	12° E
	J'	228D	1	2.0	200°	80° W
	K'	228F	1	3.0	variable	variable
	L'	228I	1	2.5	290°	~vertical
	M'	238	2	0.5	200°	~vertical
				50.0	200°	~vertical
	N'	228K	1	3.0	195°	~vertical
	O'	230C	1	1.5	230°	~vertical
	P'	233A,B	1	20.0	-	-
		TOTAL THICKNESS		118.5 m		
Elsewhere	A"	201N	1	4.0	190°	70° W
	B"	203G	1	3.0	130°	~vertical
		TOTAL THICKNESS		7.0 m		

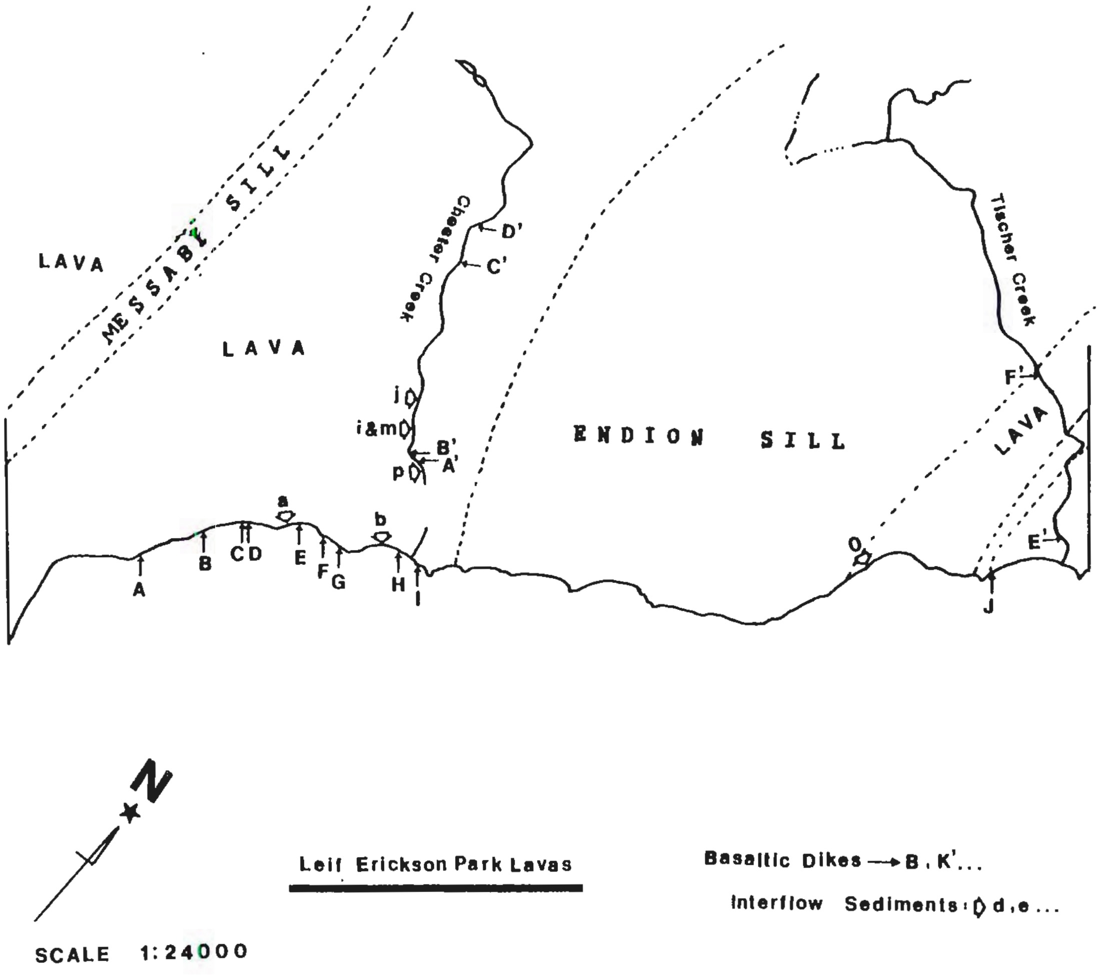


Figure 21: Location of basaltic dikes and interflow sediments from Leif Erickson Park area to Tischer Creek, Duluth, Minnesota

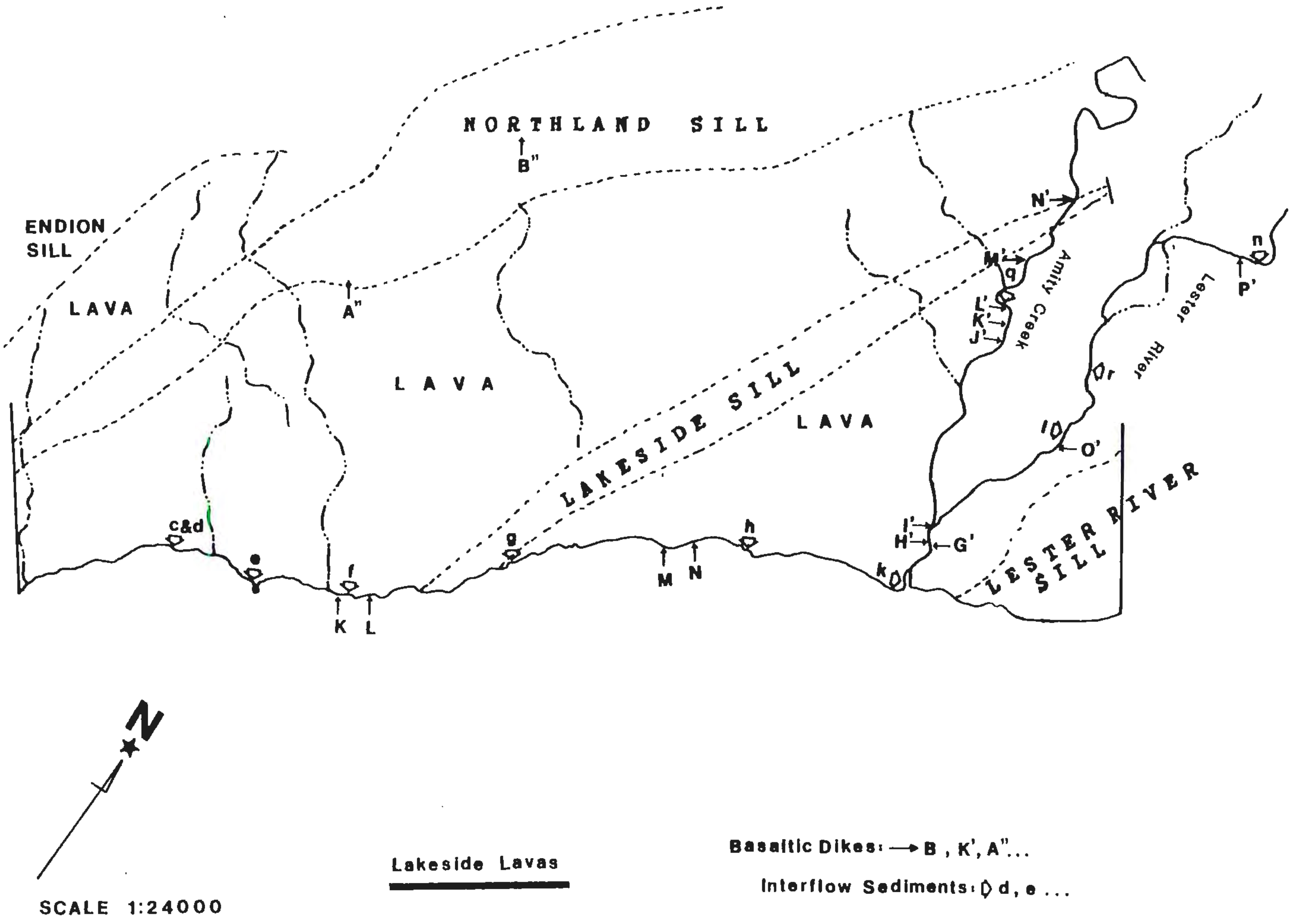


Figure 22: Location of basaltic dikes and interflow sediments from Lakeside area, Duluth, Minnesota

Red Granitic Rocks (Granophyres) in the Duluth Area

Granitic rocks in the Duluth area are exposed mostly as small and scattered pink or red outcrops along the upper portions of the sills, or locally as small dikes in the diabase and gabbro. Some relatively large and continuous bodies, however, occur which show gradational changes from the diabase to the granite. In the southwest part of the study area, granophyre is found in contact with the Duluth Complex and the flows.

The granitic rocks are composed mostly of feldspar and quartz, with a considerable amount of magnetite and less amphibole. Augite, biotite and olivine are rare but may be found locally in small amounts. The feldspars are orthoclase and plagioclase (albite?) in varying proportion, and combined form up to 70% of the rock. The feldspar typically shows graphic intergrowth with quartz, and zoning is common. The feldspars have undergone moderate to strong alteration to epidote, chlorite, kaolinite and other clay minerals and have small inclusions of hematite, which give them a dusty red color. Granitoid and micrographic textures are predominant(Fig. 23), and many feldspars show microperthite, perthite and antiperthite texture. Secondary minerals, mostly chlorite, have replaced part or most of the amphibole grains. Magnetite and ilmenite together form an unusually high proportion for this type of rock.

The origin of red granitic rocks has attracted the attention of geologists throughout the world for almost a century. Their association with diabasic rock has been recognized and described, but the genetic relationship between them still remains a petrologic problem. Different origins or a combination of various origins have been proposed by different workers. The red rock has been argued to be a *separate intrusion from diabase;* formed due to *the fractional crystallization of basaltic magma in situ; the assimilation or melting of rhyolitic flows;* and *the result of metamorphism of felsic lavas*. Although most of the workers agree that the red granitic rocks originated by igneous processes, not enough documentation to firmly advocate a single origin and to illustrate a form of evolution has been presented as yet. Specific bodies have undoubtedly formed as a result of different local combinations of circumstances and processes.

In general considering the occurrence, volume, composition and associated rocks of the red granitic rocks in the Duluth area, the hypotheses of assimilation of rhyolite, metamorphism of felsic units by diabase sills, and fractional crystallization of diabase sills or the Duluth Complex, all seem to be plausible, but none wholly satisfactory. More than one origin was probably involved in the formation of the red granitic intrusive rocks in the Duluth area.

INTERFLOW SEDIMENTS

Jirsa (1980) studied the interflow sediments of the NSVG between Duluth and Grand Portage. In the Duluth area his study includes five interflow sediment layers (D_1 -D_6), occurring along the shore of Lake Superior. In the present study three occurrences which he located and measured (D_2, D_4, D_6 which are the same as a, b, and k of this study) were found, but the other two (D_1 and D_3) could not be located. However, an additional 11 interflow sediment units were also identified and mapped, for a total of 14 units.

Eight of these beds occur along the shore of Lake Superior (Units a through h; Figs. 21&22), and the other six crop out in the rivers (Units i through n). These interflow sediments all occur on top of flows and dip at moderate angles to the east. Furthermore, another four clastic dikes (o, p, q, r) were observed: along the shore of Lake Superior (o), in Chester Creek (p), in Amity Creek (q), and in the Lester River (r) respectively.

The sedimentary rocks in the study area were deposited by fluvial processes (Sandberg, 1938; Jirsa, 1980). Their total thickness is about 50 meters and they appear mostly red and brown due to hematite and limonite cement, but gray and greenish sediments are also present; the later ones show a rather intense chlorite or epidote alteration. The sediments are commonly sandstone with subrounded to rounded grains.

The interflow sediments along the lake shore include one moderately thick tuffaceous sandstone unit (a), one very thick sandstone unit (b), and six thin beds (c to h). The thicknesses, dips and strikes of sedimentary units is given in Table 10, and their locations are shown in Figures 21 and 22.

The tuffaceous sandstone (a), is three meters thick with a grayish brown color and laminations of approximately one centimeter thickness. The rock is composed of abundant sand-size shards and vesicular particles with minor amounts of other grains, mainly feldspar with minor quartz (Fig. 24). The grains are surrounded by a cement of very fine-grained quartz, chlorite and small amounts of zeolite. The grains are subangular, moderately sorted and the rock is moderately to well cemented. The feldspar grains are partly to mostly converted to epidote. The volcanic grains (shards) are altered to a complex of secondary minerals with many dark spots. The subangularity and relatively immature character of the grains forming the rock indicate a limited distance of transportation.

The thick sandstone unit (b) in Leif Erickson Park, is gray, green and brown, fine to medium-grained, irregularly cross-bedded sandstone with a thickness of 34.5 meters (Fig. 25). It lies on a mafic lava unit and is cut on top by a dike which has been intruded along a fault. Feldspar and opaque minerals with minor amounts of quartz form the great majority of the grains. Chlorite, epidote and carbonates are common secondary minerals and appear in the form of cement. The grains are well sorted and

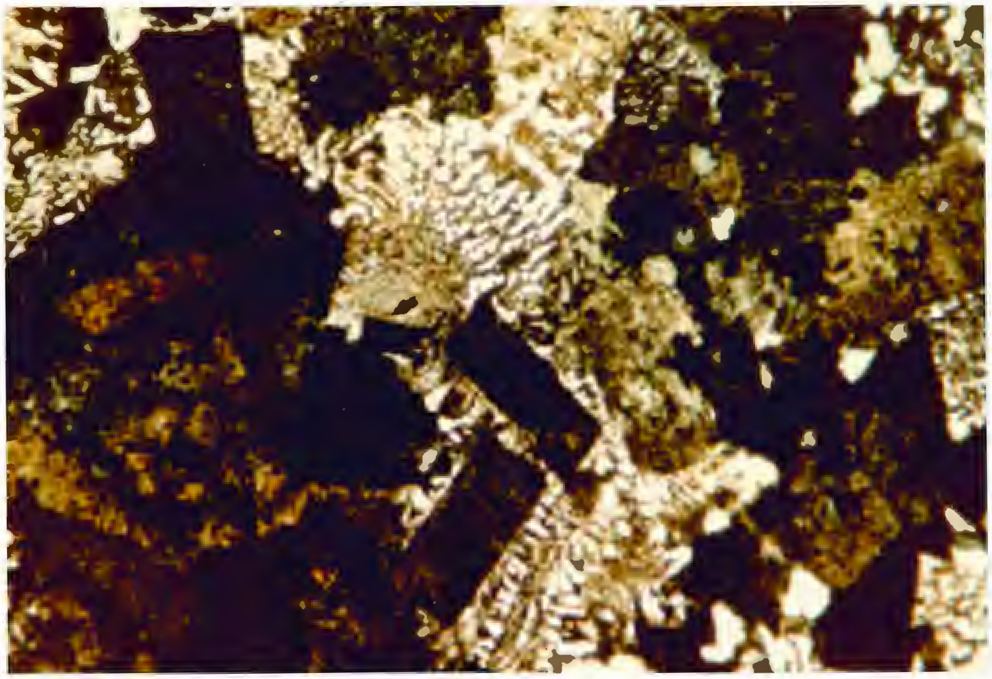


Figure 23: The radiating-fringe type micro-graphic texture with a central core of feldspar; quartz-feldspar intergrowth radiates outward. Outcrop location 184C (Crossed nicols, field of view 10 mm)

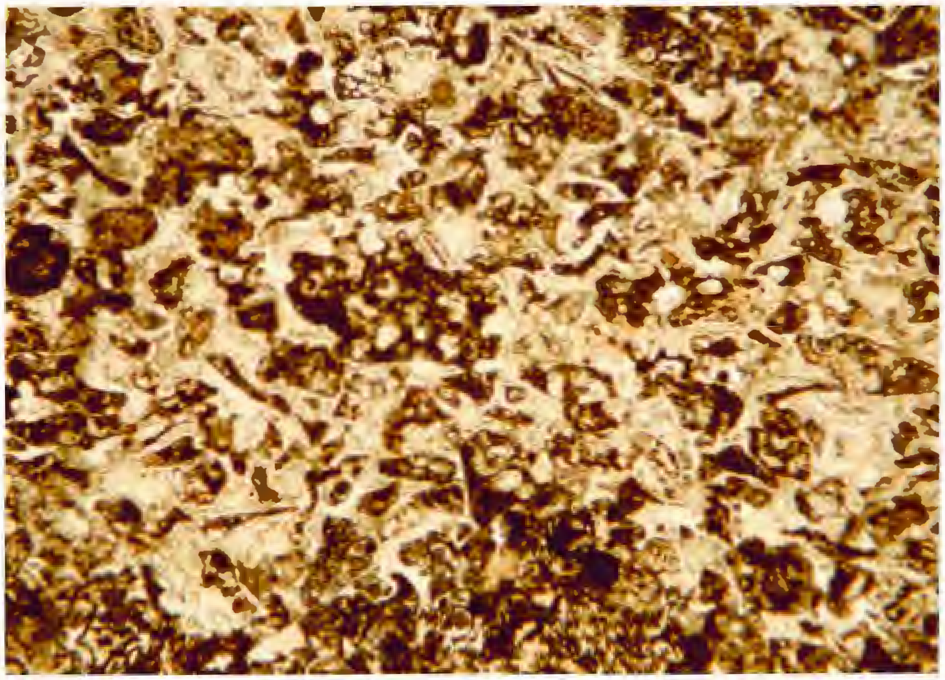


Figure 24: Tuffaceous sandstone. A well cemented interflow sediment with an abundance of shards and minor amounts of other grains. Unit a, outcrop location 141 (One polar, field of view 4 mm)

moderately cemented. Jirsa (1980) found a high percent of heavy minerals (25.4%) in this sedimentary rock, of which 91.1% are epidote, 4.1% apatite, and a trace amount of clinopyroxene, altered olivine, zircon, and rutile. He found this unit to be a meandering stream deposit (P. 59). This sedimentary layer seems to crop out inland in Chester Creek between 1st Street and 3rd Street as two parts, a thinner layer on top of a felsite flow and a thicker part beneath this flow (units i and j).

The rest of the sedimentary beds along the shore (c, d, e, f, g, and h) are thin, medium-grained sandstones which filled in between the breccia fragments occurring in the upper parts of flows (aa tops), and some form lenticular bodies or irregular sheets on top of volcanic units (Fig. 26). They are commonly less than one meter thick and locally show cross-bedding. Feldspar grains form about sixty percent of these rocks; they are somewhat altered to sericite, kaolinite and epidote. Magnetite grains form ten percent of the rocks and are partly to totally altered to hematite; quartz grains form only about 6% of these sediments. Cement forms about 20%, and is mostly chlorite, but zeolite locally forms a small portion. Grains are commonly well sorted, fairly well-rounded, moderately cemented and dusted by hematite (Fig. 27).

The interflow sediments found in Chester Creek (i and j units) are continuations of the thick sandstone (b unit) that is exposed along the lakeshore and have the same characteristics. Sedimentary units (k, l, and n) occur in the upper parts of

Figure 25: Base of thick, cross-bedded sandstone, along the shore of Lake Superior, Duluth Leif Ericson Park. (Unit b, location 147)

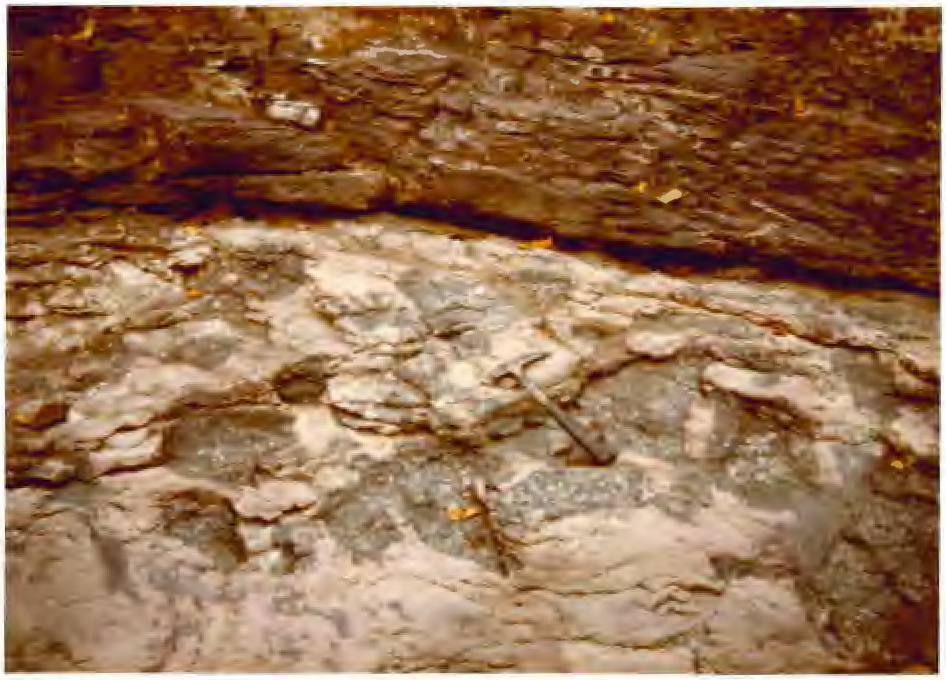


Figure 26: Interflow sandstone filling the space between rubble (aa top) of a quartz tholeiite flow. (Unit f, location 219C)

rubbly-topped flows in the space between the cobble to boulder-sized breccia fragments as lenticular layers of about one meter thick and are similar to sediment beds described in the previous paragraph. The layer (m), however, shows somewhat different alteration from the rest of the interflow sediments in the area. It occurs in Chester Creek just east of 3rd Street and appears to be about four meters thick. Field and microscopic studies could not determine whether this unit is a continuation of the thick sandstone (b, i, and j), or is a separate sedimentary layer. It is a brownish gray, fine to medium-grained sandstone, with thick laminations, and an unusual type of alteration. The rock is composed of well sorted, rounded grains with about ten percent cement which is made of a complex of altered minerals. Plagioclase grains which form about 75% of the rock are moderately to highly altered to carbonate minerals and small amounts of epidote. Magnetite forms about eight percent of the unit. Zeolite and epidote are present in roughly equal amounts. The alteration gives a mottled appearance to the rock, which shows greenish rounded spots ranging in size from 1 mm to more than 1 cm in diameter. The spots are commonly connected together through narrow veins. They are composed of 60% epidote, 25% magnetite, 10% plagioclase, and a few percent chlorite.

The clastic dikes have thicknesses of a few centimeters and fill fissures in the flows. They have a color varying from gray to green to pinkish and appear to be well sorted sandstone.

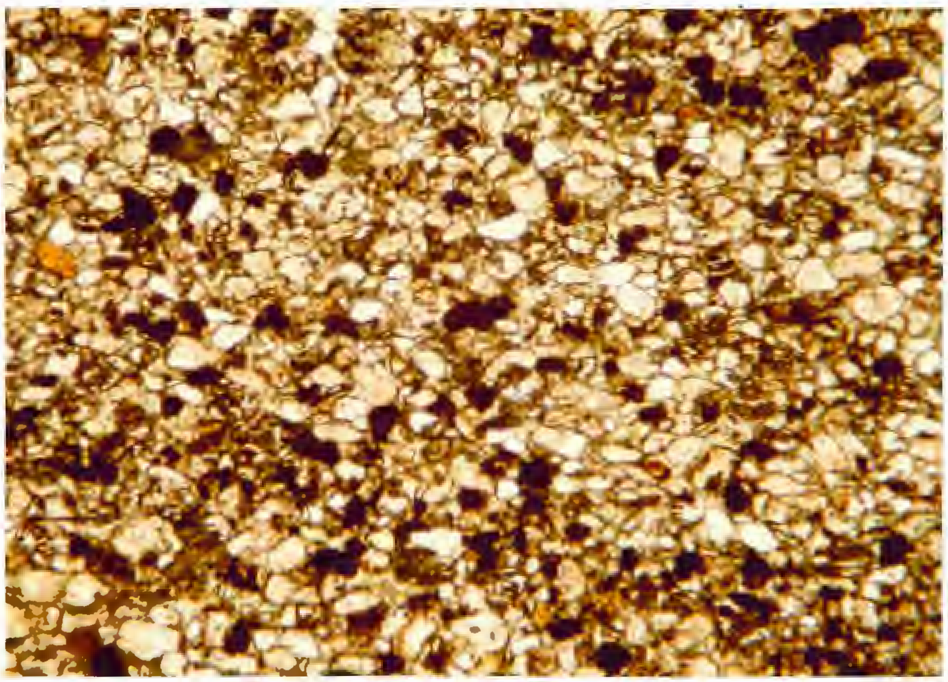


Figure 27: Moderately sorted, moderately rounded volcanic sandstone with about 20% chlorite as cement. Unit k, location 208C (One polar, field of view 12 mm)

Table 10: Interflow sediments of the Duluth arera

	location (see Figs. 21&22)	sample No.	thickness	strike azimuth	dip
Lake Shore	a	141	3 m	185°	35° E
	b	147	34.5 m	140°	12° E
	c	215 B	filling the space between rubble	-	-
	d	216 B	filling the space between rubble	195°	20° E
	e	217 D	filling the space between rubble	-	-
	f	219 C	filling the space between the space	190°	25° E
	g	222 B	filling the space between rubble	-	-
	h	223 G	1 m	210°	25° E
Inland Streams	i	168 A	continuation of unit b	210°	17° E
	j	170	continuation of unit b	210°	15° E
	k	208 C	~1 m	240°	10° E
	l	230 D	~1 m	210°	13° E
	m	169 B	4 m	200°	20° E
	n	234 B	1 m	200°	22° E
Clastic dikes	o	163 B	0.1 m	65°	80° N
	p	167 A	0.04 m	140°	variable
	q	228 G	0.02	260°	vertical
	r	231 B	0.30	260°	vertical

ALTERATION and METAMORPHISM

Alteration

In this section an effort has been made to define any change(s) in the primary composition of flows caused by alteration. The alteration and burial metamorphism are found to have somewhat similar effects on the volcanic rocks of the Duluth area, and the following discussion under the title of alteration may show their combined effects. Alteration of volcanic rocks in the study area is viewed from three lines of investigation:

A - Alteration products.

B - The oxide molecular proportions of rocks (Beswick and Soucie, 1978).

C - Classification of altered flows based on their mode and CIPW norm.

Volcanic samples which have been chosen for analysis in this study have been representative of the massive portions of the volcanic units. Care has been taken so they are free of veins and amygdules. Nevertheless, all of the analyzed samples have been altered to some degree.

A universally recognized and accepted method has not yet been introduced to determine the degree of alteration in volcanic rocks. In most cases, geologists have simply attempted subjectively to distinguish rocks which have been altered "too extensively", from the rocks which are thought more nearly to represent the primary composition of the flow. In the following discussion, an effort was made to use some of the most suitable criteria developed by other workers to define the degree of alteration of volcanic rocks of the Duluth area, by interpreting the rock analyses of this region. This, in the end, may give a reasonable indication and a good estimation of the extent of alteration in these rocks.

A - Alteration products:

The volcanic rocks of the study area are affected by alteration with various intensities depending on their composition. In general, the felsic rocks are more altered than intermediate or mafic units. Alteration commonly embraces most of the thickness of a felsic units and gives a pinkish color to these rocks. Less altered parts of felsic units appear as brown patches. These patches are scattered throughout some of the felsic units in a random fashion and show rather sharp contacts with the pinkish-colored, altered parts (Fig. 17). The microscopically visible difference between the altered and less altered part of felsic rocks is a few percent magnetite which still exists in the less altered portion, but is absent in the altered part. Amygdaloidal tops and bases of intermediate and mafic flows also show considerable alteration.

The secondary minerals have totally replaced the intersertal glasses; have partially or almost totally replaced the groundmass minerals; and partially (e.g. plagioclase and augite) or totally (e.g. olivine) replaced the phenocrysts of the flows. However, none of the flows is completely converted to secondary minerals (at least in their massive central portions), and the primary textures of rocks are generally well preserved. The secondary minerals have also filled vesicles and appear as amygdules; they also occur in veins in numerous places in the Duluth area.

Secondary minerals are as follows:

Calcite is abundant in the veins and amygdules and as an alteration product of some of the original minerals, particularly feldspars, and less commonly pyroxene. In some of the flows calcite replaces the primary crystals completely and the replaced minerals cannot be identified. In rare cases calcite forms up to 15% of flows, but commonly it makes up only a few percent or less.

Epidote is one of the most common alteration products in the Duluth area and appears in about half of the flows in various proportions. The quantity of epidote ranges from less than 1% to more than 40% of lavas with an average of about 7%, and samples with 20% epidote are not rare. Epidote not only is an alteration product of primary minerals, but also replaces the intersertal materials (glasses?) which had filled the spaces between the crystals in the last stage of crystallization. Many veins and amygdules, especially in the lower portion of the sequence, contain epidote.

Chlorite appears in 1/4 of the flows of the area and commonly occurs with epidote. It occurs as a pseudomorph of some of the primary phenocrysts - particularly olivine and to a lesser extent, plagioclase and pyroxene. It also replaces part of the groundmass and intersertal glasses of some of the flows. Chlorite, commonly along with epidote and with or without the other secondary minerals, also appears in the veins, fissures, and amygdules of some flows. In the flows in which chlorite replaces the phenocrysts, its amounts approach 20% of the rocks. In the other instances it forms only a few percent. Chlorite, on the average, comprises about 7% of the samples examined.

Quartz as a secondary mineral occurs in the veins and amygdules of a limited number of the flows. The secondary quartz is more prominent in felsic rocks where it is locally abundant in the groundmass (Figs. 19 and 20).

Kaolinite, sericite, serpentine, iddingsite, hematite, actinolite, and sphene are the other secondary minerals found commonly in small amounts within the volcanic rocks of the study area. Kaolinite and sericite are for the most part alteration products of feldspars. Serpentine and iddingsite appear as replacements of olivine grains. Hematite is the result of oxidation of the titanomagnetite minerals and Fe-rich silicates. Actinolite is rare and occurs at the altered edges and cracks of some of the augite crystals. Sphene may be present around the opaque minerals, and occasionally forms a complete halo around them. Coarser-grained, subhedral to anhedral crystals of sphene are locally observed, particularly in the lavas affected by contact metamorphism.

Amygdule Minerals:

Amydules in the lower part of the sequence (west part of area, consisting in major part of the Leif Ericson Park lavas of Green (1972a; 1972b)) are filled mostly by epidote and chlorite; calcite and feldspars and rarely andradite form the minor minerals. In the middle of the sequence calcite and quartz are the predominant minerals, accompanied by small amounts of feldspar and/or chlorite, and/or epidote. The amygdules of some flows of the middle part are filled with plagioclase, or pyrite and chalcopyrite (Figs. 28 and 29). This zone extends for a limited thickness and could be considered as a transitional zone between the upper and lower parts.

Amygdules in the upper part of the sequence (east part of area, consisting in major part of the Lakeside lavas of Green (1972a; 1972b)) are mostly filled with calcite, laumontite, quartz, and chlorite with locally a small amount of epidote. Opaque minerals (magnetite, ilmenite plus or minus pyrite) are commonly present in the amygdules of the majority of flows and locally may be abundant. Fluorite, apatite, and actinolite are locally present in minor amounts.

The veins in the lower part of the sequence are filled with epidote, calcite, chlorite, plus or minus quartz, whereas in the upper part, calcite appears to be almost the only mineral present in the veins. Sulfides (pyrite and chalcopyrite) locally may be found in very small amounts as scattered crystals in the veins of the Duluth area.

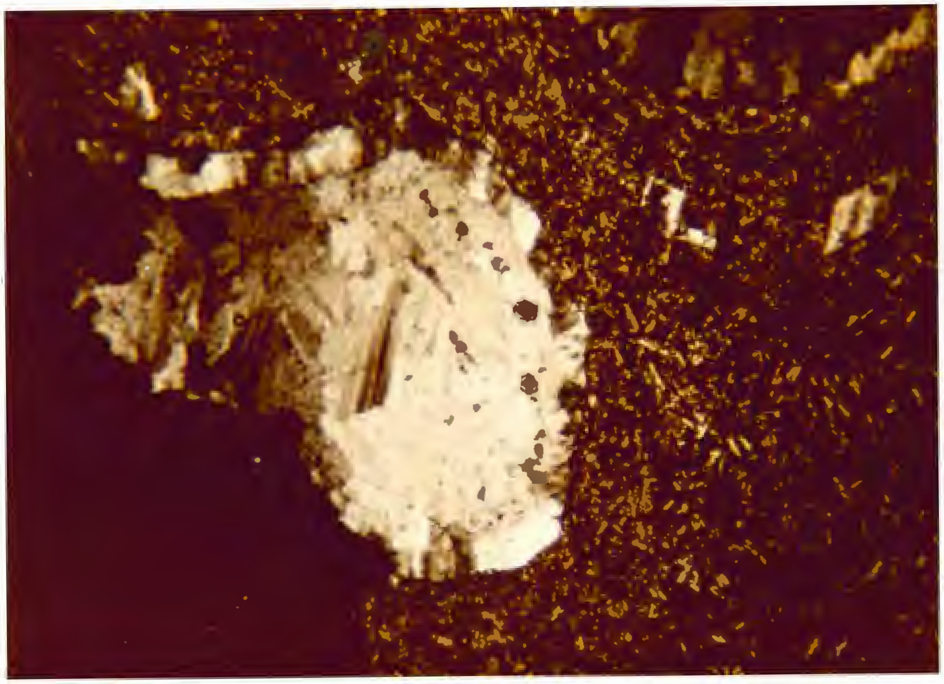


Figure 28: Amygdule in andesite filled with plagioclase. (Crossed nicols, field of view 10 mm) Unit LEP-38

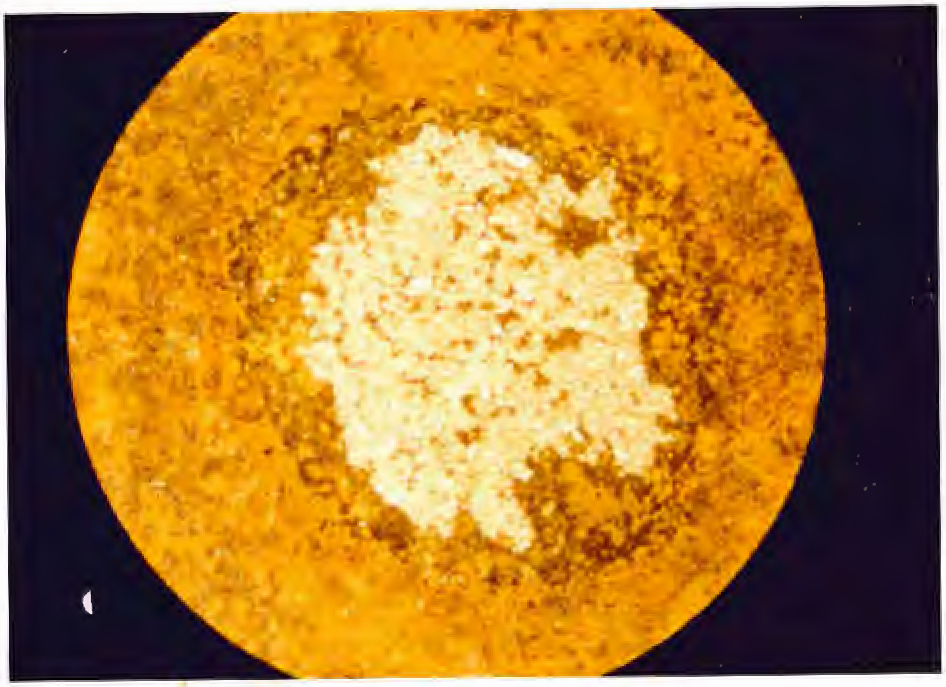


Figure 29: Amygdule in andesite filled with chalcopyrite, pyrite and minor amount of chlorite and epidote. (Reflected light, field of view 4 mm) Unit LEP-45

B - The oxide molecular proportion of rocks as a clue to alteration

Alteration and burial metamorphism may remove or add one or more elements to the primary composition of a rock. This phenomenon is particularly important in Tertiary and older volcanic rocks that have been buried to considerable depth and thus saturated in heated groundwater (Jolly and Smith, 1972). In a sequence of rocks which have undergone such metasomatism, chemical classification of rocks must be done with circumspection. Depending on the degree of change and the elements involved, relationships between the chemical characteristics and tectonic environment may be inconclusive, and genetic interpretations can be misleading (see Petrology Chapter).

Although the sequence of volcanic rocks in the Duluth area is basically tholeiitic, as established in the petrology chapter, some of the samples show dispersion from the general trend, and fall near the limits or slightly outside of the tholeiitic field. This phenomenon is also found elsewhere in the Keweenawan lavas and in other Pre-Tertiary volcanic rocks. These dispersions are believed to be due to metasomatic alteration processes (Beswick and Soucie 1978, P. 236). In order to examine the validity of classification of the rocks in the study area, and to evaluate the relationship between their composition and tectonic setting, determination of their primary composition and the kind and intensity of any change in their composition is profoundly important.

Beswick and Soucie (1978) proposed a method that can be a great help in approaching the above objective. In this method, the oxide molecular proportions obtained from rock weight percent analyses are presented on X, Y, and Z axes (e.g. SiO_2=X, Na_2O=Y, K_2O=Z, etc.) and the log X/Y vs. log Y/Z are plotted on a diagram (e.g. Fig. 30a). A single X/Y/Z diagram does not demonstrate all the possible change(s) in X/Y and Z accurately. In order to increase the usefulness of the procedure, they proposed a set of diagrams with different X, Y, and Z ratios. They plotted 580 samples of volcanic rocks from Chile, Mexico, Atlantic Ocean, Hawaii, and northwest Iceland in this manner. They found that regardless of whether the suite of rocks is subalkaline, calc-alkaline, or alkaline, they all show "well defined trends" for each comparison of the oxides chosen. The method is based upon two assumptions:

1 - The altered Pre-Mesozoic volcanic rocks had the same initial composition as Post-Mesozoic volcanic rocks and show the same trends.

2 - The Al_2O_3 is an immobile oxide during alteration.

In order to define any change in primary composition of the rock, the log ratio of oxides is plotted in pertinent diagrams. Any dispersion from the determined trends is an indication of change(s) in primary composition. The farther the point representing a sample falls outside the trend, the more intense the change(s) have been. They applied this method to several volcanic sequences and determined the compositional changes which had occurred in the rocks after formation (e.g. samples of the Archean Timagami greenstone belt, northeast Ontario).

In this section, the samples from the Duluth area are plotted in Figures 30b to 30h. Since K_2O is one of the most mobile oxides , and very susceptible to metasomatism, and also due to the relatively high percentage of this oxide in the volcanic rocks of the Duluth area, this oxide was chosen as a ratioing oxide. In addition, two diagrams with Na_2O as the basis of the ratio are also presented to confirm the results. The K_2O mostly remains in the liquid phase during fractionation, and so, the more fractionated magmas become, the more enriched in potassium the resultant rocks become. Since the percentage of SiO_2 also increases during fractionation, although at a lower rate, the felsic rocks fall near the origin of figures with K_2O as ratioing oxide, whereas the more mafic rocks plot farther from the origin.

As the figures show, most of the samples of the study area fall within or close to the trends of modern volcanic rocks, although a few show considerable dispersion. There are considerable numbers of anomalous samples in some of the figures. These samples appear to indicate considerable local effects of metasomatism. The farther samples fall from the modern volcanic trends, the greater the amount of change in primary composition that can be inferred. Since the specific changes of elements in every sample would make this discussion very lengthy, in the following pages only the common changes of the sequence as a whole will be discussed.

In Figure 30b ($Al_2O_3/SiO_2/K_2O$), samples fall within the limits of modern trends. Based on the assumption of the immobility of Al_2O_3 in alteration processes, the initial amount of SiO_2 also appears to have remained unchanged, while the concentration of samples in the lower part of the trend suggests an increase in the amount of K_2O.

Figure 30c (SiO_2/Fm/K_2O) suggests an increase in the amount of K_2O for a majority of samples, considering the fact that any change in K_2O causes the samples to move along a line with 45 degree slope. This figure also suggests a possible Fm increase in quartz tholeiite and intermediate rocks, consistent with the recognized strong primary iron-enrichment trend of the series.

In Figure 30d (CaO/Al_2O_3/K_2O), the amount of K_2O shows increases and that of CaO suggest decreases particularly in felsic rocks, and so, the samples have fallen on the lower left side of the trend. Mafic rocks show a lesser decrease in the amount of CaO.

Figures 30e (CaO/Fm/K_2O) and 30f (CaO/SiO_2/K_2O) support the increase in the amount of K_2O. They may also show an Fm increase in quartz tholeiite and intermediate rocks and a decrease of Fm in felsic rocks. Depletion of CaO especially in intermediate and in felsic rocks, is also implied by Figures 30e and 30g (CaO/Fm/Na_2O). The olivine tholeiitic flows occur close to the primary trend, and do not show a demonstrable change. Quartz tholeiite and intermediate flows exhibit a considerable enrichment in Fm, and/or depletion in Na_2O. Furthermore, drastic dispersion of felsic rocks suggest a considerable decrease in amount of Na_2O for this rock type. Figure 30h (SiO_2/Fm/Na_2O)

indicates a considerable depletion in Fm for felsic rocks. This figure also shows higher log SiO_2/Na_2O value for felsic rocks; since SiO_2 is proven constant (Fig. 30b), it can be deduced that Na_2O has decreased in these rocks.

It can be concluded that in the volcanic rocks of the Duluth area, the amount of SiO_2 has remained unchanged and the amount of K_2O either has been abnormally high in the parent magmas or has increased during alteration. The quantity of Fm in olivine tholeiite remained almost unchanged, but it is considerably increased in quartz tholeiite and intermediate flows. This probably is a primary feature since most of the suites used as reference by Beswich and Soucie (1978) did not show the strong continental iron enrichment trend so typical of Keweenawan magmas in general. Felsic rocks show a considerable decrease in Fm. Felsic rocks also exhibit depletion in CaO and Na_2O, but more mafic rocks do not show a significant change in these oxides.

Considering the fact that any change in the amount of K_2O will affect log SiO_2/K_2O extensively, and will cause a marked displacement of samples from limits of modern trends, the proximity of samples to this trend may express only a rather slight increase in K_2O. However, in general felsic rocks show more increase in K_2O than mafic flows.

Since Fm included the FeO and MgO collectively, any change in its amount may have been due to change of either or both of them; more precise determination may be made with regard to the FeO/MgO ratio of each individual rock sample.

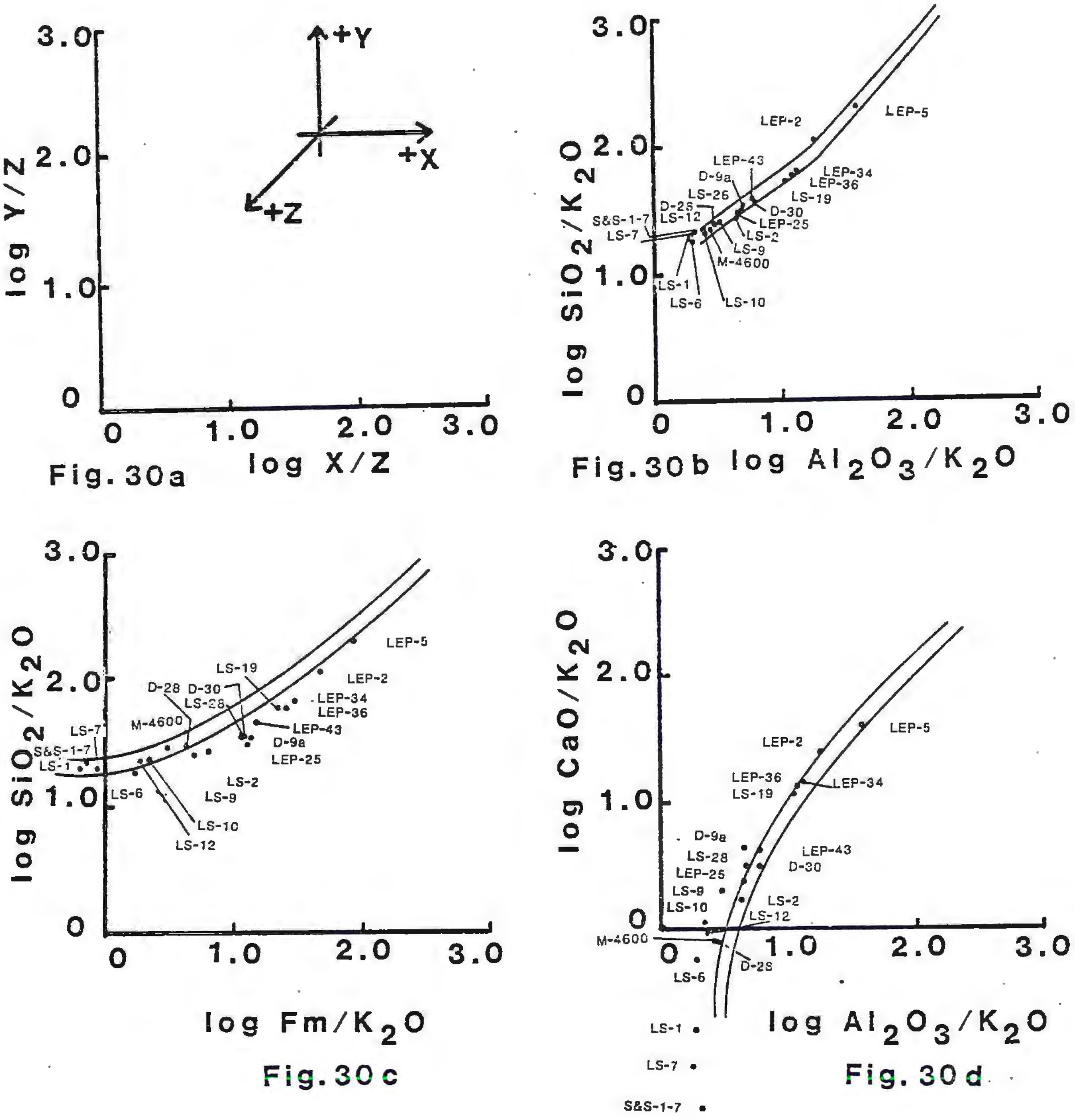


Fig. 30a

Fig. 30b

Fig. 30c

Fig. 30d

Figure 30a to 30h: Logarithmic oxide molecular proportion ratio (LMPR) plots (Figs. 30b to 30f K_2O denominator; Figs. 30g and 30h Na_2O denominator) for volcanic rocks of the Duluth area. The limits of the trends for modern suites are shown by the solid lines. (Note: Fm is the sum of molecular proportions of total FeO and MgO). After Beswick and Soucie, 1978

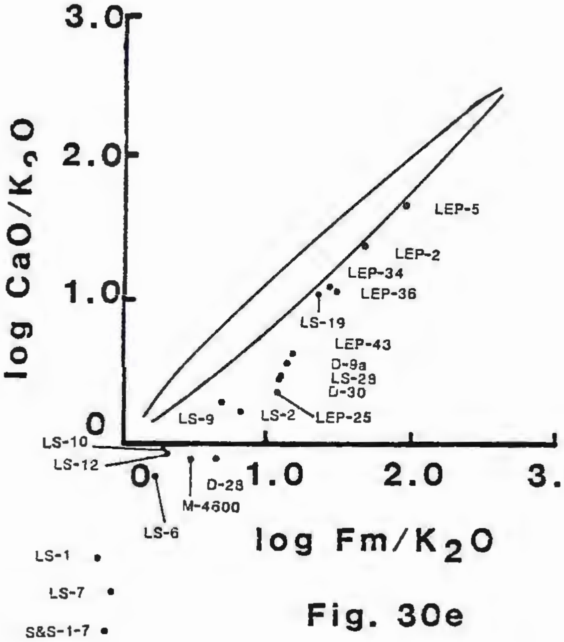


Fig. 30e

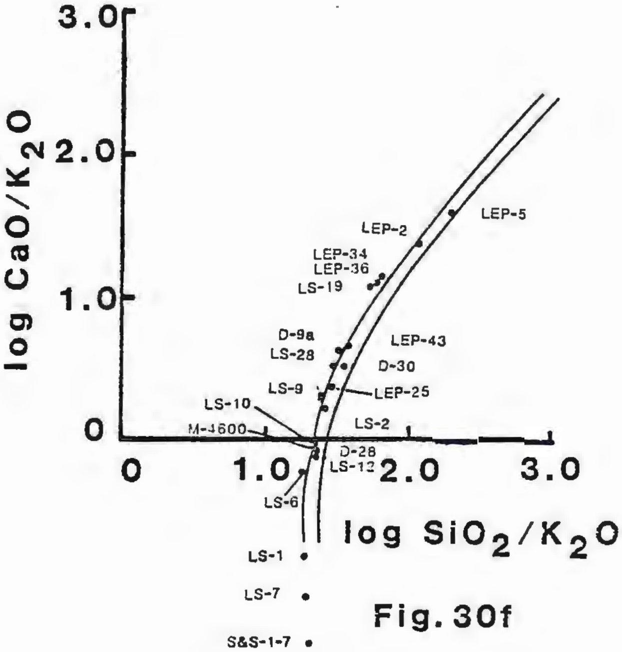


Fig. 30f

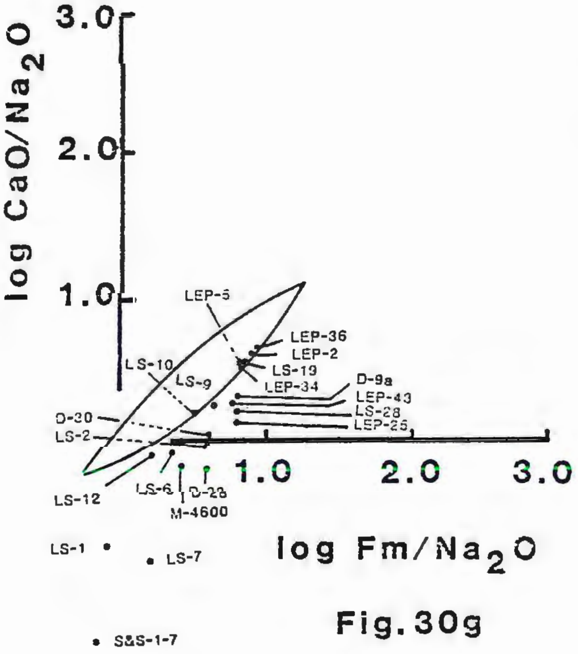


Fig. 30g

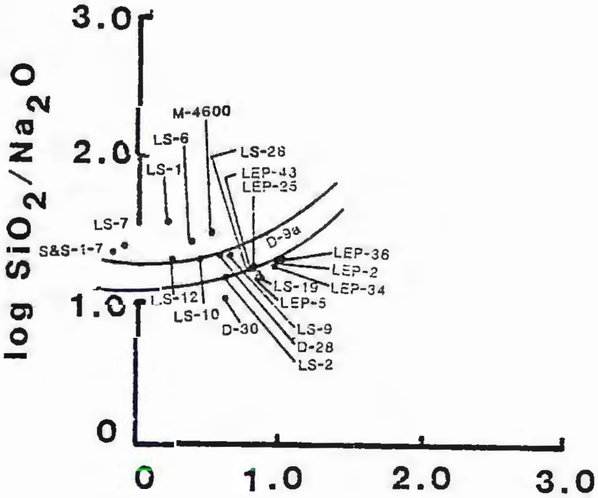


Fig. 30h

C - Determination of altered flows based on their mode and CIPW norms:

Irvine and Baragar (1971, P. 525-526) pointed out the importance of volatiles (H_2O, CO_2, and O_2) in the chemical classification of rocks. They also refer to the considerable changes which occur in the amount of alkalies and the ratio of Fe_2O_3/FeO in alteration processes. They proposed, in the cases in which the amount of volatiles exceeds two or three percent of rock composition, that analyses should be recalculated to 100 percent without volatiles. They also recommended that, for rock analyses in which the percentage of Fe_2O_3 is more than TiO_2 + 1.5, the excess of Fe_2O_3 should be converted to FeO. However, they have not specified which chemical composition suggests an altered rock or what percent of volatiles and/or Fe_2O_3/FeO ratio indicates extensive alteration and which rock analyses should be rejected. Chayes (1966), in working with alkaline and subalkaline basalts, rejected the data of rocks which showed a Fe_2O_3/FeO ratio greater than 0.6. Miyashiro and Shido (1975) considered the rocks with Fe_2O_3/FeO of more than 0.5 and/or H_2O of greater than 2.0 percent altered and rejected such analyses.

For the study area the following criteria are found to be the most suitable and are used:

1 - Volatile content. In the cases in which the total chemical composition contains more than 3.8 percent total H_2O and CO_2, the rocks are considered to be intensely altered. This percentage of volatiles as an indicator of altered rocks has been

used in the past for this purpose by other geologists (e.g. Wilson et al., 1965; Brooks et al., 1969). According to this procedure only one of the samples (sample LS-9) in the study area, with 4.77 percent volatiles, may be suspected of being "intensely" altered (Table 11).

2 - Abnormal normative minerals. Gélinas et al. (1977) in the study of the Abitibi Volcanic Belt, Quebec, considered the existence of corundum, nepheline, and wollastonite in the CIPW norm of subalkaline volcanic rocks as a possible indication of considerable alteration. In the study area, six samples (LS-7, LEP-5, D-28, S&S-1-7, LS-1, LS-2) contain some amount of corundum or nepheline in their norms (Table 11) although the amounts are small.

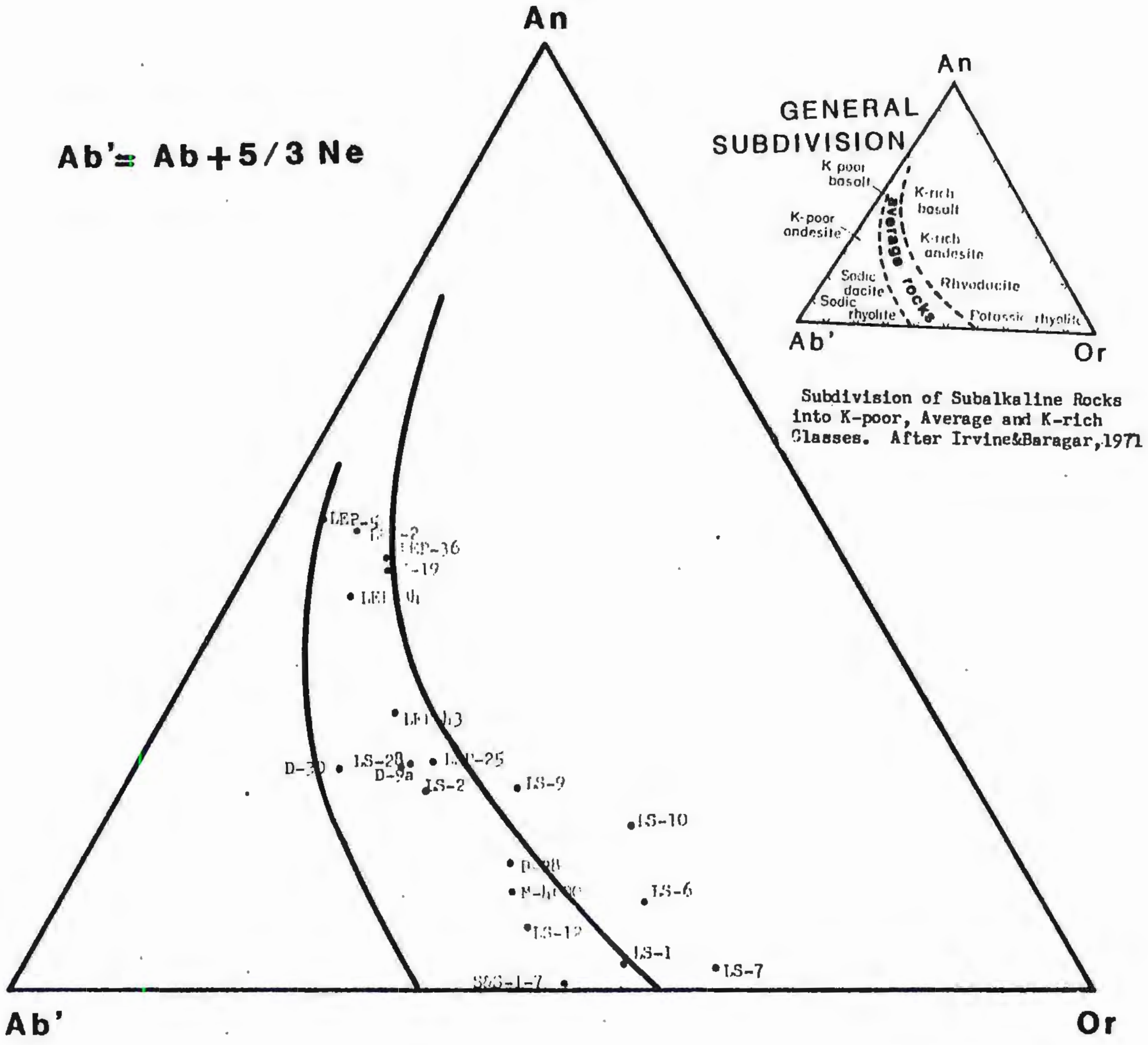
3 - High Potassium content. Gélinas et al. (1977) in the same study, also used the diagram proposed by Irvine and Baragar (1971) for normative anorthite, albite, and orthoclase for subalkaline rocks. The rocks in which the chemical composition had fallen in the potassic field of this diagram were considered altered and their analyses were rejected. The chemical compositions of twenty rocks from the Duluth area are plotted in this diagram (Fig. 31). Four of these analyses (LS-9, LS-10, LS-6, LS-7) fall in the potassic field.

For a final determination of the degree of alteration of a rock and to decide whether or not its analysis should be rejected, more than one criterion should be used. Gélinas et al. (1977), considered a sample intensely altered and rejected its analysis if it contained more than 3.8% volatiles and corundum appeared in its norm. They called it "the most common combination for rejection".

However, the above combination of criteria will not lead to rejection of any rock analyses in the study area, although samples LEP-5, LS-6, LS-7, LS-9, and LS-10 show the greatest indication of some degree of alteration. Table 11 summarizes these indices of alteration for the Duluth extrusives.

Table 11: Volatile content and abnormal normative minerals in analyses of volcanic rocks, in the Duluth area

Sample No.	Volatile Contents (H_2O+CO_2)	Abnormal Normative Minerals and Their Weight Percent	
LEP-2	0.38%	-	-
M-4600	0.89	-	-
D-28	0.81	Corundum	0.31
LEP-5	2.92	Nepheline	0.64
D-30	2.92	-	-
LEP-25	2.23	-	-
LEP-34	3.15	-	-
LEP-36	1.00	-	-
LEP-43	2.31	-	-
S&S-1-7	0.28	Corundum	0.85
LS-1	0.92	Corundum	0.10
LS-2	3.31	Corundum	0.80
LS-6	2.38	-	-
LS-7	0.92	Corundum	1.56
LS-9	4.77	-	-
LS-10	3.77	-	-
LS-12	2.46	-	-
LS-19	2.54	-	-
D-9a	3.09	-	-
LS-28	2.92	-	-



Subdivision of Subalkaline Rocks into K-poor, Average and K-rich Classes. After Irvine&Baragar,1971

Figure 31: Normative feldspar compositions of twenty rock samples from the Duluth area.

Metamorphism

Volcanic rocks in the study area have undergone two types of metamorphism: I-regional (burial) and II-contact metamorphism.

A - Regional metamorphism

Regional metamorphism of the flows was caused mostly by chemical reaction with heated percolating fluids. Burial of flows and associated sedimentary rocks subjects them to higher pressure and temperature. With water in the environment, reactions between the minerals and fluid begin. These reactions have continued to different degrees depending upon the depth of burial and the compositions of minerals as well as the permeabilities of each local volume of rock. However, the primary fabric and texture of the flows tend to remain unchanged by burial metamorphism.

In this section the mineral assemblages in different parts of the area will be defined and metamorphic grades will be discussed accordingly.

The regional (burial) metamorphism of lava flows of Lake Superior have been described by many geologists who have worked with this sequence of extrusives (e.g. Kilburg 1972, and Green 1972a in the North Shore Volcanic Group; Jolly and Smith, 1972 in Portage Lake Volcanics, northern Michigan; Smith, 1974 in the Mamainse Point basalts, Ontario). In this study the degree or grade of burial metamorphism is mainly based on the classification of Turner(1968). Turner divided low-grade, low-pressure regional metamorphism into (1) zeolite facies; (2) prehnite - pumpellyite facies; and (3) greenschist facies.

1 - Zeolite facies: Characteristic mineral assemblages of the zeolite facies in New Zealand (a type locality), include zeolites, quartz, albite, plus or minus chlorite and sphene. This facies forms at a depth of 3 to 10 km and could be formed at depths as great as 15 km (Turner, 1968, P. 266). The pressure is in the range of 0.5-4 kb, and the resulting temperature up to 160°C. (Turner 1968, P. 360). The upper portion of the sequence of flows in the Duluth area contains large amounts of zeolite and calcite, and minor amounts of quartz and chlorite which are best developed in the veins and amgydules, and their burial metamorphism could be regarded as zeolite facies.

2 - Prehnite-pumpellyite facies is defined by the abundance of prehnite and pumpellyite. Development of this facies is at a depth of about 10 to 20 km, with corresponding load pressure of 2.5 to 5 kb, and the temperature of around 200 ±50 degrees C. (Turner, 1968, P. 360). This facies commonly occurs between the zeolite and greenschist facies and shows the assemblage quartz - albite-chlorite-sphene, plus or minus epidote, calcite, muscovite, stilpnomelane, and lawsonite in addition to the prehnite and pumpellyite. Prehnite and pumpellyite have not been found in the Duluth area and this facies seems to be missing in this sequence.

3 - The greenschist facies can be recognized by the absence of zeolites, prehnite, and pumpellyite. The assemblage of albite, chlorite, epidote, sphene, plus or minus calcite, and plus or minus actinolite are representative of this facies in basaltic

rocks (Turner, 1968). This facies appears in the lower (southwest) portion of the study area, with epidote, chlorite and quartz as the predominant minerals and albite and calcite as minor minerals with a trace of actinolite.

Figure 32 gives a rough estimate of the pressure and temperature of these facies. Zeolite facies is formed at a depth of between 4-12 km, and a temperature between 100-200° C. The prehnite-pumpellyite facies formed at a depth of 10-20 km, and temperature of 150-250°C. Greenschist facies forms in a wide range of burial depth between 7 and 30 km and a temperature between 250-400°C.

Walker (1960) found an upper zeolite-free zone in Tertiary volcanic rocks of eastern Iceland. Based on the estimates from Walker's data, Green (1972a) due to the lack of this zone in the NSVG, concluded that the present top of NSVG (at Tofte) was at least 1500 m below the surface during hydrothermal alteration. The estimated thickness of extrusives (6300-8700m) and intrusives (5000-6000m), (Green, 1972a) in the NSVG indicate a depth around 12 km below the surface for the most deeply buried rock units of the study area.

It appears that greenschist facies is reached, in the study area, at the shallower range of burial depth required for formation of this facies. This could reflect the heating effect of intrusive rocks underlying the area, and/or the higher regional geothermal gradients that probably existed during the Keweenawan, as suggested by Jirsa (1980).

However, another likely possibility is that the NSVG is in fact a thicker sequence than previously has been estimated. Cross-section profiles of the study area (see plate 1) give a thickness of 2920 m for the volcanic rocks, vs. the 1890 m estimated by Sandberg (1938). If the thickness of the rest of the extrusive rocks of the southwest limb from the top of the Lester River sill to Tofte has been underestimated in the same degree, the greenschist facies in the study area, indeed may have formed at a depth of about 15 km. In this case, based on Figure 32, a geothermal gradient of about 25° to 40° C per km can be proposed for these Keweenawan rocks.

B - Contact metamorphism

Intrusion of the Duluth Complex has recrystallized the adjacent flows. Examination of the mineral assemblages formed disclosed that the lavas are metamorphosed to pyroxene - hornfels facies at the immediate contact zone; the intensity of metamorphism decreases outward from the contact and changes to hornblende-hornfels facies, and still farther out to albite - epidote hornfels facies. All facies of contact metamorphism show a retrograded burial metamorphism overprint which has taken place after contact metamorphism. It should be clarified that in some places the Duluth Complex and lava flows in the contact zone are very similar in hand specimen. This problem together with the rare exposures around the contact zone makes it difficult to define precise contact lines between the flows and the Duluth Complex. Nevertheless, the high-grade metamorphic facies, and its change to lower grades of metamorphism, are clear and traceable; however, the extent of each facies is found to be rather irregular.

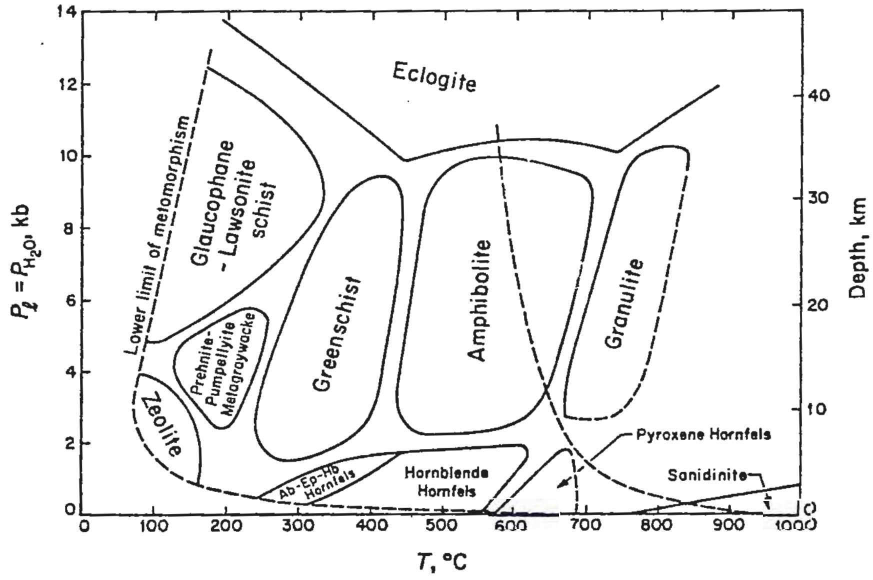


Figure 32: Pressure and Temperature of metamorphic facies. All boundaries gradational. From Turner, 1968

Pyroxene-hornfels facies. The rocks of this facies commonly are fine-grained and granoblastic, and contain plagioclase, clinopyroxene, orthopyroxene, opaque minerals, and trace amounts of biotite. Clinopyroxenes are augite and are commonly less than one mm across. Many augite crystals contain opaque minerals in their central part which may comprise as much as 40% of the grains by visual estimate (Fig. 33).

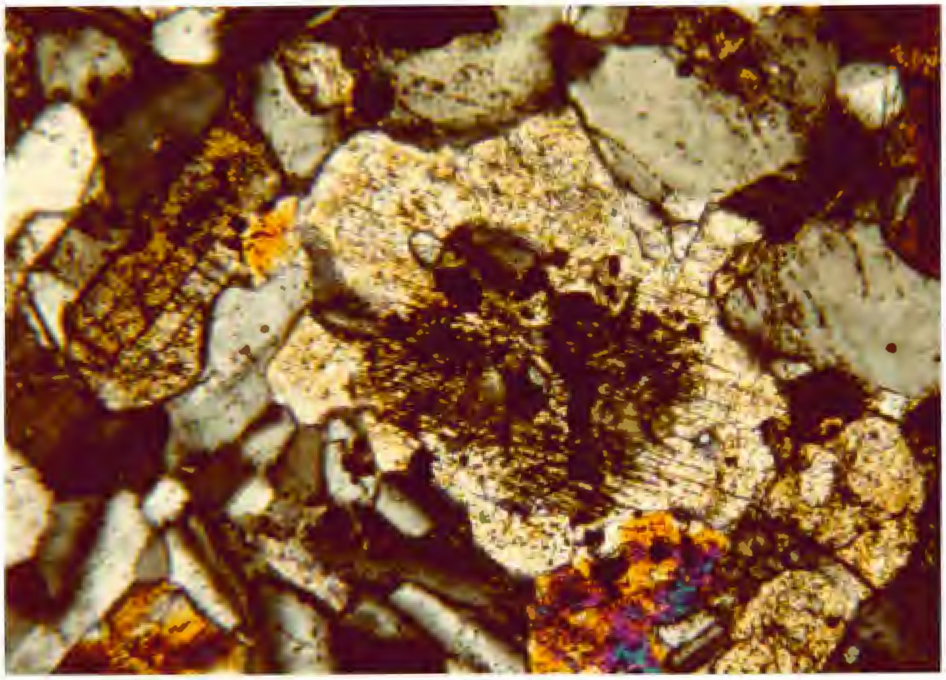


Figure 33: Augite crystal with opaque minerals in the core, in pyroxene-hornfels facies of contact metamorphism. The rock shows a recrystallized texture. Unit LEP-5, location 125; (Crossed nicols, field of view 1 mm)

Plagioclase grains in this facies are recrystallized and appear as large tabular crystals of 2mm or more, as well as small-sized groundmass laths and granules. Albite twinning is very common and carlsbad twinning is locally present. Plagioclase grains are clear, subhedral or anhedral, and some are zoned.

Orthopyroxene crystals are rare and appear as crystals of hypersthene less than 1mm across, some of which show exsolution blebs of augite. The exsolved crystals were most likely formed by inversion of pigeonite, which may have crystallized from a combination of augite and chlorite during prograde metamorphism.

The opaque minerals are magnetite, which occurs as fine-grained, recrystallized interstitial, anhedral crystals, in addition to the small granules in the cores of some of the clinopyroxene crystals. Ilmenite was not identified.

Hornblende - hornfels facies. Hornblende, actinolite and plagioclase are the predominant minerals in this facies, commonly along with a few percent of biotite, a small amount of clinopyroxene, and minor amounts of opaque minerals (Fig. 34). Actinolite is abundant and commonly forms large anhedral megacrysts, probably after augite,which locally may approach 2mm in size (Fig. 35). Recrystallized, relatively clear plagioclase is visible both as phenocrysts and as fine grains in the groundmass. Pyroxene and opaque minerals are very fine-grained and show intergranular texture.

Albite-epidote-hornfels facies. The mineral asemblage in this facies commonly includes epidote, chlorite, quartz, plus or minus albite, and plus or minus actinolite. Recrystallization and reaction in this facies are imperfect, and its mineralogy is known imperfectly. This mineral assemblage generally appears in some outer fringes of contact aureoles at low temperature. In the study area the mineral assemblages of this facies and the greenschist facies of burial metamorphism are identical and they may be distinguishable only by the absence of recrystallization in the burial metamorphism.

In contact metamorphism the temperature at any distance from the contact of the intrusive body depends on variables such as initial temperature and water content of the country rock; density, specific heat and diffusivity of country rocks and solidified magma; ΔH of metamorphic reactions in the affected zone, as well as size and initial temperature of the intrusive body. None of these variables in this study has been adequately investigated to allow any specific conclusion. However, the hornblende-hornfels facies in the Duluth area is found up to 300 m from the defined contact zone of Duluth Complex. According to Jaeger (1957), the temperature at contacts with basic plutons under deep cover reaches 700°C. This temperature decreases to about 400°C at a distance of 300 m from the contact (neglecting effects of water) and this temperature could be maintaind for tens of thousands of years. As far as pressure is concerned, the Duluth Complex was intruded under about 15 km thickness of rocks (see discussion on regional metamorphism), where a pressure of about 5 kb is expected.

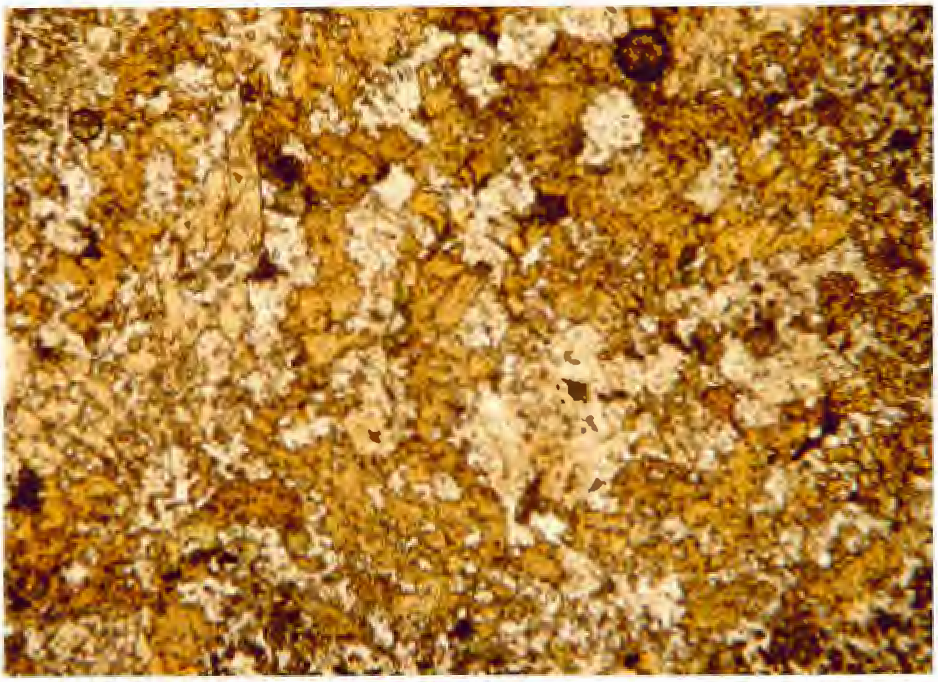


Figure 34: Biotite and hornblende crystals with altered plagioclase in hornblende-hornfels facies. Unit LEP-9, location 123 (one polar, field of view 4 mm)

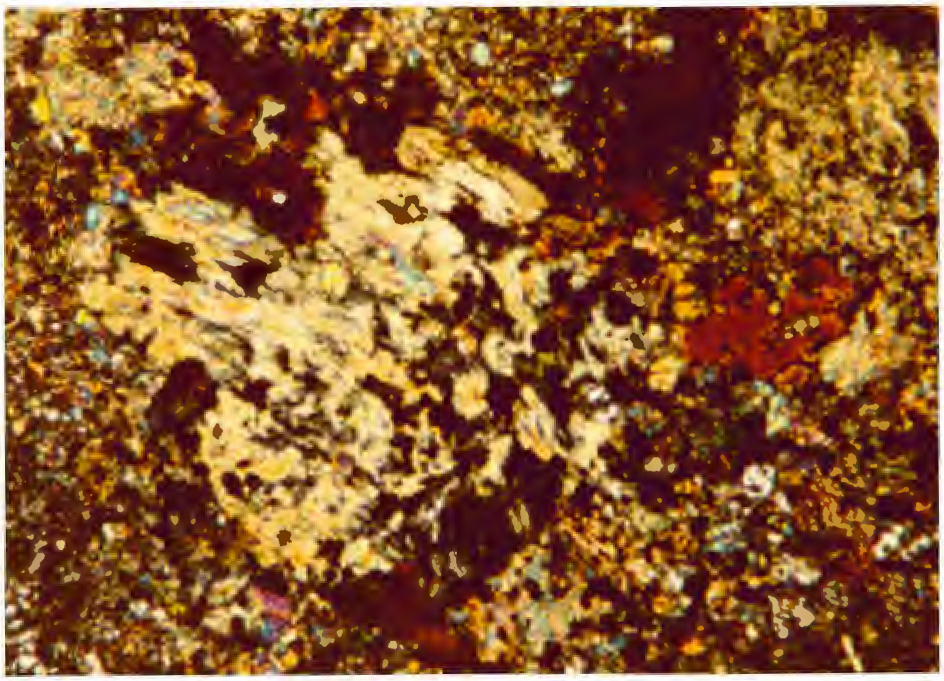


Figure 35: Actinolite and biotite grains in hornblende-hornfels facies of contact metamorphism. Unit LEP-34, location 171 (Crossed nicols, field of view 4 mm)

PALEOMAGNETISM AND EXTENT OF BAKED CONTACT OF VOLCANIC ROCKS SURROUNDING THE DULUTH COMPLEX IN THE DULUTH AREA

Introduction

All rocks have some magnetic properties due to the presence of a certain percentage of iron oxides as accessory minerals. The magnetic minerals in rocks may be used to attempt to determine the direction and intensity of the geomagnetic field at the time the rock was formed. This primary magnetic property of igneous rocks, caused by cooling from a high temperature through curie point(s) of the minerals is called "natural remanent magnetization" (NRM) and it is subject to change depending on the subsequent history of the rock and the character of the magnetic minerals. This primary magnetic property in sedimentary rocks is caused by alignment of sediment grains during or prior to lithification, and is called detrital remanent magnetization (DRM).

Secondary magnetization includes metamorphism which may affect the primary magnetization of sedimentary and igneous rocks. For example, at the contacts of igneous intrusions or the bases of thick lava flows, the adjacent rocks will be heated. The consequent metamorphism may obliterate the NRM, and produce a thermoremanent magnetization(TRM) parallel to the magnetic field in which it cools. The effect of metamorphism will gradually diminish with distance from the contact, and so does the intensity of the TRM.

Another type of secondary magnetization is produced when the recrystallization or redistribution of iron minerals or formation of new ones take place, when temperature is not raised to the curie point(s), and fluids cause chemical change. The magnetization acquired in this way is known as chemical remanent magnetization (CRM).

Secondary magnetization may replace the natural remanent magnetization totally, partly, or not at all. One of the challenges in the study of the natural remanent magnetization of rocks is to correct for or eliminate the effects of secondary magnetization.

Magnetic properties of the Keweenawan rocks of Lake Superior region have been studied by many geophysicists. DuBois (1962), Palmer (1970), Books (1972), Jahren (1965), and Green and Books (1972) among others investigated the paleomagnetism of the NSVG, Duluth Complex, and other intrusive bodies cutting the NSVG, and defined their average direction of remanent magnetization.

The extent of this study is limited to the area where the Duluth Complex, with normal magnetic polarity (DuBois, 1962), is in contact with the Ely's Peak basalt with reversed magnetic polarity (Beck, 1970) in the basal part of the NSVG, near Nopeming (Fig. 37), and with the lower part of the NSVG in the Duluth area, just above the Duluth Complex with normal magnetic polarity (Books, 1972; Green and Books, 1972), (see Fig. 38). Intrusion of the Duluth Complex heated the surrounding volcanic rocks, producing the contact metamorphism described in the previous section. The purpose of the study is to determine the effect of the Duluth Complex intrusion on the magnetic polarity of the surrounding rocks, as well as defining the extent of this effect. To accomplish this aim, a small portable magnetometer was used (a fluxgate magnetometer, model 70 of CALEX CO. CA., designed to identify the normal or reversed magnetic polarity, and measure the relative intensity of the remanent magnetism of rocks at outcrops). The magnetometer may not be sensitive enough to measure magnetic polarity of interflow sediments, but is quite sufficient for measurement of the magnetic polarity of both the Duluth Complex and the lava flows. The magnetic polarity of the volcanic rocks was determined in three traverses on each side of the intrusion. Traverses were about 150, 300, and 500 meters from the contacts. Some sporadic outcrops far from the contact to the northeast of the Duluth Complex were also tested and their magnetic polarity determined. Also, one traverse was made in the Duluth Complex itself. The location of outcrops which have been tested are shown on Figures 37 and 38.

Baked Contacts

As stated before, when a rock is intruded by a younger igneous rock, the country rock close to the contact with the intrusion will heat up and acquire a remanent magnetic field (TRM) of the same direction as the adjacent intrusive rocks. This effect also applies to the baked rock underlying an extruded lava flow. Irving (1964) divided the zones outside of the igneous body into the metamorphic zone, the heated zone, and the warmed zone.

In the metamorphic zone, changes in magnetic minerals are extensive; in the heated zone the changes are less; in both zones rocks take on the magnetic direction of the intruding igneous rock (TRM). In the warmed zone, the temperature does not rise to the curie temperature, and magnetic direction is somewhat of a compromise between the igneous and country rock. The possible effects are illustrated in Figure 36.

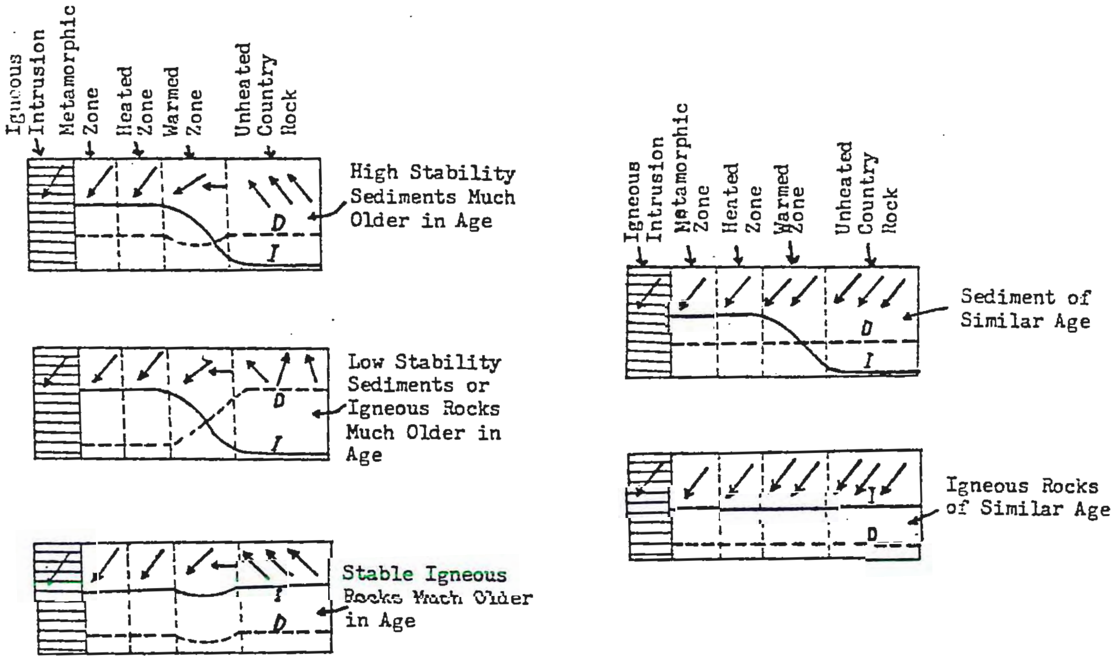


Figure 36: The various zones of baked contacts with the direction of magnetization (arrows), intensity (I), and dispersion (D). From Irving (1964), McElhinny (1973)

Determination of the Magnetic Polarity

The directions of remanent magnetization of most rocks are divided into normal and reversed groups. "Normally polarized" rocks show a remanent magnetization direction in which the north-seeking end of a compass needle points downward (in the northern hemisphere). Reversed rocks, on the other hand, represent a direction nearly opposite, in which the north-seeking end of the needle points upward.

One of the most important points in determination of the magnetic polarity is to avoid rocks that have been struck by lightning. Effects of lightning strikes may completely mask the original magnetic polarity of rock in an area 5 to 25 meters in diameter. To determine whether or not the rock outcrop has been struck by lightning a Brunton compass was used to detect such local deviations. The results of these field tests are summarized in Table 12.

Table 12: The results of field tests of magnetic properties of the Duluth Complex and the volcanic rocks surrounding this intrusion, in the Duluth area

Magnetic Polarity of Ely's Peak Basalts(beneath the Duluth Complex)

Traverse No.	Location	Rock Type	Approximate Distance from the Duluth Complex Contact	Magnetic Polarity and Intensity
1	1 a	Basalt	150 meters	weak normal
1	1 b	Basalt	150 meters	weak normal
1	1 c	Basalt	140 meters	v.weak normal
2	2 a	Basalt	290 meters	Med. reversed
2	2 b	Basalt	250 meters	Med. reversed
2	2 c	Basalt	340 meters	weak normal
2	2 d	Basalt	300 meters	Med. normal
3	3 a	Basalt	600 meters	reversed
3	3 b	Basalt	580 meters	normal

Magnetic Polarity of Lava Flows above the Duluth Complex

4	4 a	Basalt	60 meters	strong normal
4	4 b	Basalt	70 meters	strong normal
4	4 c	Basalt	90 meters	strong normal
5	5 a	Granophyre	300 meters	Med. normal
5	5 b	Granophyre	300 meters	strong normal
5	5 c	Basalt	300 meters	strong reversed
5	5 d	Felsic Flow	300 meters	Med. normal
6	6 a	Basalt	500 meters	normal
6	6 b	Basalt	750 meters	v.strong normal
6	6 c	Basalt	1000 meters	v.strong normal

Magnetic Polarity of miscellaneous Outcrops in the Study Area

7	7 a	Basalt	2000 meters	strong normal
7	7 b	Interflow Sed.	2200 meters	v.weak normal

Magnetic Polarity of Duluth Complex

8	8 a	Anorthos. gabbro	1000 meters	normal
8	8 b	Anorthos. gabbro	300 meters	normal
8	8 c	Anorthos. gabbro	320 meters	normal
8	8 d	Anorthos. gabbro	700 meters	normal

Discussion and Conclusions

The magnetic polarity tests lead to the following general conclusions:

I - The Duluth Complex has affected and shifted the magnetic polarity of the Ely's Peak basalts from reversed to normal, in a distance of up to about 200m from the contact and sporadically beyond that.

II - Since the lava flows surrounding the Duluth Complex are metamorphosed up to about 300m from the contact, it seems that the metamorphism and magnetic effect both show roughly the same extent and go hand in hand.

III - The more altered (burial metamorphosed) rocks generally show a weaker magnetic field.

Inconsistencies in Magnetic Polarity

A. Basal Contact Zone: Outcrop 3_b occurs at a distance of 580 meters from the apparent basal contact of the intrusion and shows a normal polarity, whereas locations 2_a and 2_b, which are less than half of this distance from that contact, demonstrate a distinct reversed polarity. This behavior may be due either to an irregular base of the intrusion or to the existence of a covered offshoot of the intrusion into the flows. Considering the normal polarity at outcrop 2_c and 2_d, 340 and 300 m from the contact respectively, one could speculate that a covered offshoot of the intrusion, with a possible southwest strike may be present in this area.

B. Top Contact Zone: The outcrop located at 5_c, 300 m from the top contact of the intrusion, shows a strong reversed polarity which is not concordant with the surrounding rocks and is difficult to explain. The chance that the outcrop has been struck by lightning is very slight, since the compass needle did not exhibit anomalies anywhere on the outcrop. Also three readings were taken about ten meters apart from each other; all show a strong magnetic reversal.

The idea that this outcrop is part of the Ely's Peak basalt sequence that has been floated and carried in the top of the complex with its magnetic direction not changed either by movement and rotation, or by the baking effect of the intrusion, seems rather unlikely. Also, the possibility that the tectonic movement in this particular area have rotated the rocks about 180 degrees can be dismissed. So, this outcrop may be the original top of the Ely's Peak basalts, in its original position. The gabbro intruded beneath it and remagnetized all the flows between this outcrop and the contact. More detailed investigations of this problem are needed.

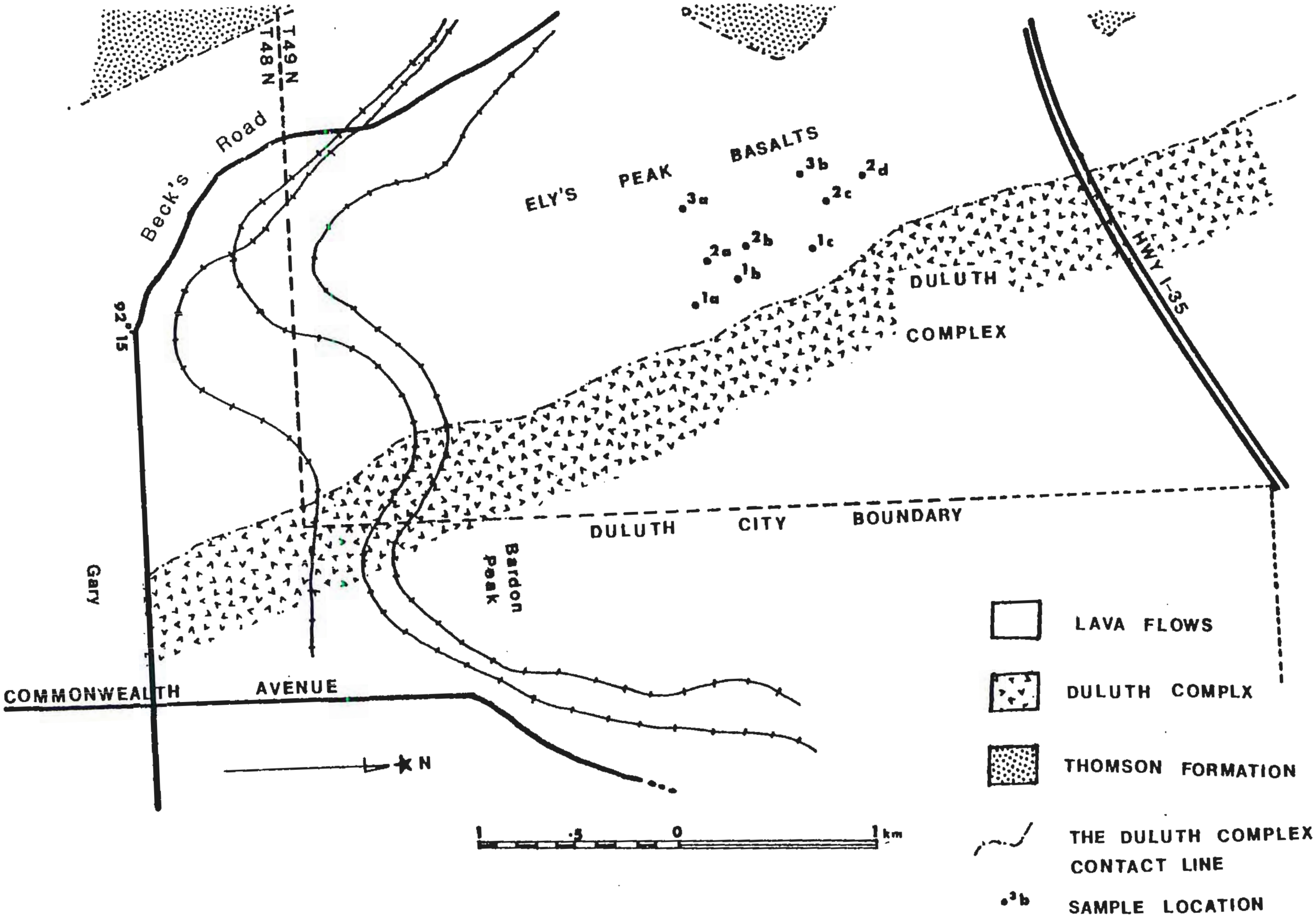


Figure 37: Map showing sample localities for study of magnetic polarity of Ely's Peak basalts near the base of the Duluth Complex. See Table 12; Geology after Taylor, 1964

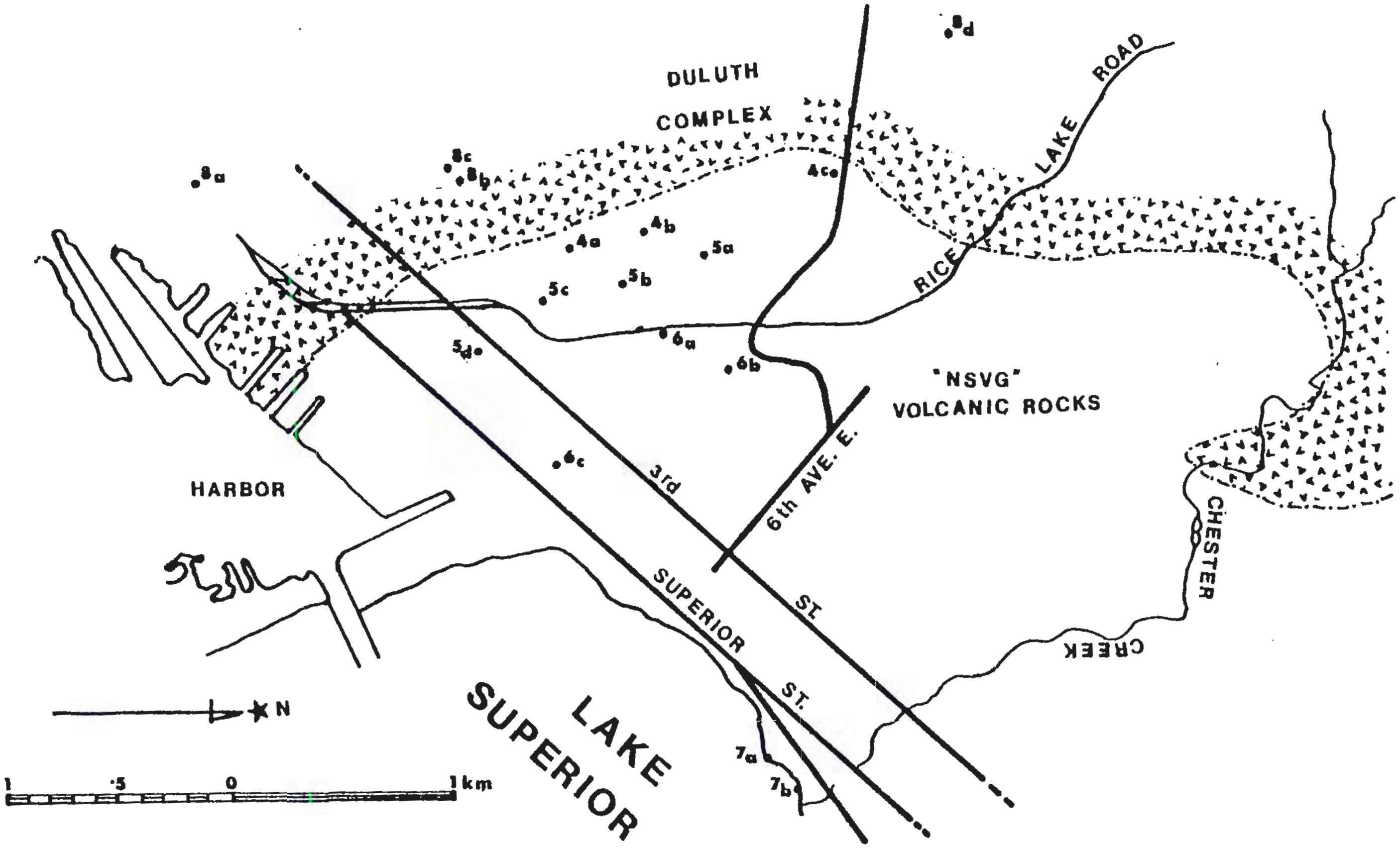


Figure 38: Map showing sample localities for study of magnetic polarity of Leif Erickson Park lavas above the Duluth Complex. See Table 12

STRUCTURAL GEOLOGY

In the NSVG, the lava flows and intrusions in both limbs show a dip toward the axis of the Lake Superior syncline. The dip in the southern limb at Duluth is slight to moderate (12° to 30° E.), whereas in the northern limb, it is more gentle (10° to 16° S.). Faulting and intrusions have disturbed the volcanic sequence and prevented correlation between the two limbs (Green 1972a).

In the Duluth area, the cross-section profile (see Plate 1) gives a thickness of about 2920 m of volcanic rocks, assuming dips of covered flows are the same as dips of adjacent exposed volcanic units. Seventy-six flow units have been distinguished, but this number represents only those units which are exposed. Since there are certainly more volcanic units in the area which have not cropped out on the surface, this number should be considered the minimum. Several of the units have been traced inland for a few km, but the majority are identifiable only in one locality.

The strike azimuths of flows range from about 140 to 155 degrees in the Leif Erickson Park area and from 5 to 30 degrees in the Lakeside area. The dip changes rather irregularly throughout the area. The maximum dip is about 30 degrees and the minimum is about 12 degrees East. No folding in the lava flows or interflow sediments was observed, but faults were detected in several outcrops. They have not involved any major visible displacement or duplication of units. The majority of faults are associated with intrusions and locally are marked by veins filled with secondary minerals. These faults have dips similar to the adjacent intrusions.

Four steeply dipping faults which are not visibly associated with an intrusion were recognized. One occurs along the shore just south of the Chester Creek gorge. This fault cuts the top of a thick sandstone (unit b of interflow sediments) at this point and continues northward and can be traced along Chester Creek for a short distance. At the shore a diabasic dike 0.5 meter thick follows the fault, but it does not continue farther in the creek (Fig. 39). The fault shows a N-S strike, with a dip of about 80 degrees West. The rocks around the fault are brecciated in a few places. .Another fault occurs at the foot of 36th Avenue East and the shore line, cutting through a quartz tholeiite flow. The only exposure of this vertical fault is along the shore, where it is visible along a small stream and is masked by a breccia zone about two meters thick (Fig. 40). Its sense of displacement could not be detected.

Above the mouth of the Lester River, where the railroad passes over the river, a small fault is present. About two kilometers further north in this river, another fault is distinguishable, where a banded felsite unit sits on top of a mafic flow. Both faults show a N-S strike and a steep dip. The faults cannot be traced from the outcrops. More faults may exist under the glacial drift.

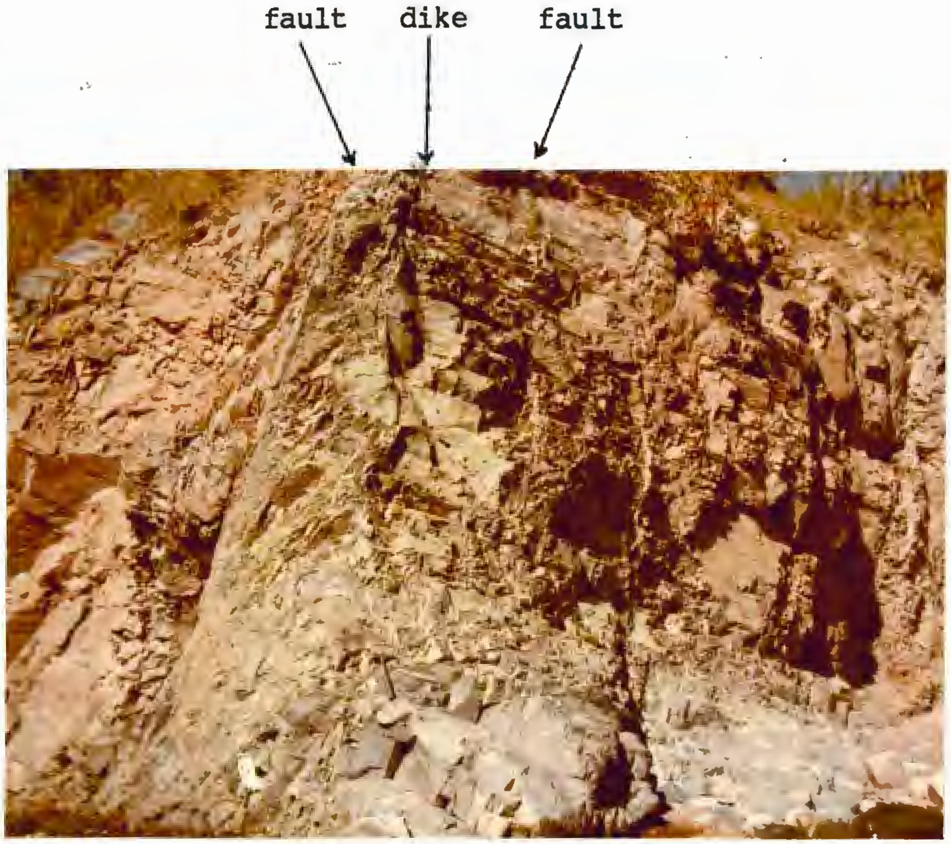


Figure 39: The fault with N-S strike, southwest of Chester Creek gorge. A diabasic dike about 0.5m thick follows the fault. Hammer for scale just to left of the center

Figure 40: A fault cutting through a quartz tholeiite flow, at at a the foot of 36th Avenue East and shore of Lake Superior.Unit LS-3; hammer for scale in the center

ECONOMIC GEOLOGY

The occurrence of copper deposits in the Lake Superior region was known by the native inhabitants before the arrival of European settlers. The mining of this native metal in the Michigan Copper District on the south side of Lake Superior was started over a century ago. No viably economic deposits of this metal have been discovered as yet in the extrusives of the NSVG in spite of exploration and some drilling. In this study the observations have been limited to the surface exposures, where mostly oxidized copper minerals are found. Chalcocite and malachite and rare azurite are the minerals found in trace amounts in the volcanic rocks of the Duluth area.

The copper minerals are products of hydrothermal deposition and weathering, and are associated with fault zones and permeable volcanic rocks, particularly felsic units. Trace amounts of chalcopyrite, commonly with pyrite, are locally present in quartz-calcite veins and also rarely appear in amygdules (Fig. 29), and in rock fragments of felsic units. Bornite was found in one flow unit associated with chalcopyrite and could be secondary. The oxidized copper minerals appear in the felsic unit in Chester Creek, along the fault which passes through this area. They also appear in an intermediate flow which is enclosed in the Endion sill (foot of 15th Ave. E. and lake shore), and is associated with a fault zone in this area. The association of copper minerals with the fault zone and permeable rocks suggests that mineralization has been caused by a circulating fluid.

In the Keweenaw Peninsula (White, 1968), copper is associated with prehnite, pumpellyite, and calcite in veins, amygdules, flow top breccias and conglomerates. Lack of significant copper mineralization in the NSVG may be due to the steep dips of the strata in this part of the Lake Superior basin (White, 1957), which have caused rapid passing of copper-bearing hydrothermal solutions. However, in the Duluth area, as mentioned in the metamorphism section, the lower portion of the sequence reveals the greenschist facies. This facies changes to the zeolite facies in the Lakeside area, through a narrow transitional zone containing mostly calcite and quartz. The prehnite-pumpellyite zone, which commonly exists between these two facies in Michigan, is not found in the Duluth area and is missing in the sequence. The occurrence of the prehnite-pumpellyite facies would be expected where the Endion sill cuts the volcanic rocks, if the geothermal gradient were the same as in the Portage Lake Volcanics to the east. The apparent lack of prehnite - pumpellyite conditions in the Duluth area may be related to the lack of significant native copper deposits.

SUMMARY AND CONCLUSIONS

A section of mid - Proterozoic plateau lavas roughly 2920 m thick, part of the Keweenawan North Shore Volcanic Group, occurs in the Duluth quadrangle, Minnesota. Mafic flows, intermediate flows and felsic rocks each form roughly one-third of this thickness. The strike (azimuth) of units ranges from about 140 to 155 degrees in the Leif Erickson Park area to from 5 to 30 degrees in the Lakeside area with a dip which changes irregularly from 30 to 12 degrees east. Faults are minor, and do not seem to have caused any considerable displacement or duplication of volcanic units.

Five of the units for which rock analyses were obtained are presently peraluminous (probably the result of feldspar alteration), and the majority of flows are oversaturated in silica. Classification of rocks by various methods places them in the tholeiitic field of the subalkaline series. Silica content of analyzed rocks ranges from 45.50 to 75.48 percent, and a full range of compositions from olivine tholeiite to rhyolite is present. The most distinct characteristics of this sequence of rocks are the high potassium content, which ranges from 0.42% in basalts to 5.86% in rhyolite, and the high volume of felsic rocks, in comparison to other tholeiitic plateau basalts in the world. Otherwise, this sequence was found to be very similar to Columbia Plateau basalt and Iceland plateau lavas. Mafic flows are composed of olivine tholeiite and quartz tholeiite. A few phenocrysts of plagioclase, commonly olivine and locally magnetite are typically present. Intermediate flows (tholeiitic andesites) commonly contain plagioclase phenocrysts, which form up to 60% of one of the units. Felsic rocks have a rhyolitic to icelandite composition, and are composed of two extrusive types: lava flows and ignimbrite. Felsic rocks generally, and ignimbrite particularly form thick units in the area (up to 400m). No basaltic composition pyroclastic rock was found. It appears, therefore, that the mafic flows formed by nonexplosive volcanic activity. Diabasic dikes, which trend roughly N - S, cut the flows, and were probably feeder dikes to higher flows. Intermittent violent explosive activity erupted felsic rocks as ignimbrite (ash-flow tuff). Occurrence of deformed basaltic xenoliths (mafic lapilli) in the felsic rocks suggest that a small amount of basalt may have been mixed with the felsic magma. The explosive eruption of felsic magma may in fact have been triggered by the introduction and mixing of a hot basaltic magma. The ignimbrites are characterized by a general lack of bedding, poor sorting and considerable thickness and lateral extent. The presence of coarse xenoliths in ignimbrite, as well as concentration of dikes in the Duluth area relative to the rest of the southwestern limb of the NSVG, may indicate that vents were nearby.

Alteration has affected the rocks with varying intensity. Felsic rocks appear to be more altered than mafic flows. Calcite, epidote, chlorite, quartz, hematite and clay minerals are the most common alteration products. However, none of the flows is completely converted to secondary minerals, and the primary textures of the rocks are mostly well preserved.

The volcanic rocks of the Duluth area have been subjected to burial and contact metamorphism. Burial metamorphism ranges from high zeolite to greenschist facies; and contact metamorphism, caused by the intrusion of the Duluth Complex, has recrystallized the adjacent rocks and metamorphosed them up to pyroxene-hornfels facies in the immediate vicinity of the contact. The intensity of contact metamorphism decreases to albite-epidote hornfels facies about 300 m from the contact.

The magnetic polarity of the Duluth Complex, volcanic rocks and interflow sediments of the study area is normal, and the Ely's Peak basalts show reversed magnetic polarity. The Duluth Complex affected the magnetic polarity of adjacent volcanic rocks up to 200m from the contact, which is almost the same distance at which contact metamorphism has been effective according to textural and mineralogical evidence.

Trace amounts of chalcopyrite, chalcocite, malachite, rarely azurite and bornite were found in the amygdaloidal zones of flows, and in shear zones, but no concentrations of economic interest were observed.

APPENDIX I

DESCRIPTION OF STRATIGRAPHIC SECTION, DULUTH

EXPLANATION:

LEP: Leif Erickson Park Section, including the volcanic rocks overlying Duluth Complex in downtown Duluth up to base of Endion Sill (See figure 52)

LS: Lakeside Section, including the volcanic rocks from top of Endion Sill to base of Lester River Sill (See figure 52)

Numbers following lettered prefixes represent stratigraphic order where 1 is the lowest unit of each section.
Example: unit LS-1 is stratigraphically lower than LS-2
D-numbers are those of J.C. Green in UMD collection

ABBREVIATIONS:

Rock Composition

ol. thol.:	olivine tholeiite
qt. thol.:	quartz tholeiite
and.:	andesite
felsic:	felsic rocks (icelandite to rhyolite in composition)

Color

gr:	gray
gn:	green
rd:	red
bn:	brown
pn:	pink
D:	dark

Texture

oph:	ophitic
por:	porphyritic
aph:	aphyric
tra:	trachytic
intg:	intergranular
mcr:	microcrystaline
ves:	vesicular
ign:	ignimbrite
lam:	lamination (flow banding)
r.f.:	rock fragment
meta:	metamorphosed

Descriptive Terms

fn:	fine or thin
med:	medium
crs:	coarse or thick
gnd:	grained
amyg:	amygdule or amygdaloidal
wk:	weakly or slightly
stg:	strongly or highly
mod:	moderately

UNIT NO.	OUTCROPS THIN SECTION	LOCATION	THICKNESS			DESCRIPTION	CORRELATION WITH OTHER OUTCROPS AND SAMPLES
			min. or visible	average or estim.	range or maximum.		
LEP-1	211E	E. Corner of 4th Ave. W. & 6th St			72m	A combination of basalts & felsic rocks with irregular contact & distribution. They are intruded by a few micro-gabbro dikes.	211F: 6th Street between 3rd & 4th Ave W. 210A: 5th Ave. West & 6th Street 210D: 8th St. at 3rd Ave. West, Duluth 212B: West corner of 4th Ave. W. & 7th St.
LEP-2	213B	Intersection of Central Entrance and Clearwood Drive, N.E. of Central High School			40-60m	ol. thol., D. gr. fn. gnd. suboph.	213A, 213C, D-20, D-21?, D-22, D-23, some locations as 213A
LEP-3	101	Corner of 4th Ave. W. & 2nd St.			26-110m	felsic, lava flow, rd-br, por.	102A: between 2nd & 3rd Ave. W. in Pittsburg Avenue 210C: 2nd Ave. W. & 8th St. D-1: W. corner of 3rd Ave. W. & 1st St. D-28: 8th St., below 2nd & 3rd Ave. W. M-4600: 8th St. and 3rd Ave W.
LEP-4	103A	8th St. between 1st Ave. W. and Lake Avenue	3m			felsic, gr.ign.	103B: E. side of Lake Ave between 8th and 7th St.
LEP-5	106A	W. corner of 2nd Ave. E. and 8th St.		150m		ol.thol, D.gr., fn.grd, por.	105: 2nd Ave. E. between 6th & 7th St. 107: extention of 3rd Ave. E. & 10th St. 110: E. corner extention of 4th Ave. E. and Parkway. 119: E of Cliff Ave. between Plum St. & High Street 120A: Westword extension of Kelly St. West of College of St. Scholastica 125: Kennebec Ave between Hickory St. & Ohio St. West of College of St. Scholastica
LEP-6	108	E. corner of 4th Ave. E. and extension of 11th St.		20m		ol. thol., gr., fn. gnd.,	
LEP-7	109	W. corner of 5th Ave. E. and 11th St.		30m		ol. thol., gn-gr., fn. gnd., por	
LEP-8	111	N. 10th St. between 4th & 5th Ave. E.		20m		and., gr.-br., fn.gnd, por.,tra.	
LEP-9	104A	N. 1st St. between Lake Ave. & 1st Ave. E.		120m		ol. thol., D.gr, fn.gnd, por	104B: S. 2nd St. between Lake Ave. and 1st St. E. 123: W. of St. Scholastica College 124: W. of St. Scholastica College
LEP-10	115	E. corner of 9th Ave. N & Martha St.		85m		and., gr-br, por.	118A: N. extension of Skywood Ave. 118B: N. extension of Skywood Ave. 118C: N. extension of Skywood Ave. 118D: W. extension of Plum St. & N. Skywood Ave.
MESSABI SILL		11th St. between 9th and 10th Ave. E.		37.5m		diabase, D.gr., med.-crs. gnd.	See figure 52 and plate 1

UNIT NO.	OUTCROPS THIN SECTION	LOCATION	THICKNESS			DESCRIPTION	CORRELATION WITH OTHER OUTCROPS AND SAMPLES
			min. or visible	average or estim.	range or maximum.		
LEP-11	122B	Kenwood Quarry, N.E. Kenwood Ave.		30m		and., gr, por, wk. meta,	D-52: Kenwood Ave.-Slope excavation behind new apts. S. of quarry
LEP-12	112A	W. Miller Hospital between 1st and 2nd St.		20m		and., D.gr-br, por	
LEP-13	113	7th Ave. E. between 5th & 6th St.		40m		and., gn-gr, fn.gnd, stg. por	
LEP-14	117A & B	W. Missouri Ave. between Missouri Ave. and Kenwood Ave.		30m		and., gn, fn.gnd, wk. meta,	
LEP-15	126A	S. Parkway between 12th & 14th Ave. E.		40m		and., br-gr, fn. gnd, por	126B: W. corner of 13th Ave. E. & 11th St
LEP-16	127A	S. Parkway between 13th & 14th Ave. E. (W. Lakeview Park)		30m		and., br-gr, fn. gnd, mod. por	
LEP-17	112B	below Miller Hospital on 1st St. between 5th & 6th Ave. E.		25m		and., gr-br, fn. gnd. tra, mod. por.	D-30: Same location as LEP-17
LEP-18	112C	below Miller Hospital on 1st St., W. 6th Ave. E.		20m		and., gr-br, tra, mod. por	
LEP-19	129, 130, 131, 132, 133	foot of 5th Ave. E. and shore of Lake Superior			50-80m	and., br-gr, fn. gnd. stg. por.	
LEP-20	127C	W. corner of 13th Ave. E. and Belmont Road.		20m		and, gr, fn.gnd, por.	
LEP-21	134	between 5th and 6th Ave. E. & shore of Lake Superior			35-45m	and, br-gr, fn. gnd, mod. por.	
LEP-22	135	foot of 7th Ave. E. & shore of Lake Superior		10m		and, br-gr, fn. gnd, aph	
LEP-23	136A	E. foot of 7th Ave. E. & shore of Lake Superior		8m		and, br-gr, aph.	
LEP-24	137	between 7th & 8th Ave. E. and shore of Lake Superior		15m		qt.thol., br-gr, wk. por.	
LEP-25	138	foot of 8th Ave. E. and shore of Lake Superior		17m		qt.thol., br-gr, fn.gnd., aph	
LEP-26	139	E. foot of 8th Ave. E. and shore of Lake Superior		15m		qt.thol., br-gr, very fn.gnd., aph	
LEP-27	140A	E. foot of 8th Ave. E. and shore of Lake Superior		8.5m		and., br-gr, fn.gnd, wk. por	
LEP-28	140B	between 8th & 9th Ave. E. and shore of Lake Superior		22.5m		and., D.gr, mcr, aph	
LEP-29	142A	W. foot of 9th Ave. E. and shore of Lake Superior		41m		and., gr-br, aph	
LEP-30	143A & C	between 9th Ave. E. and shore of Lake Superior		50m		and., D.br, fn.gnd, wk por.	
LEP-31	143D	between 9th & 10th Ave. E. and shore of Lake Superior		1m		and., D.br, fn.gnd, aph, tra., stg. ves.	

UNIT NO.	OUTCROPS THIN SECTION	LOCATION	THICKNESS			DESCRIPTION	CORRELATION WITH OTHER OUTCROPS AND SAMPLES
			min. or visible	average or estim.	range or maximum.		
LEP-32	144A	foot of 10th Ave. E. and shore of Lake Superior		37m		and, gr, fn, gnd, aph. tra.	
LEP-33	145A	E. foot of 11th Ave. E. and shore of Lake Superior		30m		ol. thol., gr. mcr, por	
LEP-34	146	shore of Lake Superior below the stage of Leif Erickson Park		22.5m		ol. thol., D.gr., fn.gnd, por. sub oph.-oph	117: Chester creek & 4th Street D-6: Same location in LEP-34
LEP-35	198A	N.Arrowhead Rd. in Berwick Ct.		120m?		and., gr., mcr., wk.por.	198C: W. of Woodrich Circle.
LEP-36	196A to H	Hartley Park (scattered outcrops)			500m?	ol. thol., D. gr., oph, wk.por.	197: Hartley Park
LEP-37	169A	W. 13th Ave. E. in small creek between 2nd and 3rd Street		20m		felsic, br,fn.gnd,mod.por.,lam.	170A: W. of 13th Ave. E. between 3rd & 4th St. in a small creek.
LEP-38	148	between 12th and 13th Ave. E. and shore of Lake Superior		15m		and., D.br, fn.gnd, wk.por., stg., ves.	
LEP-39	149	W. foot of 13th Ave. E. and shore of Lake Superior		10m		and., D.br, fn.gnd, wk.por, stg. ves.	
LEP-40	150B	foot of 13th Ave. E. and shore of Lake Superior		1m		ol. thol., D.gr., very fn. gnd., suboph.	
LEP-41	150A	foot of 13th Ave. E. and shore of Lake Superior		30m		and., gr, mcr., aph.	166A: below London Road in Chester Creek
LEP-42	166B	Chester Creek, between London Rd. and shore of Lake Superior		25m		and., br, fn.gnd, aph	
LEP-43	151	Shore of Lake Superior between 14th & 15th Ave. E.		50m		qt, thol., D.br-gr, fn.gnd, wk.-por, mod. ves.	
LEP-44	153	foot of 15th Ave. E. and shore of Lake Superior			8m	felsic, br, fn.gnd, wk.por, lam. ign	
LEP-45	154A	foot of 16th Ave. E. and shore of Lake Superior			25m	and., gr-br, mcr., fn.grn., wk.por.	
ENDION SILL		foot of 16th Ave. E. to foot of 26th Ave. E. on the shore of Lake Superior		500m		diabase, intermediate rocks, and granophyres	See figure 52 and plate 1
LS-1	163	foot of 26th Ave. E. and shore of Lake Superior		400m		felsic, br-rd, ign. lam	164: E. of foot of 28th Ave. E. and shore of Lake Superior. 182A&B: Tischer Creek between London Road and shore of Lake Superior. 183A: Tischer Creek below Greysolon Road 183B: Tischer Creek and Greysolon Place 183D: Tischer Creek near 2nd Street. 199A-E: In small creek E. of Tischer Creek between 1st St. and London Road. 200A: In small creek E. of Tischer Creek above 1st St. S&S-1-7: Tischer Creek near 2nd Street. (from Schwartz and Sandberg, 1940)

UNIT NO.	OUTCROPS THIN SECTION	LOCATION	THICKNESS			DESCRIPTION	CORRELATION WITH OTHER OUTCROPS AND SAMPLES
			min. or visible	average or estim.	range or maximum.		
NORTHLAND SILL		foot of 30th Ave. E. and shore of Lake Superior	10m		1000m	diabase	See figure 52 and plate 1
LS-2	214A	W. of foot of 35th Ave. E. and shore of Lake Superior		48m		and., br, mcr, por., plag. phenocrysts up to 4cm with honeycomb structure (zoning)	D-45: knob behind Northland Country Club.
LS-3	214B	foot of 36th Ave. E. and shore of Lake Superior		42m		qt thol., br, mcr, wk. por.	214C: foot of 38th Ave. E. & shore of Lake Superior
LS-4	215	E. of foot of 38th Ave. E. and shore of Lake Superior		7m		felsic, br, mcr, por	
LS-5	216A	E. of foot of 38th Ave. E. and shore of Lake Superior		10m		and., br, fn.gnd., wk. por.	
LS-6	217A	E. of foot of 38th Ave. E. and shore of Lake Superior		130m		felsic, br-rd, mcr-fn.gnd, por.	217B: between 40th & 41st Ave. E. & shore of Lake Superior in gorge of a small creek 217C: E. of foot of 41th Ave. E. & shore of Lake Superior
LS-7	218A	foot of 42nd Ave. E. and shore of Lake Superior		120m		felsic, br-pn, por., ign, abundance of r. f. & lam	209G: W. of 43rd Ave. E. between Lombard St. and Luverne St.
LS-8	219	between 43rd and 44th Ave. E. & shore of Lake Superior		38m		qt thol., br, mcr, wk.por.	
LS-9	220A	foot of 45th Ave. E. and shore of Lake Superior		90m		and, tra., mcr-fn.gnd, wk.por.	209C: between Cambridge St. & 45th Ave. E. in the Kelso Park 209E: London Road between 45th & 46th Ave. E. D-8: Same location as 209E.
LS-10	221A	shore of Lake Superior between 46th & 47th Ave. E.		40m		felsic, gr-br,mcr-fn.gnd, wk.por	D-53: London Rd 47th Ave. E. excavation
LAKESIDE SILL		between 47th and 49th Ave. E & shore of Lake Superior		50m		diabase, D.gr., med.-crs.gnd.	See figure 52 and plate 1
LS-11	222A	shore of Lake Superior between 48th & 49th Ave. E.		35m		and., D. rd-br, mcr-fn.gnd, wk. por., tra.	
LS-12	223A to G	shore of Lake Superior between 49th & 55th Ave. E.		180m	250m?	felsic, br-pn, mcr-fn.gnd, por. r.f.	207A-C: W. of Amity Creek and Groves Ave. in a small creek 228A-J: In Amity Creek between Groves Ave. to S. of 3rd bridge on Occidental Rd. 232B-D: Lester River W. of Lester River Golf Course 235A: Lester River W. of Valley Farm D-50: Superior Street near 53rd Ave. E.
LS-13	224A	shore of Lake Superior between 55th and 56th Ave. E.		10m		qt thol., D.br-gr,fn.gnd., wk.por.	

UNIT NO.	OUTCROPS THIN SECTION	LOCATION	THICKNESS			DESCRIPTION	CORRELATION WITH OTHER OUTCROPS AND SAMPLES
			min. or visible	average or estim.	range or maximum.		
LS-14	224B	shore of Lake Superior between 55th and 56th Ave. E.		15m		qt thol., D.br-gr, intg, wk.por, suboph.	227B: Amity Creek below Groves Ave.
LS-15	225A	shore of Lake Superior and foot of 56th Ave. E.		35m		qt thol., D.br-gr, vis., tra, wk. por.	
LS-16	234G	Lester River, W. of Valley Farm			10-20m	ol thol., br, fn.gnd, wk.por, suboph-oph	
LS-17	234F	Lester River, N. of Lester Park Golf Course		10m		qt. thol., br-gr, fn.gnd, wk.por tra?	
LS-18	234E	Lester River, N. of Lester Park Golf Course	6m			qt. thol., D.br-gr, wk.por, suboph	
LS-19	227A	Amity Creek and extension of Wyoming Street		20m		ol. thol., D.gr., fn.gnd, wk.por oph-suboph	232A: Lester River W. of Lester Park Golf Course 233A: Lester River N.W. of Lester Park Golf Course 234C-D: Lester River N.W. of Lester Park Golf Course
LS-20	234A	Lester River & W. corner of Lester Park Golf Course		15m		ol. thol, gr-br, mcr-fn.gnd, stg. oph-suboph	
LS-21	231C	Lester River below the bridge W. of Lester Park Golf Course.		20m		qt. thol., gr-br, fn. to med. gnd, wk.por.	
LS-22	S-F	Amity Creek and Juniata Street	3m	25m?		qt thol., D.br-gr, fn.gnd, intg, aph, suboph	
LS-23	S-G	Small creek E. of 61st Ave. E. & W. of Lester Park Golf Course	2m	12m?		ol. thol, br-gr, suboph.	
LS-24	231A	Lester River, 280m N. of gate Lester River Golf Course		22m		ol. thol., br-gr, mcr-fn.gnd, wk por, tra, oph.	
LS-25	230B	Lester River, W. of gate of Lester River Golf Course		18m		ol. thol., br-gr, fn.gnd, aph, intg., suboph, tra.	230D: Same locality as 230B 230C: about 50m S. of 230D
LS-26	230A	Lester River, 600m N. of Superior Street		20m		ol. thol., br-gr, mcr.fn.gnd, oph, tra, suboph.	226A: Lester River below Superior St. D-9A: 900m N. of shore of Lake Superior in Lester River
LS-27	208E	Lester River, below Duluth & Iron Range railroad bridge.			15m	ol. thol., intg., wk.por., ves.	
LS-28	208A to D	Lester River, 700m below Railroad bridge.		20m		qt. thol., D.br, fn.gnd, tra? intg., wk.por.	
LS-29	S-E	S. of Duluth & Iron Range Railroad & extension of 62nd Ave. E.		20m		ol. thol., D.br, fn.gnd, intg wk.por.	
LS-30	S-D	Duluth & Iron Range Railroad & 63rd Ave. E.		30m		qt. thol., wk.por, intg?	
LS-31	S-C	shore of Lake Superior about 400m E. of gorge of Lester River	12m			qt. thol., fn.gnd, intg, wk.por.	
LESTER RIVER SILL		220 m east of the mouth of Lester River & shore of Lake Superior		290m		diabase & granophyre	See figure 52 and plate 1

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