DRIFT LITHOLOGY IN RELATION TO BEDROCK GEOLOGY LONG ISLAND LAKE QUADRANGLE, COOK COUNTY, MINNESOTA

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

BY
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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

June, 1977

ABSTRACT

Lithologic studies in northeastern Minnesota suggest that drift prospecting is a useful tool for mapping drift-covered bedrock. A detailed study of till clasts composition in the Long Island Lake Quadrangle revealed a significant relationship between drift lithology and bedrock geology.

The Long Island Lake Quadrangle is a suitable area for this study for the following reasons: (1) outcrops are numerous enough to have allowed the construction of a detailed geologic map; (2) the area contains eight distinctive rock units; (3) the local bedrock experienced glacial erosion, indicated by the existence of glacially abraded and quarried outcrops.

The distribution of glacial sediments, mainly till and outwash, were mapped, and one hundred and one samples of drift were collected along traverses parallel to ice flow (perpendicular to strike of the bedrock). Both till and outwash contain a large quantity of local bedrock clasts in the size ranges greater than 1mm in diameter. Clasts smaller than 1mm are mainly minerals, and therefore not so diagnostic of local bedrock. As a test, boulders greater than 1 meter in diameter were used in the field for inferring bedrock contacts. These contacts were found to be within ± 60 meters (200 ft.) of

contacts placed by outcrop mapping.

Lack of local bedrock clasts in the smaller size fractions indicate either high resistance of local bedrock to crushing, or lack of opportunity for crushing because of short residence time in the glacial system (short distance transport). In either case, the fine-grained fraction therefore represents a contribution to the glacial load from more distant sources and the coarse-grained fraction represents a contribution form local sources.

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INTRODUCTION

In Minnesota, as is true in all areas that have been subject to glacial erosion and deposition, "glacial overburden" has caused serious problems in the exploration for mineral resources and geologic mapping. Glacial deposits cover a large portion of the bedrock in these glaciated areas, making mineral exploration difficult and the accurate mapping of bedrock distribution impossible, without the aid of expensive exploration methods.

The main purpose of this investigation was to explore the relationship between glacial drift lithology and bedrock geology, so as to determine the usefulness of drift studies in prospecting for mineral dposits or mapping bedrock contacts. A second purpose of the investigation was to study the sedimentology and stratigraphy of the glacial deposits, to gain insight into the process of glacial erosion and transportation, and to determine ice flow directions.

The Long Island Lake Quadrangle was chosen to study for the following reasons: (1) bedrock outcrops are numerous enough to have allowed the completion of a reasonably detailed geologic map, (2) within the area are eight distinctive Precambrian rock units which are comprised of easily recognizable sources for clasts within the drift, (3) the drift of just one glacial event appears to be present, (4) the local bedrock experienced glacial erosion, indicated by the existence of glacially abraded and quarried outcrops, (5) the direction of glacier flow in the area was transverse to the strike of the local bedrock, and (6) no detailed work on the glacial geology has been done in this area of Minnesota.

Location and General Description

The study area is located in the Long Island Lake Quadrangle (7.5 minute series), Cook County, Minnesota (Fig. 1). Located in the northwest portion of Cook County, the quadrangle is bordered in its northeastern corner by Canada. The Gunflint Trail, one of the few roads in Cook County, bisects the northern half of the quadrangle.

Locally the area is hilly, with a maximum relief of about 172 meters. Altitudes range from 626 meters in the northwestern portion of the quadrangle to 450 meters along the northern border. If the water were drained from the lakes, the total relief would increase nearly 30 meters.

The Long Island Lake area is essentially a sparsely settled wilderness with few roads and trails. It is covered by a dense second growth forest of deciduous and coniferous trees, with

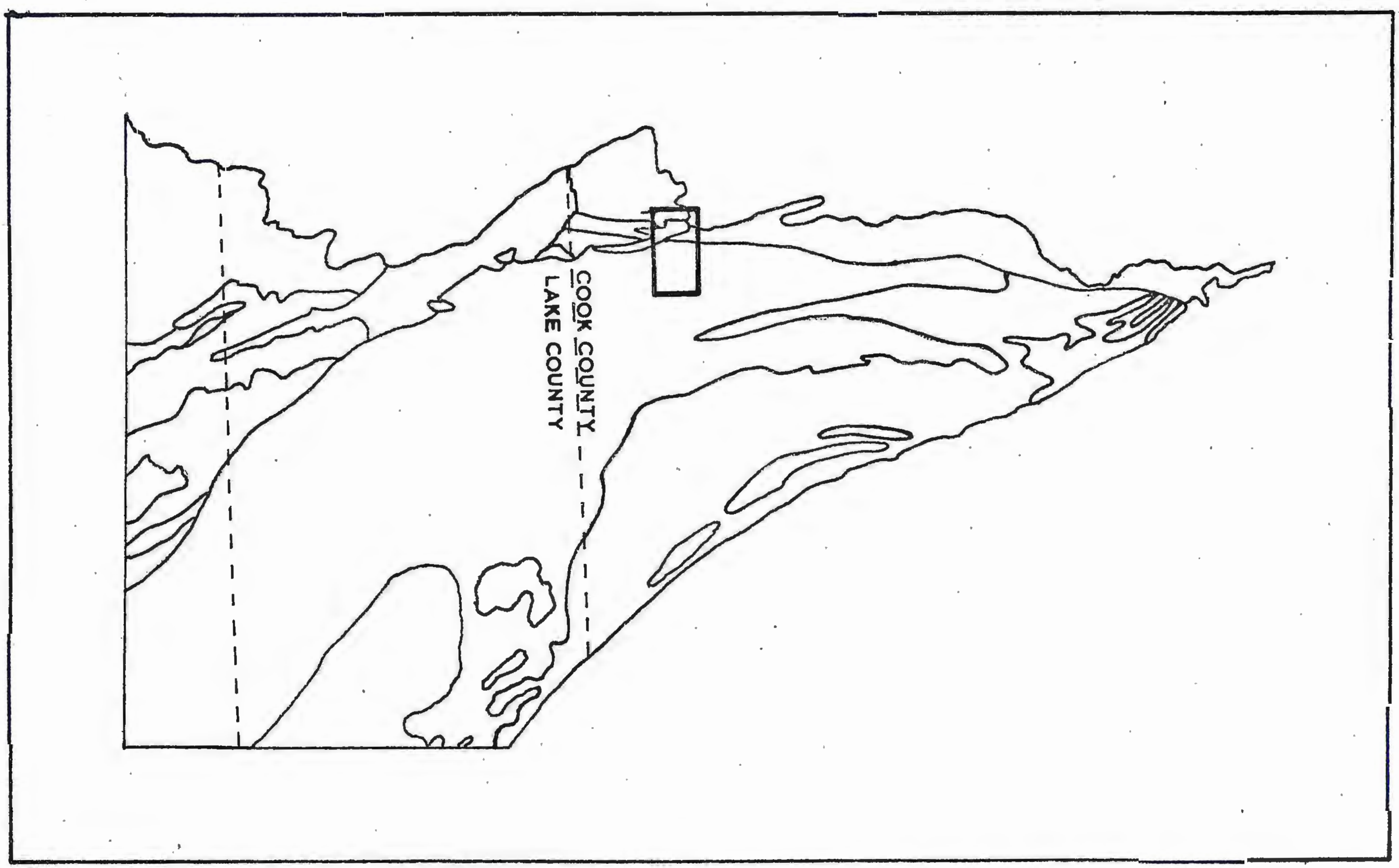


Figure 1: Location of Long Island Lake Quadrangle, northeastern Minnesota.

an undergrowth of smaller plants. Portions of the quadrangle are included in the Boundary Waters Canoe Area of the Superior National Forest, while the remainder of the quadrangle is privately owned.

Acknowledgements

I would like to thank Dr. Charles L. Matsch, University of Minnesota-Duluth, who served as my advisor during this investigation. I would also like to thank Mark Severson and Bill Feirn for their help in the field, John Beck who spent the long hard days of canoeing and backpacking in the field with me, Randee Zarth for her laboratory assistance, and to my wife, Deb, for her patience and consideration. A very special thanks goes to the Minnesota Geological Survey for the financial support of the investigation.

Previous Work

The Long Island Lake area is not only a wilderness in the eyes of the biologist but also in the eyes of the geologist, for little geologic work has been completed in the area. The most recent work, on the bedrock, is summarized on an open file geologic map (Morey and others, 1969), in the office of the Minnesota Geological Survey. Earlier studies (Grout, Sharp, and Schwartz, 1959) were conducted on the Precambrian bedrock. In these earlier studies the glacial geology was only mentioned to the degree that the area had been subjected to glaciation and covered with a thin veneer of drift.

Method of Study

Approximately 20 days were spent in the field during the summer of 1976. A U.S.G.S. 7.5 minute topographic map was used as a base map; the pace and compass method was used for locating glacial deposits and glacial features on the base map.

Traverses were made parallel to ice flow, in order to map glacial sediment distribution, boulder trains, roches moutonnees, striations and gossen boulders. One hundred and one samples of till and outwash were collected along the parallel traverses. Samples were taken wherever a good exposure of drift was located. All samples were stored in large plastic sample bags to be returned to the laboratory. Random pebble, cobble, and boulder counts were made in the field, with about 100-200 counts per locality.

Laboratory work consisted of weighing out approximately 100 gram samples of till and placing each sample in a sodium Hexametaphosphate (calgon) solution (10 grams/liter of water). The sample remained in the solution for over 24 hours so as to disperse the clays.

After 24 hours, the sample was washed through a 62 micron sieve to separate the coarse fraction (sand) from the fines (silt and clay). After removing the fines and catching them in a pan, they were than transferred to a mixer and stirred for five minutes. The sample was then transferred to a 1000 ml cylinder which was then filled to the 1000 ml level with sodium Hexametaphosphate solution.

The sample was analyzed for fines by using the pipette method to determine the weight in each Ø interval and the cumulative percent coarser. After wet sieving, the coarse fraction was placed in an oven to dry overnight. When dried, the sample was allowed to come to ambient conditions of temperature and humidity, weighed to the nearest 0.01 gram and sieved. The sieving was done using sieve numbers 5-230 (U.S. Standard sieve numbers).

Upon completion of sieving (10-15 minutes), the fraction weight, cumulative weight, weight percent, and cumulative weight percent were determined for each sample. When all sieving and pipetting was completed, the size fractions greater than 1mm were viewed under a binocular microscope to determine the composition of rock fragments for each sample. The data was plotted on a bedrock base map to show the distribution of clasts, for each size fraction greater than 1mm, throughout the area.

REGIONAL GEOLOGY

Regional Setting

The bedrock geology of the Long Island Lake Quadrangle (plate 1) is largely related to its position on the north limb of the Lake Superior syncline (Grout and others, 1959). The rock units in the southern two-thirds of the quadrangle (Gunflint Lake and southward) trend generally east-west. The oldest rocks outcrop in the northern and northwestern portion of the quadrangle. These include the Saganaga tonalite, unnamed granite, and the Chub Lake volcanics. The structure of these rock units is complex and the relationship of one to another is explanined by Feirn (1977). Figure 2 is a complete geologic column of the Long Island Lake Quadrangle.

Rocks of Early Precambrian age (Chub Lake volcanics, unnamed granite and Saganaga tonalite) are unconformably overlain by the Middle Precambrian Animikian Group (Gunflint Iron-Formation and Rove Formation). The Duluth Complex and Logan Intrusions intrude and truncate the Middle Precambrian rocks. These two units make up most of the Upper Precambrian section.

Lower Precambrian

Chub Lake Volcanic Complex

The Chub Lake Volcanic Complex is located in

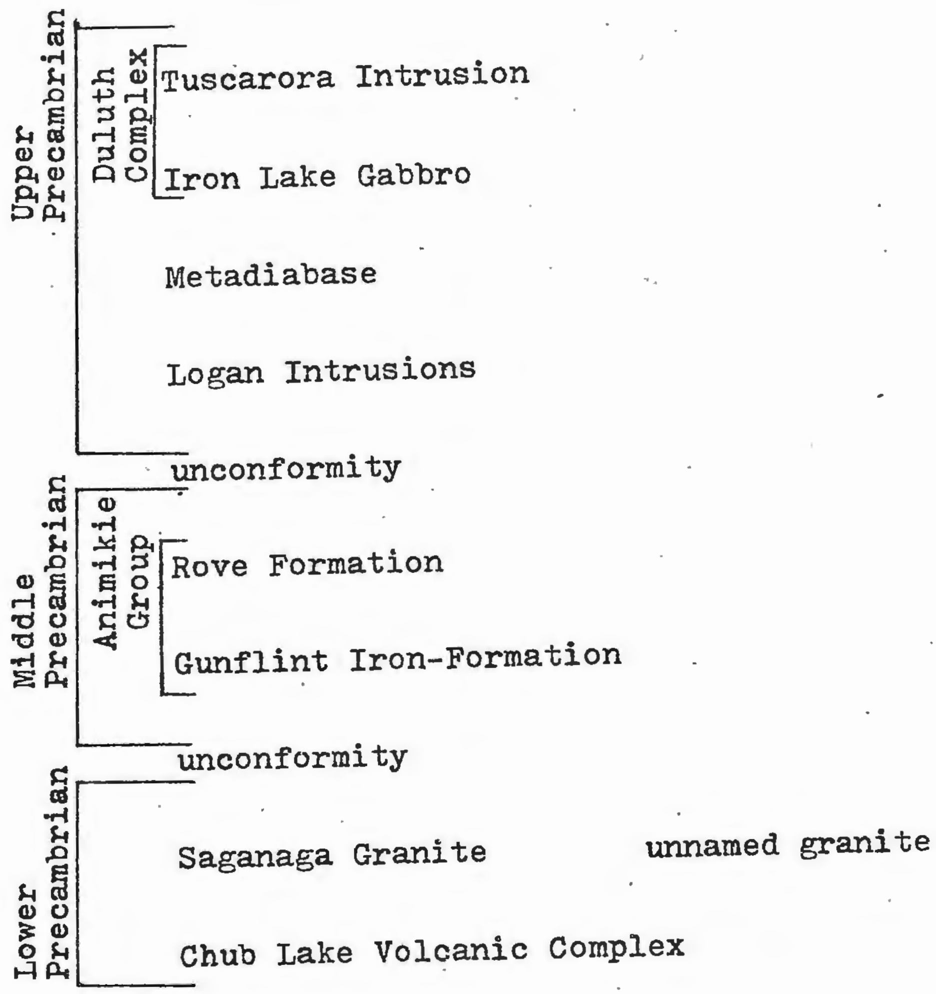


Figure 2: Geologic column of the Long Island Lake area.

the northwest portion of the Long Island Lake Quadrangle. The volcanic complex is an eastward extension of the Jasper Lake greenstone unit (Feirn, 1977), that includes an assembledge of metabasalt, meta-andesite, agglomerate and tuff, hornblende andesite porphyry and intercalated metagraywacke and slate.

The greenstone is a dense greenish, somewhat schistose rock, consisting largely of hornblende, feldspar and lesser chlorite, leucoxene and magnetite. Veinlets of calcite, chlorite, quartz, and pyrite are sometimes found. Some of the greenstone shows spherulitic and ellipsoidal structure.

The Chub Lake Volcanic Complex constitutes a homoclinal sequence which dips southward toward what Gruner inferred to be the axis of a southeastward-plunging synclinorium. This sequence becomes stratigraphically younger to the south, according to pillow-top directions (Feirn, 1977).

Saganaga Granite

The Saganaga granite of A. Winchell (1888) has been renamed the Sganaga tonalite by Hanson and others (1971), inasmuch as plagioclase is the dominant feldspar. It intruded the Chub Lake Volcanic Complex around 2.7 billion years ago.

The main phase of the granite is a gray, medium- to coarse-grained tonalite characterized by large quartz aggregates that resemble phenocrysts. The quartz "eyes" are aggregates of grains 1-2mm in diameter. Other phases include: (1) a younger fine-grained tonalite which lacks conspicious quartz "eyes"; (2) a border phase which is a quartz-bearing hornblende diorite; (3) a red, coarse-grained biotite-fluorite granodiorite and pegmatite; and (4) a quartz-feldspar pegmatite which occurs as vienlets in the main phase.

A major, northwesterly trending fault (Lookout Fault) separates rocks showing no metamorphic effect on the granite. The fault apparently was related to the final emplacement of the granite (Morey and others, 1970) which makes it a Lower Precambrian structure, even though later movement has occured.

<u>Middle Precambrian</u>

<u>Gunflint Iron-Formation</u>

The Gunflint Iron-Formation trends northeasterly from Sec. 34, T.65N, R5W to Gunflint Lake. West of section 34 the iron-formation is overlain by or engulfed by the gabbro. The iron-formation is represented by a narrow band ranging from one hundred meters up to three hundred meters wide.

The Gunflint formation consists of four main subdividions: (1) lower cherty member; (2) lower slatey member; (3) upper cherty member; and (4) upper slatey member. The lower cherty member contains a basal conglomerate that is mainly chert with a granular texture. It also contains a thin coarse-grained bed of magnetite, quartz and amphiboles. The lower slatey member consists of a thin-bedded, black, graphic slatey layer, a massive cherty layer and a fine-grained, thin-bedded, bluish to greenish black layer. The upper cherty member contains a massive coarse-grained, gray cherty layer with wavy and irregular magnetite layers. The upper sltey member contains a fine-grained, thin-bedded layer composed of quartz, amphibole and magnetite, with a carbonate layer containing abundant silicates.

Rove Formation

The Rove Formation extends from Sec. 26, T65N, R4W eastward to Gunflint Lake. The formation is characterized by intercalated black to grayish black, locally carbonaceous argillite, argillaceous siltstone and fine-grained graywacke (Morey, 1971). It is intruded by a complex of sills and dikes of diabase (Logan Intrusion) and is truncated by the Duluth Complex. The diabase is much more resistant to erosion, thus, making the Rove area stand out as a series of valley and ridges.

Locally the Duluth Complex has metamorphosed the Rove to a medium-grained, granoblastic hornfel. The Rove is well-bedded with an average strike of N70°E and sips 4°-10° to the south except where the sills and dikes have intruded and distorted the beds.

Upper Precambrian

Logan Intrusions

The Logan Intrusions include sills and dikes of fine- to medium-grained diabasic gabbro. Most of the Logan bodies are sill-like, which result in a sawtooth topography due to the differential erosion of the inclined sills and the Rove Formation. The Logan sills and Rove Formation are truncated by the Duluth Complex along strike at a low angle. The contact of the Rove and Gunflint Formations is concordant with bedding.

Fine-grained Metadiabase

A fine-grained metadiabase is found in the southwestern portion of the quadrangle. It is similar in mode, texture and variation to the diabase of the Logan Intrusion.

Iron Lake Gabbro

A medium-grained, foliated gabbro termed the Iron Lake Gabbro outcrops in the eastern portion of the quadrangle. The unit is characterized by a well-developed planar orientation of plagioclase, tabular augite and elongate iron-titanium oxides.

Tuscarora Intrusion

The Tuscarora Intrusion makes up alomost all of the southern half of the quadrangle. It is a sequence of rock types common to other parts of the Duluth Complex. The rock types appear in the following succession away from the base: (1) a fine- to medium-grained augite-troctolite, (2) fine- to medium-grained troctolite, (3) a medium-grained troctolite, (4) a fine-grained granoblastic gabbro, (5) an interlayered anorthositic gabbro and troctolite, (6) medium-grained anorthosite, (7) medium grained ferrogranodiorite, and (9) a fine- to medium-grained granophyre.

The basal contact of the intrusion is nearly flat lying and it crosscuts the steeply-dipping Animikie strata and the Logan Intrusion. The troctolite sequence strikes eastward and dips 15^{o} south towards Lake Superior.

Generalized Geology

To make the identification and classification of rock fragments easier during the investigation, the bedrock geology was simplified into the following units: (1) granite, (2) volcanics, (3) iron-formation, (4) slate and diabase, (5) gabbro, and (6) others (which include units from outside the area). Figure 3 is a plan map showing the simplified and generalized geology for use in studying the composition of glacial drift in the area.

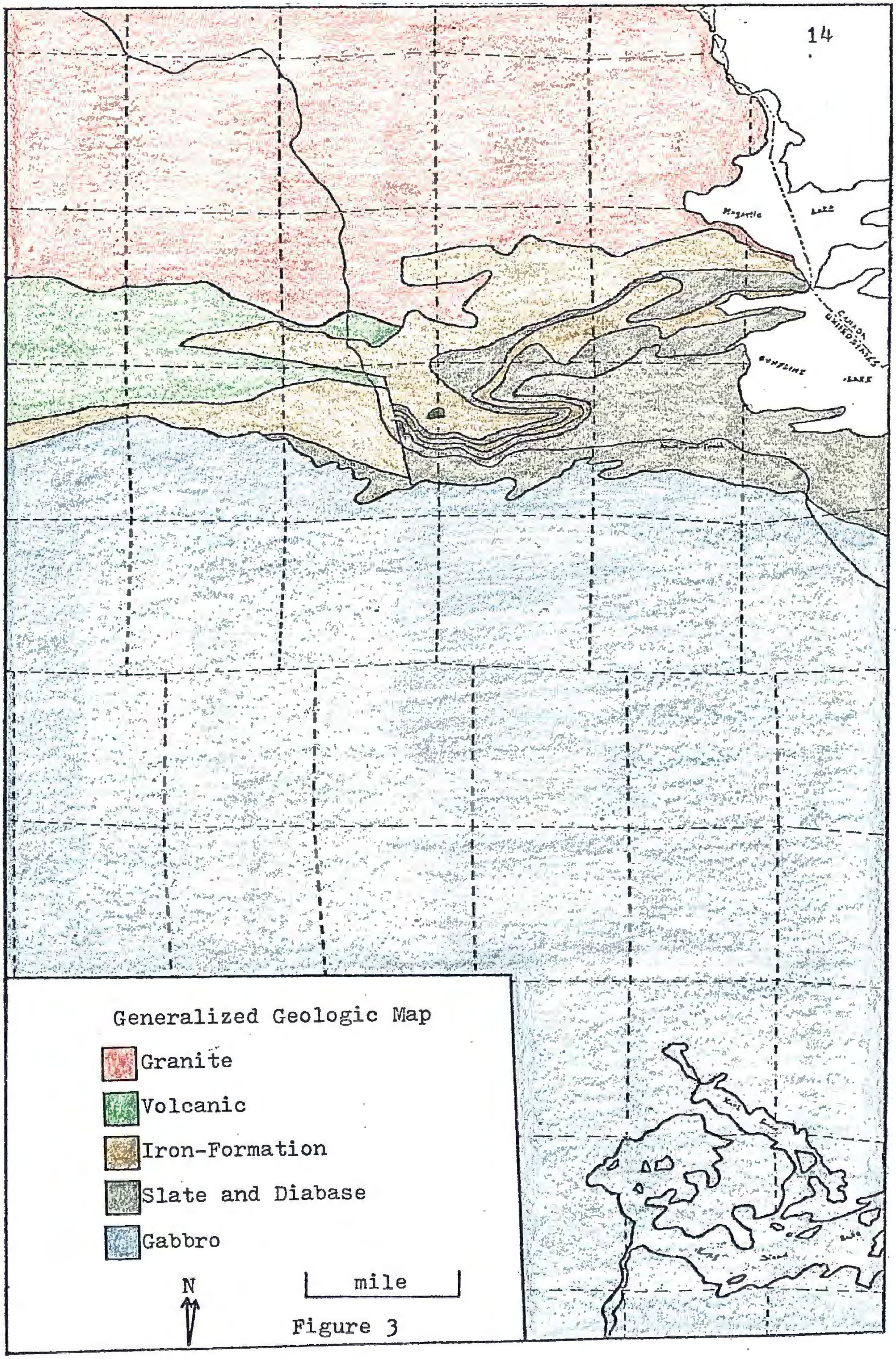

Generalized Geologic Map
Granite
Volcanic
Iron-Formation
Slate and Diabase
Gabbro
N
mile

Figure 3

QUATERNARY GEOLOGY

Introduction

A complex history of advance and retreat of the Laurentide ice sheet is indicated by stratigraphic relationships in Minnesota and elsewhere in the upper Midwest. Drift sheets of possible Illinoian and Kansan age have been identified in southern Minnesota (Leverett, 1932). However, the landforms and surficial deposits for most of the state record events of the Wisconsin Glaciation.

The glacial record of Minnesota is complex, because of the interaction of several distinct lobes of ice which protruded from the front of the Laurentide ice sheet. These protrusions were in part controlled in their movement by preglacial bedrock lowlands which formed by differential erosion of the different bedrock types. Wright (1972) has recently summarized the Quaternary history of the state in some detail.

During the Wisconsin Glaciation, two separate lobes of ice invaded Cook County (Sharp, 1953) as seen in figure 4. The earlier lobe, termed the Rainy Lobe (Elftman, 1898), was the only lobe to advance across the Long Island Lake area. The later Superior Lobe (Leverett, 1929) followed the Lake Superior trough, and covered only a narrow strip of land along the southern edge of Cook County.

The Rainy Lobe advanced and retreated several times (Fig. 4). During the St. Croix phase, the Rainy Lobe extended south and west into central Minnesota, where it terminated at the St. Croix Moraine. This advance produced the impressive Toimi drumlin field in St. Louis and Lake Counties. In the Vermilion phase, the lobe extended as far south as Isabella, Minnesota, where it formed the Vermilion Moraine.

Glacial Erosion

The principal small scale erosional features displayed are striations, glacial polish, grooves and various types of friction cracks. Large scale erosional features include roches moutonnees, stream-lined and glaciated bedrock hills, and excavated bedrock basins. Most of the erosional features, whether large of small, are developed in bedrock areas underlain by granite, volcanics, iron-formation, slate and diabase. These features tend to be absent in the gabbro due to intense post-glacial weathering of the bedrock surface.

The striations trend between S30°E and S30°W indicating that the Rainy Lobe advanced into the area from the north and moved generally southward (Fig. 5). Sharp (1953) suggested that variations in direction appear to reflect the influence of local topography. Undoubtedly, ice flow was controlled to some degree by the direction of slope of the glacier's surface.

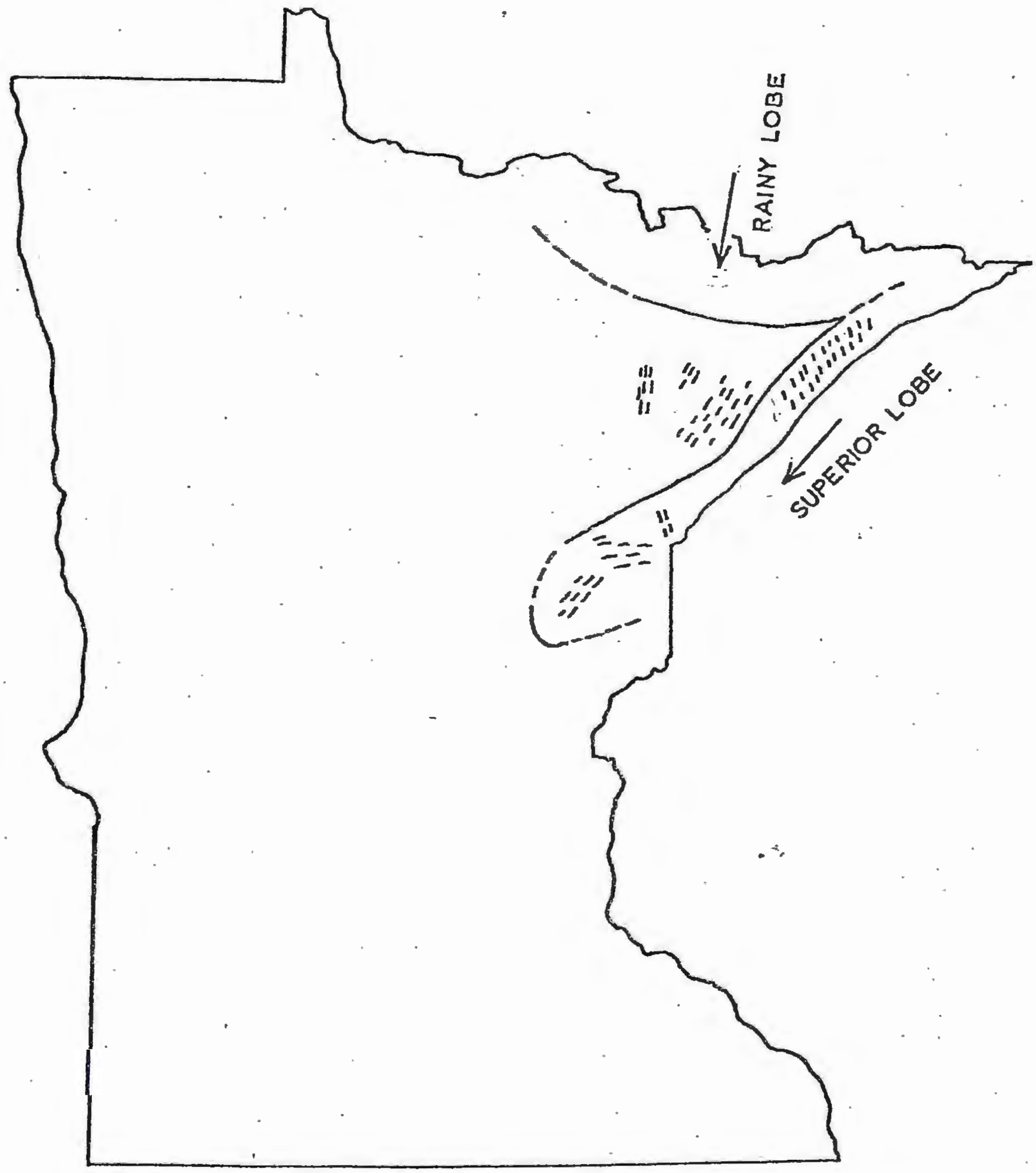


Figure 4: Phases of glaciation in northeastern Minnesota. (after Wright,1972)

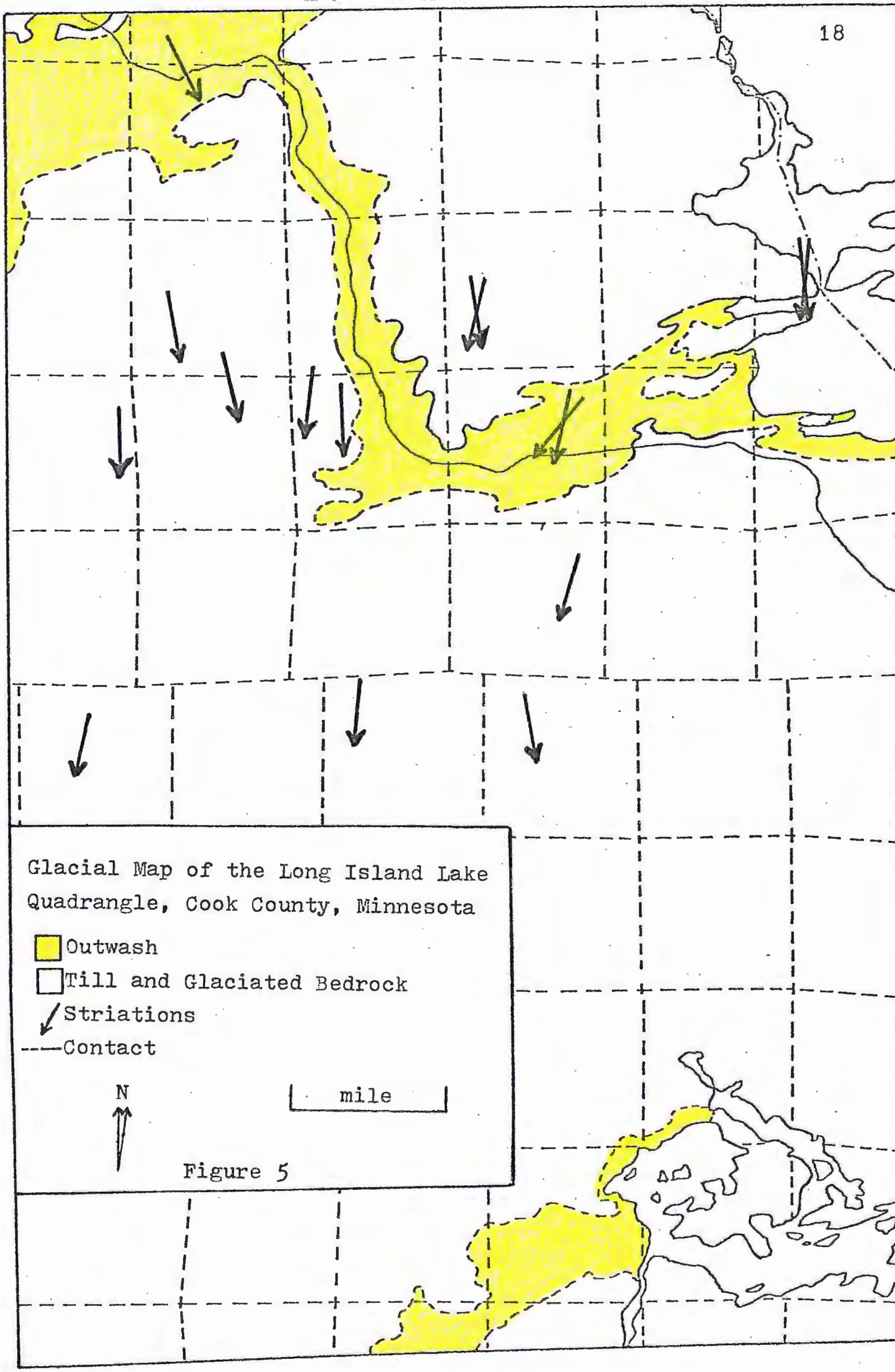

Glacial Map of the Long Island Lake Quadrangle, Cook County, Minnesota
Outwash
Till and Glaciated Bedrock
Striations
Contact
N
mile

Figure 5

Many of the glaciated bedrock surfaces, especially roches moutonnees, have joint-controlled scars. These scars range from a meter to tens of meters in length, from which a large portion of the mass has been plucked away. Most of these scars are defined by one joint plane dipping 80° transverse to the direction of flow. The modification of these surfaces by striations indicates that they were formed beneath the advancing ice sheet, or at least overridden by it.

Glacial erosion rather than deposition has been responsible for the distribution and shape of the lakes. Many of the lakes exceed 30 meters in depth. These are generally underlain by the Saganaga granite, Duluth gabbro or Rove Formation. The shallow lakes, a meter or two in depth are underlain by a mantle of drift.

Each of the major rock units are characterized by a distinctive configuration of the lakes developed upon them. Lakes underlain by the granite have linear segments which reflect the regional trend of the jointing. Within the Duluth gabbro, the lakes are narrow, elongate and lie parallel to mineralogical zones in the layered intrusions (Grout, 1933). The lakes underlain by the slate and diabase are elongate and trend east-west. The elongation reflects the valley and ridge topography formed by differential erosion of interlayered slates and diabase sills.

The absence of major north-south lakes or streams suggests that the preglacial drainage pattern was controlled by the bedrock structure. The absence of ice flow indicators trending east-west indicates that glacial erosion did little to alter the preglacial topography. Alternatively, the intensity of glacial erosion is influenced by differences in bedrock strength, regardless of glacier flow direction.

Glacial Deposits

Till

Throughout most of the area, the till is thin and patchy, never exceeding more than a few meters in thickness. Most of the till is found on the lee side (down glacier) of topographic highs. It is generally loose and uncemented, except in the east-central portion (sections 24,25,26 and 30), where iron oxide-cemented till is exposed in a few places.

The till is yellowish brown (10YR 5/4) and sandy, composed of 60-90% sand size particles, with an average of 90% (Fig. 6). Only four samples were completely analyzed because most of the samples contained less than 5% silt and clay combined. The pebbles and boulders found in the till are of the same composition as the local bedrock. The boulders range up to more than 3 meters in diameter.

Many of the rock types in the area contain similar minerals, so in the analyses of the till the

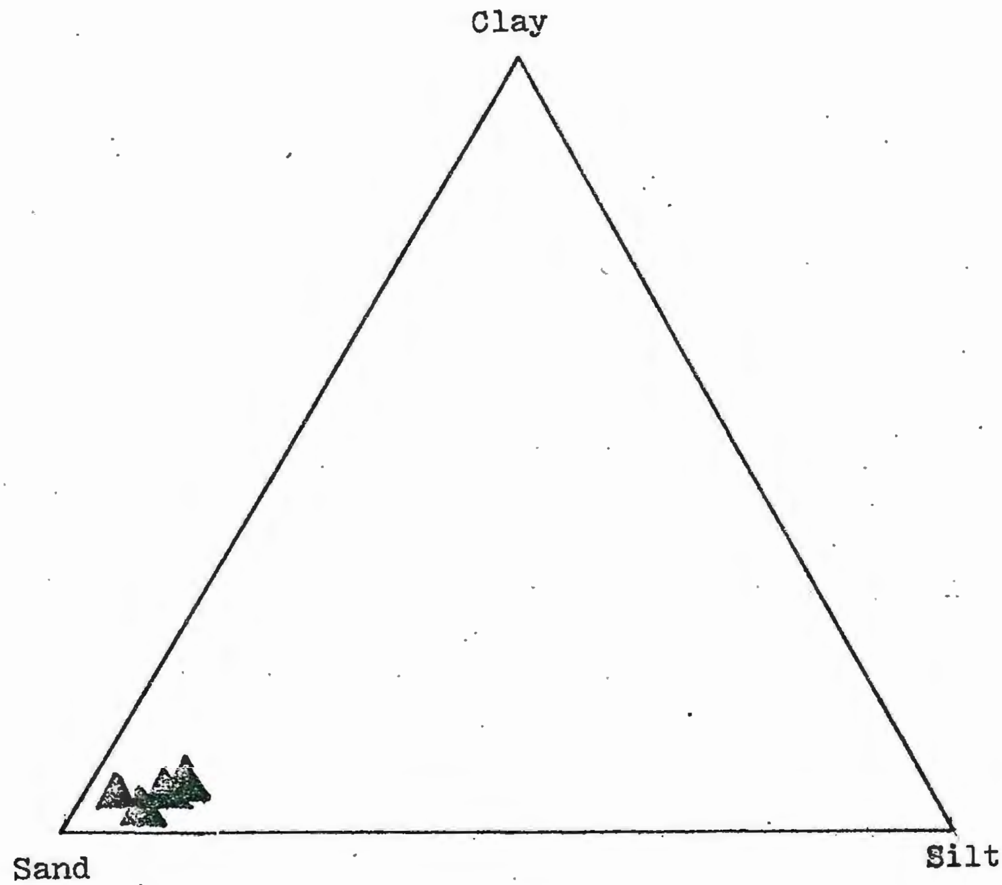


Figure 6: Ternary diagram.

clasts less than 1mm in diameter were not helpful in the determination of their bedrock sources. Therefore, only the lithologic composition for clasts greater than 1mm were determined. The results of the till analyses are listed in Tables I and II.

Outwash

Outwash is located in three major areas (Fig. 5). The northern outwash areas are connected by a 300 meter wide channel of bedded and sorted sand and gravel that was formed by spill-over from the northernmost outwash area. This relationship is supported by the existence of a high percent of granitic clasts within the channel, as well as cross-bedding that indicates southward flow. At the present time, the channel is occupied by a northward flowing stream.

The outwash contains pebbles and boulders of the local bedrock. Unlike the till, these boulders and pebbles are rounded and usually stained by limonite. Grout and others (1959) suggest that the outwash near Gunflint Lake reaches a thickness of 33 meters. Along the western shore of Long Island Lake, exposures of outwash rise 20 meters or more above the lake level. Topographically the outwash areas are found in lowlands or valleys, especially the valleys within the slate and diabase.

Depositional Landforms

No glacial landforms such as moraines, drumlins or sekers are found in the Long Island Lake area. The Vermilion Moraine, formed during the retreat of the Vermilion phase, is located about 60 km southwest of the area. The Toimi drumlin field, which formed during the St. Croix phase, is about 90 km southwest. With the lack of glacial landforms, such as these, one could assume a constant rate of retreat for the glacier.

RELATIONSHIPS OF DRIFT LITHOLOGY TO BEDROCK

Introduction

Drift Lithology

Although little work has been completed on the glacial geology of the area, many studies of glacial dispersion, drift lithology, or drift prospecting have been unertaken in the past one hyndred years, with most literature published in the past thirty years.

One of the earliest modern studies of regional drift lithology was completed by C. D. Holmes (1952). He studied the progressive changes in drift composition southward from the Lake Ontario basin into North Central New York by means of pebble counts within a single grain size (5mm to 11mm). Holmes concluded that till varies systematically in lithologic composition down glacier from bedrock sources, with rate of decrease dependent upon rock type.

Harrison (1959, 1960) conducted a detailed lithologic investigation of tills in Indiana. He looked at 16 different size fractions in 11 till samples. He concluded that the abundance of various lithologic components of the till was porportional to the area of the corresponding bedrock that was traversed by the glacier.

Indicator studies have commonly dealt with boulder and pebble distribution. Since 1950, distribution patterns of sand-size clasts, clay minerals, and trace elements have received increased attention. Dreimanis (1956) gives an excellent discussion and bibliography on boulder tracing; Potter and Pettijohn (1963) also present a discussion of till provenance studies. Hawkes and Webb (1962) and several authors in Kvalheim (1967) discuss the development of geochemical prospecting techniques in glacial or related deposits.

One of the few complete investigations of drift lithology was conducted by Dreimanis and Vagners (1969). They concluded that: (1) local bedrock material is not always predominant in till; (2) during glacial transport, each rock eventually becomes comminuted to the terminal grade of its constituent minerals; (3) before a rock has been comminuted to it terminal grades, its frequency distribution in till is bimodal or multimodal. Rock fragments generally are found in one or more coarse-grained modes, and each constituent mineral in its own fine-grained mode; (4) the lithologic composition of till depends on many factors.

The publication by Dreimanis and Vagners (1969) along with other publications, such as Lee (1963), Sitler (1963), Willman and others (1963, 1966), Gillberg (1964, 1967); and White and others (1969) are examples of systematic modern approaches to regional mineral and rock dispersal studies for till.

Various workers in the Baltic area have done similar till investigations, such as Raukas (1961) in Estonia, Savvaitor (1962) and Stinkule (1964) in Latvia, and Gaigalas (1964) in Lithuania.

In southeastern Quebec, McDonald (1966, 1967) mapped indicator trains trailing southeast from several distinct source areas. He interpreted erratics found west of their source areas as having been transported southwest across regional strike during a southwest flow phase of the penultimate glaciation. Cooke (1937) and Dunquette (1960) interpreted a similar occurence of erratics as reflecting north or northwestward flow of ice into Quebec from highlands in New England.

W. W. Shilts (1973) based on studies of rocks, minerals, and trace elements in Wisconsin age till components could be ascribed to distant sources, except where topographic prominences had blocked or deflected ice-transported sediment.

C. L. Matsch (1971) studied the distribution of Pierre shale in the Des Moines lobe in central Minnesota. He found that in the central portion of the lobe, shale persisted (50% or more of the very coarse sand fraction, 1mm-2mm) along the entire path of flow in Minnesota and that the content of shale clasts decreased systematically towards the ice margins. He showed that contary to other findings, compositional isopeths are sometimes parallel to regional flow lines rather than normal to them.

Glacial Erosion

J. D. Forbes (1843) described the effects of a glacier as "a stupendous unwieldly mass dragged over the rocky surface, denuding it of every blade of grass and every fragment of soil, that proceeds to wear down the solid granite, or slate, or limestone, and leaves most undeniable proof of its action upon these rocks". Ever since this statement, glacial geologist have tried to understand the erosional processes of a glacier. Like drift lithology, glacial erosion has been a widely studied process in the past one hundred years.

The intricacy of striation patterns and their implications were first discussed superbly by Chamberlain in 1888. Gilbert, 1906; Harris, 1943; Carol, 1947; Dahl, 1965; and Gjessing, 1967 discuss in detail the processes that are responsible for the formation of striae, friction cracks, Sichelwannen, and stoss and lee topography. Veyret (1971) noted that during a recent advance of the Glacier des Bossons, grooves 0.4m long, 10-20mm across and 35mm deep were abraded by boulders within a span of four weeks. Boulton and Vivan (1973) recorded the abrasive effects on blocks bolted to the bedrock beneath part of Bjeidamerkurjokull in Iceland

The understanding of abrasion beneath glaciers has come from observations associated with subglacial hydro-electric tunnels (Galibert, 1962; Vivan, 1970), from theoretical considerations (Rothlesbergen, 1968) and from the laboratory (Lister et al., 1968; hope et al., 1972). Sugden and John (1976) summarize the processes of glacial erosion inwhich they give a tentative list of variables affecting the process of glacial abrasion.

A large quanity of work has also been completed on the fracture of fresh bedrock by glacial activity (Embleton and King, 1975; Trainer, 1973; Glen and Lewis, 1961). Boulton (1974) discusses fracture of bedrock along with other processes and patterns of glacial ersion. He suggests that differences in pressure between the upstream side of a protuberance and the downstream side is sufficient to cause rock fracture.

Another effective erosional process is plucking and freeze-thaw. Boye (1950), Cailleux (1952), and Tricant and Cailleux (1962) suggest that erosion by a glacier is most effective when preglacial rocks have first been broken up by periglacial freeze-thaw activity. Since the observations of Carol (1947), plucking and freeze-thaw have seemed an attractive explanation of the block loosening in the lee of roches moutonnees. Weertman (1961) and Boulton (1972) suggest that, where a glacier is cold in its marginal area, net freezing of meltwater (derived from a temperate interior) to its sole would incorporate debris from subglacial sediments. In their model subglacial materials which were themselves frozen could be incorporated in some bulk to produce very large erratics (Boulton, 1972). Observers of alpine glaciers (Corbel, 1968; Vivian, 1970) suggest that temperatures of -20°C are necessary before frost can shatter fresh blocks of hard bedrock.

Many studies have been published on glacial erosional processes and many more probably will be done in the future. Not all published papers have been mentioned because it would take many pages to mention them all. The observations seen, the ideas suggested, and the theories presented in this paper on erosional processes are an accumulation of past ideas of others and the ideas of the author.

<u>Distribution of 1mm-2mm Clasts in Till</u>

Figure 7 is a map showing the distribution of 1mm-2mm clasts in till. The distribution shows that granite clasts are found in abundance throughou the area. In the area underlain by granite, a small percent of clasts classed as "others" is found. These clasts are gneissic fragments whose source may be the Northern Light Gneiss located about 7km north of the Long Island Lake Quadrangle.

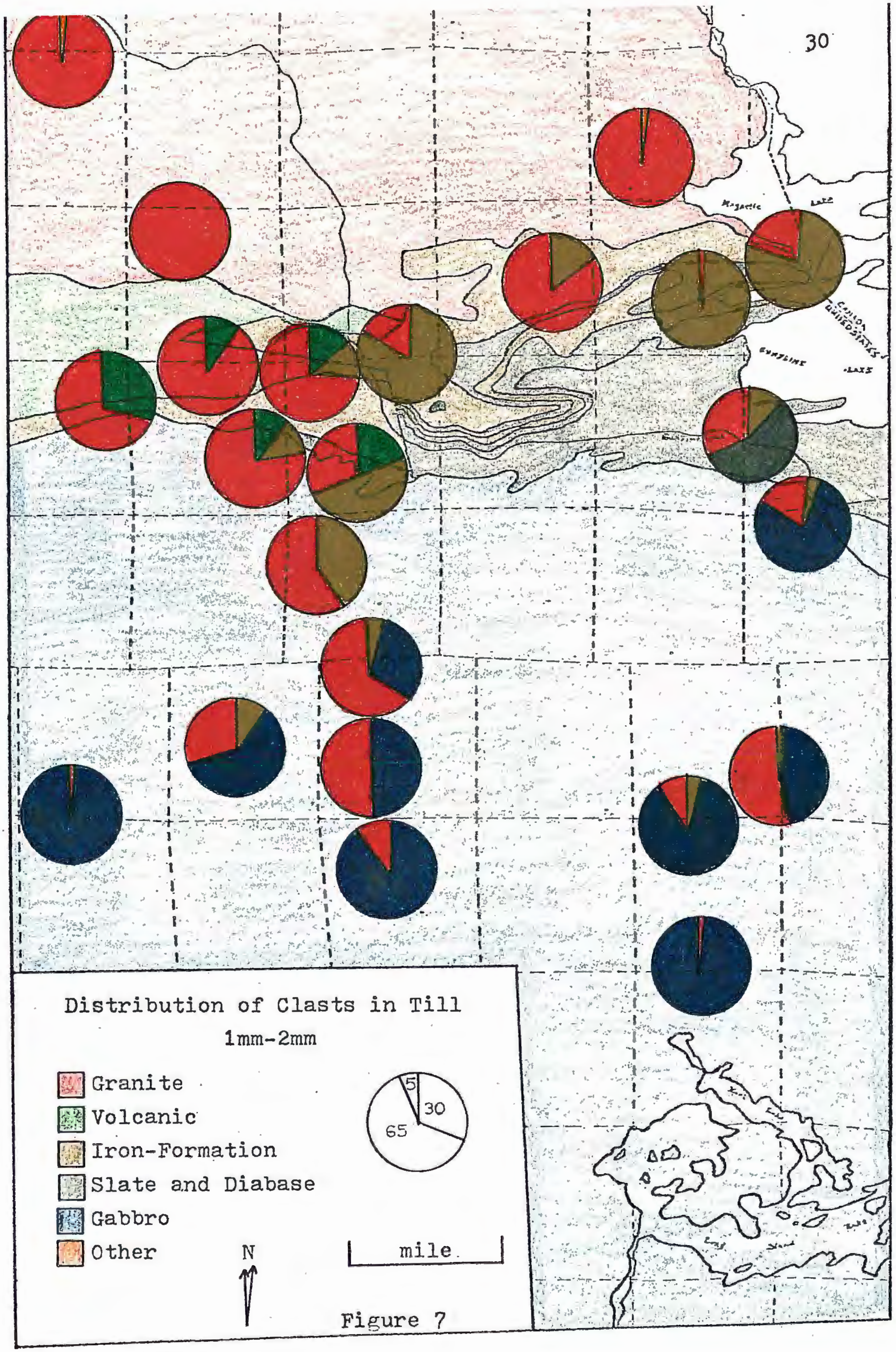

Distribution of Clasts in Till
1mm-2mm
Granite
Volcanic
Iron-Formation
Slate and Diabase
Gabbro
Other
5
30
65
N
mile

Figure 7

Other fragments in this category are diabase fragments whose source are dikes that have intruded the granitic batholith.

Although granite is abundant in all the samples, the percent decreases down glacier away from the bedrock source. Volcanics, iron-formation, slate and diabase show up as clasts in the till only at those sample sites located a fair distance into and downglacier from their contacts. The clast abundance for each litholgy reaches a maximum percent within 1km of their contact then decreases within the same distance along a flow path parallel to glacial flow.

South of the slate and diabase, the sample sites show a rapid increase of gabbro within 500 meters of crossing the contact, then a decrease accompanied by an increase in granite and finally an increase in gabbro again. The increase in granite could only be possible by the addition of new granitic material to the till. Therefore, it is postulated that within the gabbro, granite bodies, as yet undetected, and perhaps similar to those in the extreme southwest part of the quadrangle could be the source.

Rapid changes in the abundances of volcanics, iron-formation, slate and diabase could be related to the low resistance of these units to crushing. The material would be crushed easily into clast sizes 1mm-2mm, but also crushed out of this size fraction into a smaller size fraction just as easily. A narrow outcrop width would also control the total volume of material supplied to the basal ice; Therefore, would take place rapidly as the ice moved beyond the source area.

The major relationship that can be seen in the distribution of 1mm-2mm clasts is that as the distance from a particular bedrock source becomes greater down glacier, the percent of those bedrock fragments decreases. This is consistent with observations elsewhere by Holmes (1952) and White (1969).

Distribution of 2mm-4mm Clasts in Till

Figure 8 represents the distribution of 2mm-4mm clasts in till. In this size fraction the granite is abundant again except in the extreme southern portion. The fragments labeled "others" are gneissic and dike material within the granite. Near the U.S.-Canadian border, the high percent of non-ganite fragments includes a basal conglomerate of the iron-formation.

In this size fraction, as in the 1mm-2mm fraction, abundances of volcanic, iron-formation, slate and diabase fragments decrease more rapidly than does the granite fragments. At the same locality, the percent of foreign bedrock fragments is less in the larger fraction indicating that crushing has removed clasts from this size fraction.

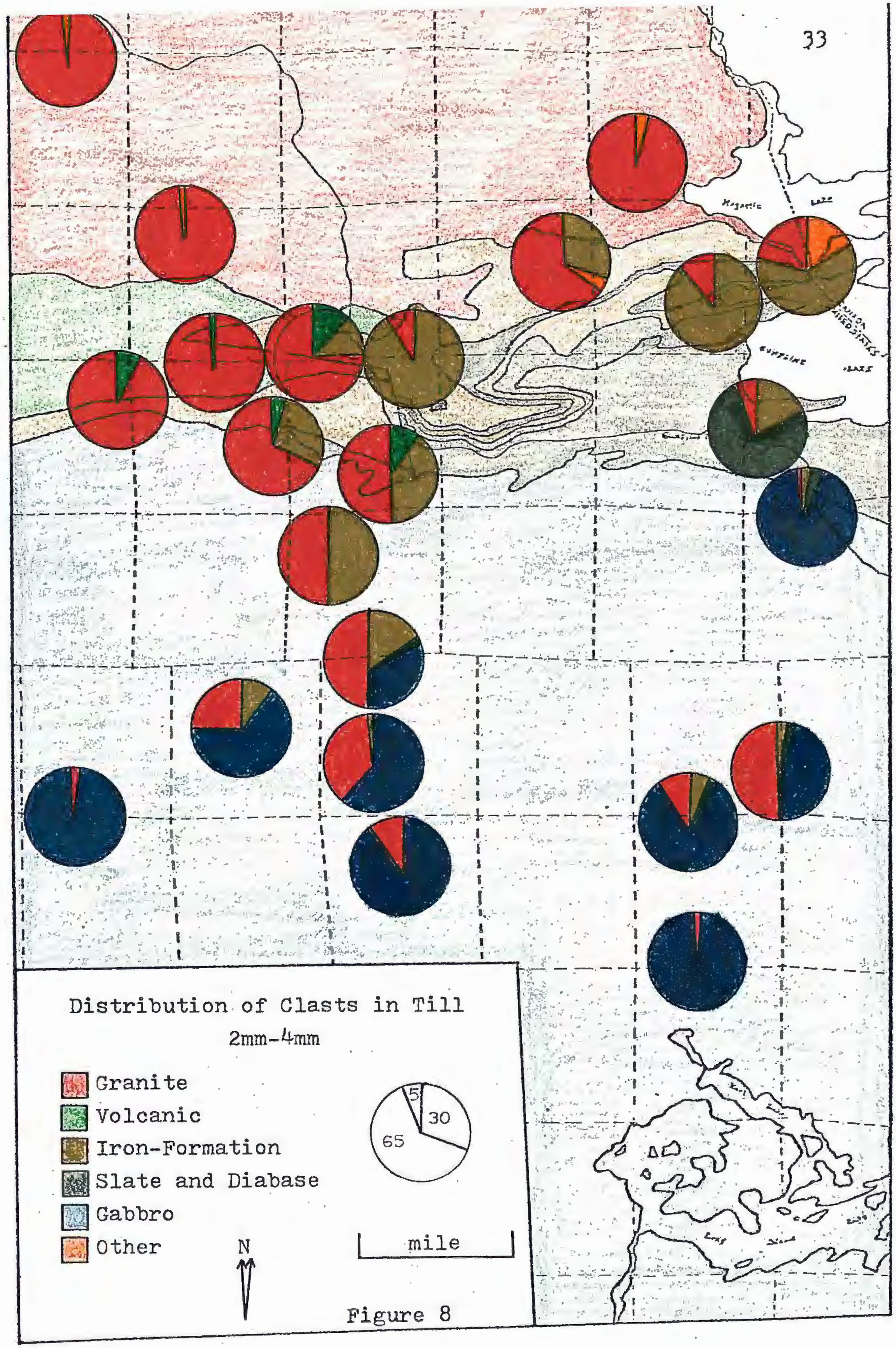

Distribution of Clasts in Till
2mm-4mm
Granite
Volcanic
Iron-Formation
Slate and Diabase
Gabbro
Other
5
30
65
N
mile

Figure 8

In the eastern portion of the mapped area, the percent of granite clasts increases in both the 1mm-2mm and the 2mm-4mm sizes at the same locality. This increase in several fractions indicates an uptake of granitic material from a new bedrock source, rather than a change resulting from crushing of larger clasts into smaller fractions.

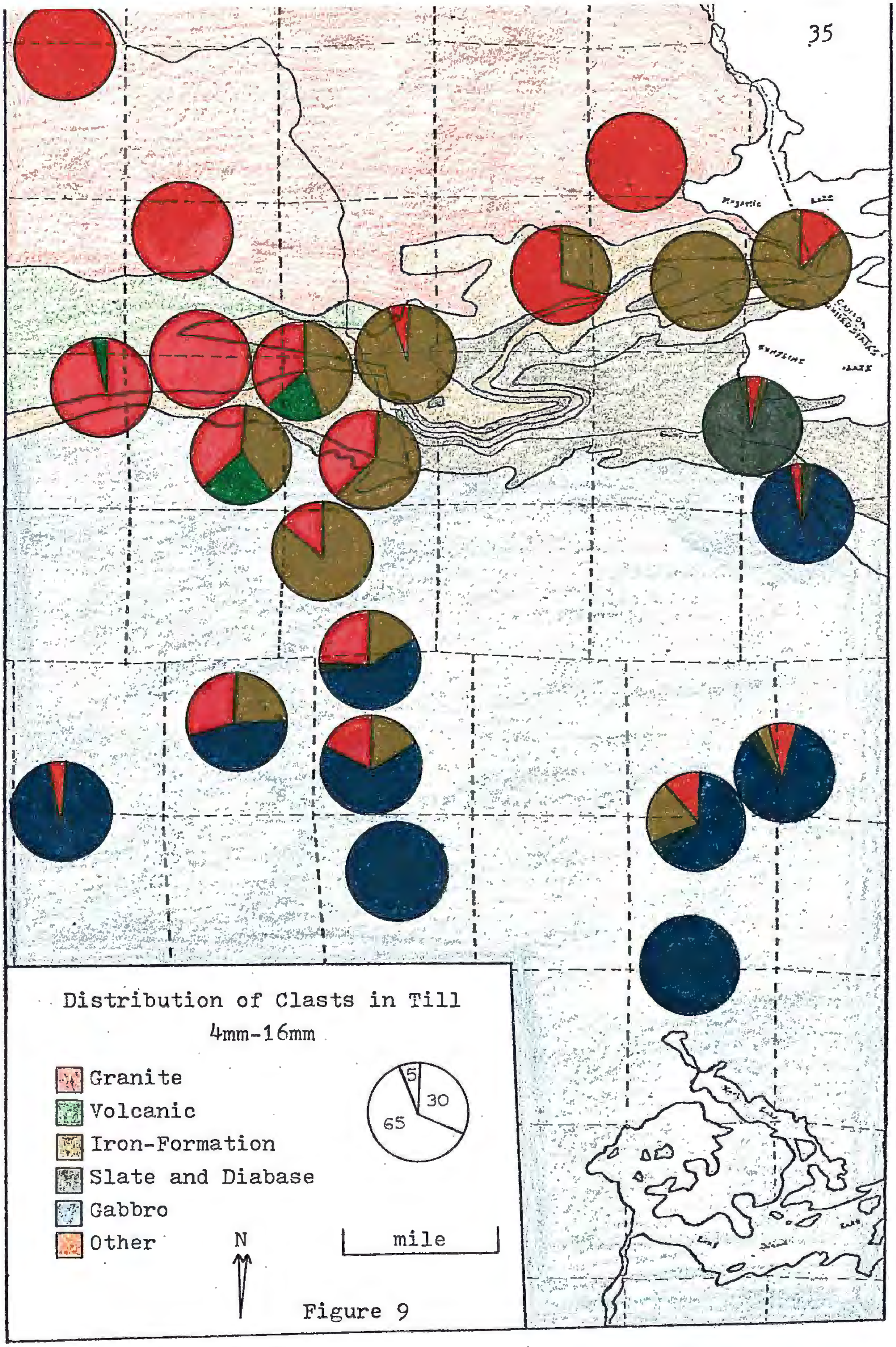
Distribution of 4mm-16mm Clasts in Till

Figure 9 represents the distribution of 4mm-16mm clasts in till. In this size fraction, all the same relationships in distributions already noted above continue to be apparent.

Distribution of 16mm-1m Clasts in Till

Figure 10 represents the distribution of 16mm-1m clasts in till. Many of the localities are not coincident with sample sites previously discussed. The difference is due to the lack of this size at the previous localities. An average area of 100sq. meters was needed to obtain 100-200 counts per locality.

In this size fraction, the percent of granite, volcanics and iron-formation decrease slower away from their sources. This relationship is probably due to the greater range of sizes used in this distribution. Also, this figure shows that the gabbro contributes to the composition of the till more rapidly then in the previous size fractions.



Distribution of Clasts in Till
4mm-16mm

Figure 9

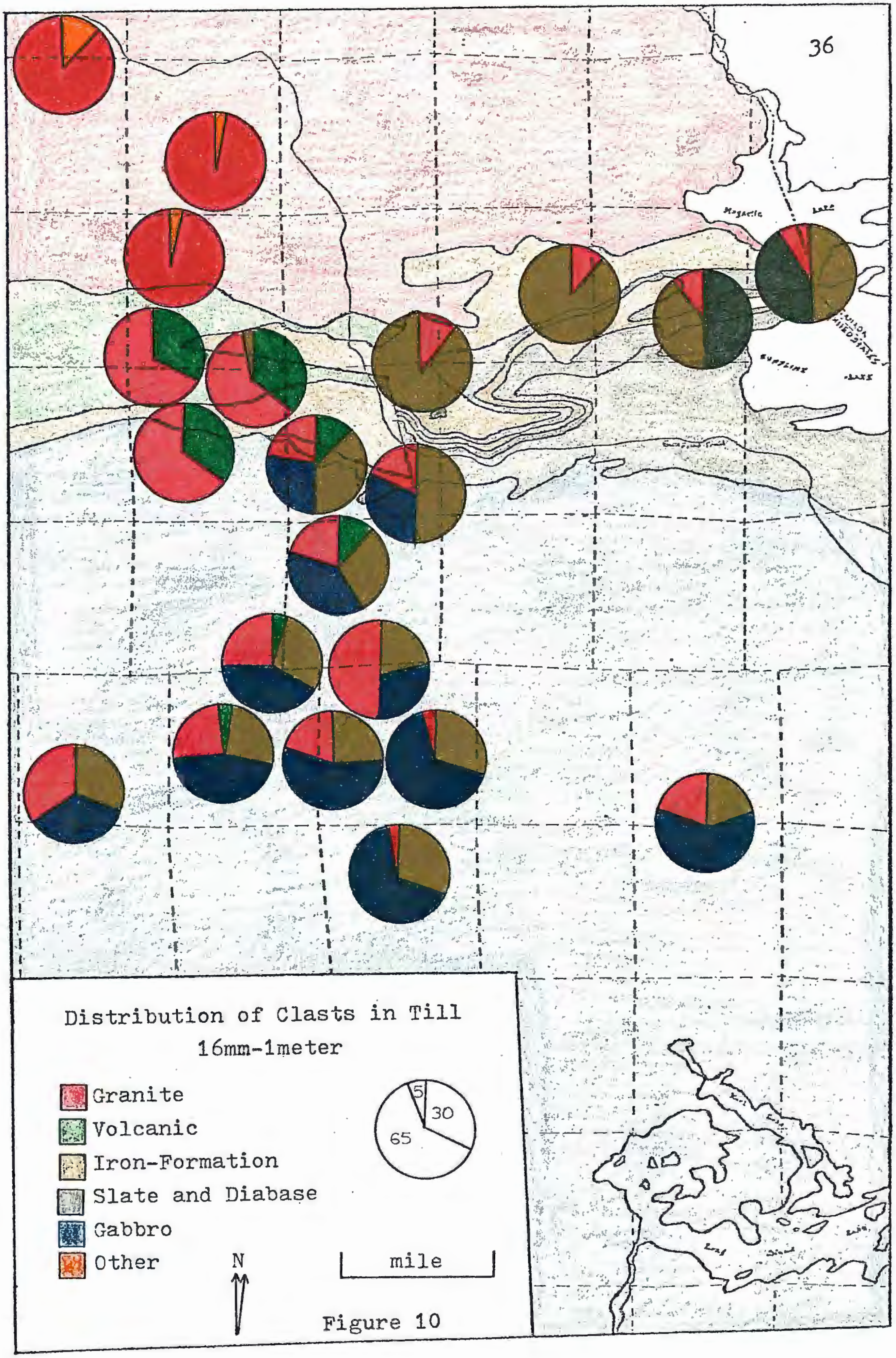

Distribution of Clasts in Till
16mm-1meter
Granite
Volcanic
Iron-Formation
Slate and Diabase
Gabbro
Other
5
30
65
N
mile

Figure 10

Distribution of >1meter Clasts in Till

Figure 11 represents the distribution of >1meter clasts in till. In every locality except one, 100% of the rock fragments found were of the same lithology as the underlying bedrock. Along all contacts, no boulder larger than 1 meter of the upstream bedrock was found more than 60 meters down glacier from the contact.

An example of this relationship can be seen along the volcanic-granite contact. No granite boulder larger than 1 meter was found more than 60 meters into the volcanic unit. Only one locality shows less than 100% because it is located less than 60 meters from the contact.

Summary of Distributions

The relationships found in the size fractions less than 1 meter are the result of two processes: (1) dilution, by the incorporation of new bedrock sources as the glacier crossed contacts and (2) crushing of large clasts into smaller clasts. Dilution is proved by the appearance of new bedrock types as sampling sites cross contacts. Crushing is reflected by the fining of the texture of till down glacier.

Lithologic trends in the smaller size fractions are similar to those detected by Dreimanis and Vagners (1970). They concluded that local bedrock is not always predominent in tills. In this in-

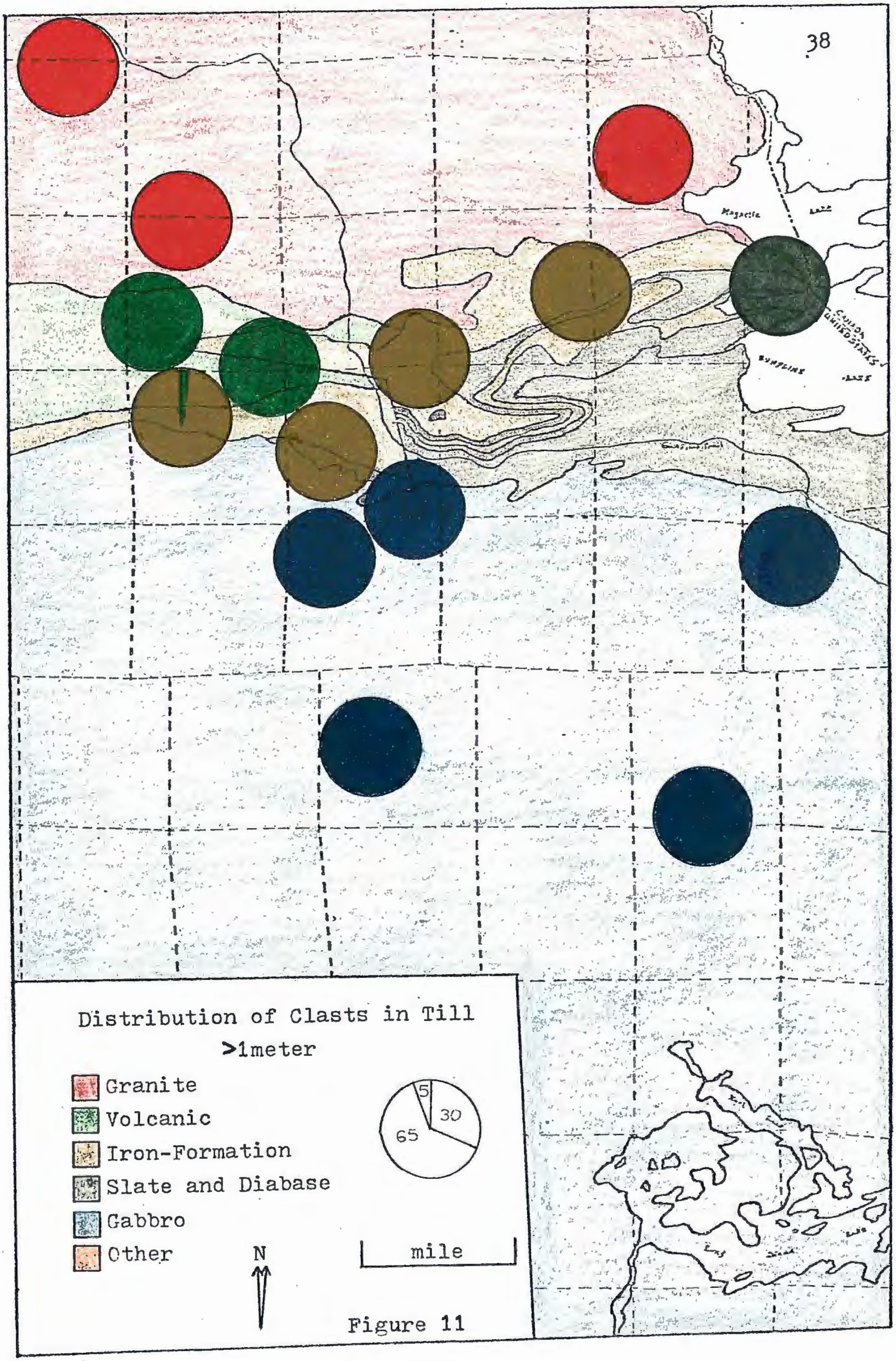

Distribution of Clasts in Till
>1meter
Granite
Volcanic
Iron-Formation
Slate and Diabase
Gabbro
Other
N
mile
5
30
65

Figure 11

vestigation the underlying bedrock, though well-represented in many samples, was not predominant. However, most clasts were derived from within a 7km radius. Their conclusions that the lithologic composition depends upon distance from the source area, the properties of the source material, the modes of glacial transport, the processes of comminution, and the configuration and flow directions of glacial lobes, are also supported by this study, except for the size fraction greater than 1 meter.

In many studies of drift lithology the greater than 1 meter size fraction has seemed to have been neglected, perhaps because clasts in this size range are rare, or considered to be from some distant source.

The relationships found between drift composition and bedrock distribution can be explained in terms of the glacial history of the area and the glacial physics, especially temperature changes during advance and retreat. It is apropriate to discuss possible models that would explain the distribution results found in this investigation.

Models to Explain Clast Distribution

In order to understand the distribution of the clasts just discussed, the processes of glacial erosion and deposition that produced them must be understood. Figure 12 shows a possible model of glacial advance and its effects on the bedrock over northeastern Minnesota.

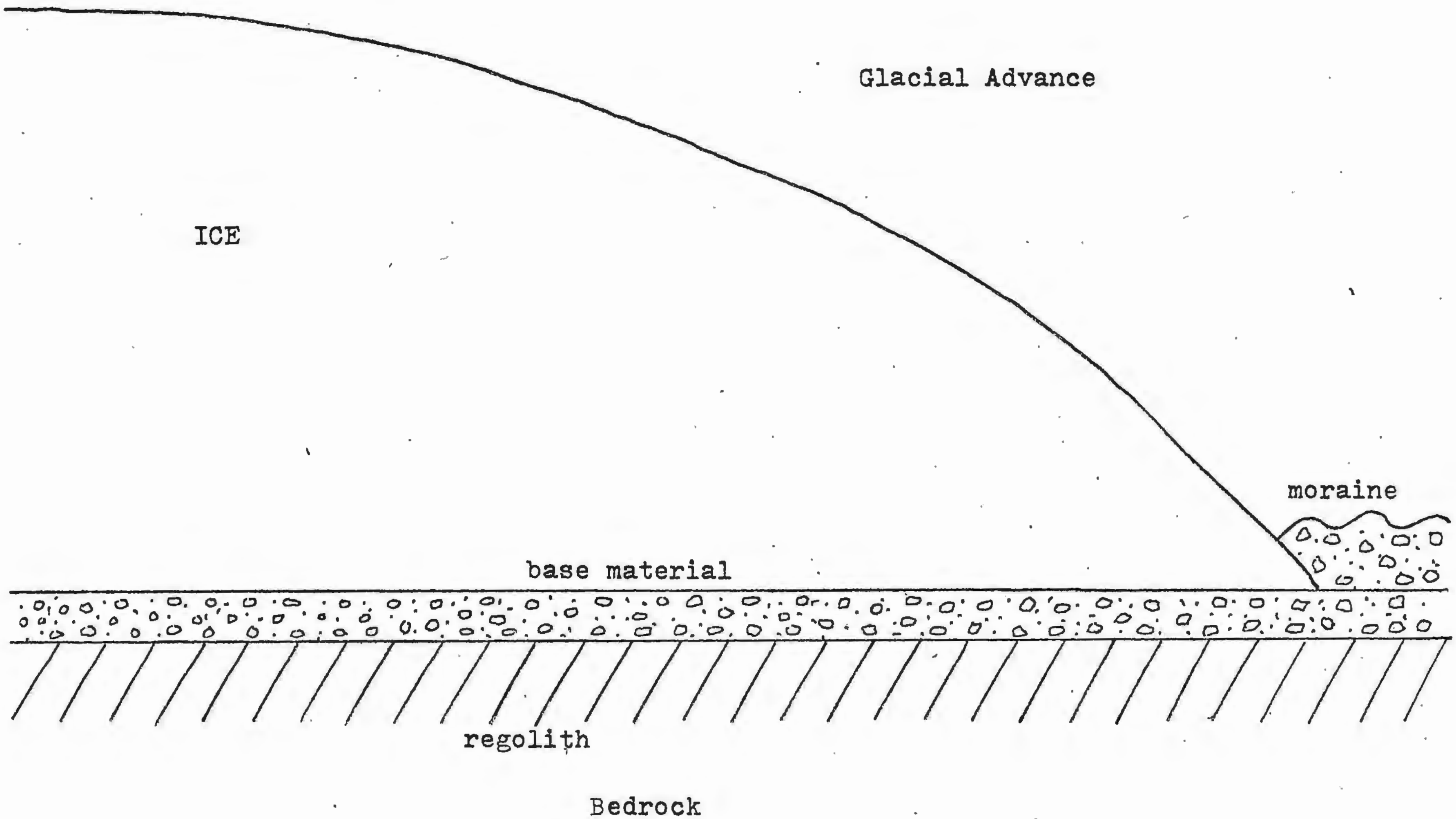

Glacial Advance
ICE
moraine
base material
regolith
Bedrock

Figure 12

Between advances, bedrock was subject to weathering and erosion possibly as much as it has during the present post-glacial interlude (Fig. 13). According to Sugden and John (1976), there are two effective processes of glacial erosion: abrasion and plucking. To erode fresh bedrock, the fragmental debris produced by abrasion and crushing must be incorporated into the moving ice stream by plucking. There are two requirements for these processes to be effective: First, moving dirty basal ice must make contact with the bedrock and the ice must exert a tractive force against the loosened fragments greater than the frictional drag between the fragments and subjacent materials. To remove regolith, which is already loose, plucking is the sole requirement. After incorporation, the clastic material is transported either near the base of the glacier or at some height above the base. At the base, the material is subject to continuious abrasion and crushing. Above the base, the glacial sediment is less concentrated, and able to travel long distances with minor abrasion.

During advance, material incorporated in the base or above the base may be carried to a distant ice margin and deposited as moraine or outwash. In northeastern Minnesota such a distant ice margin for the Rainy Lobe was the Vermilion Moraine located about 60km southwest.

Figure 13: Post-glacial weathering of gabbro.

As regolith is progressively removed, more resistant bedrock is encountered and abrasion becomes important. Evidence of abrasion features in the Long Island Lake area are shown in figure 14.

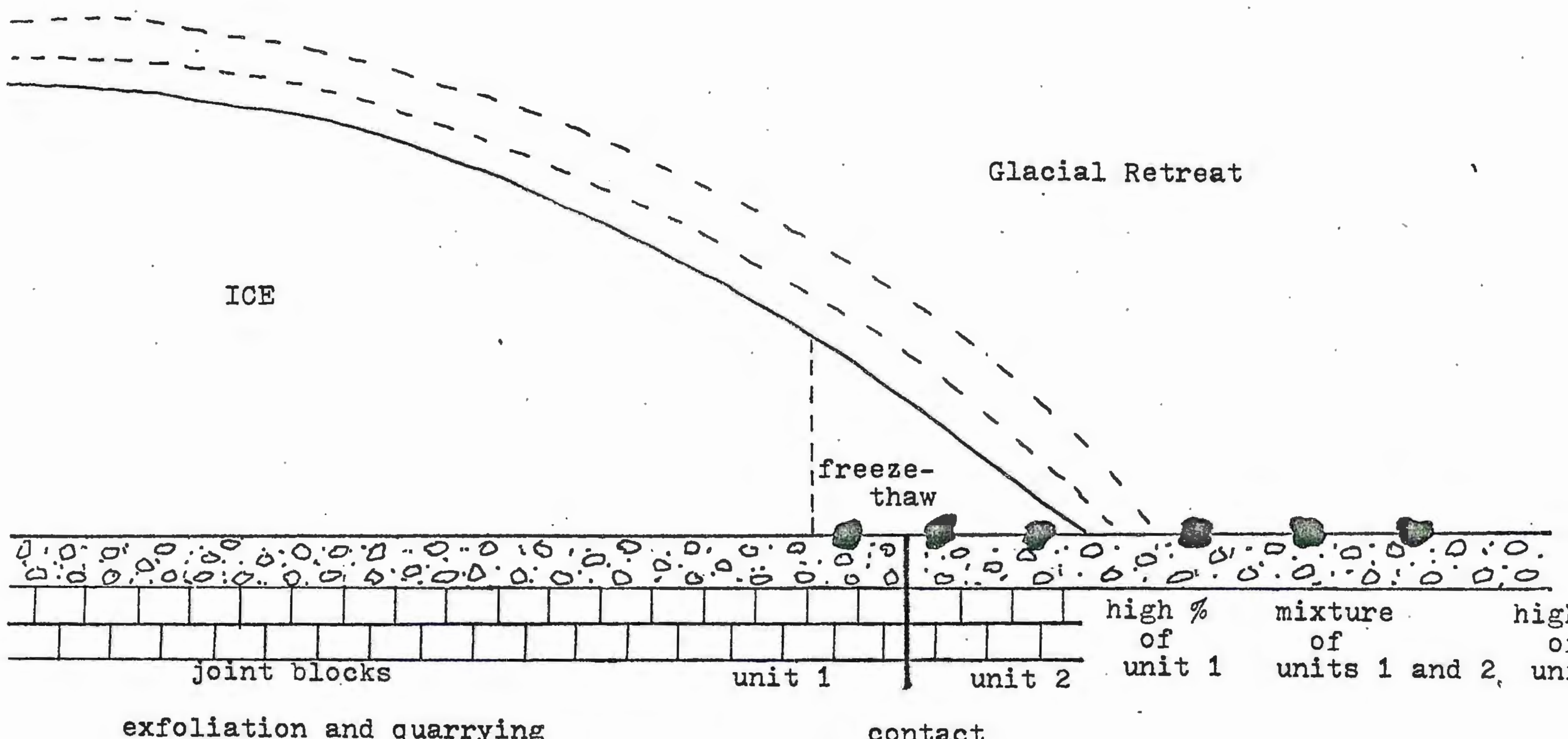
During glacial retreat erosional processes continue as long as the ice continues to flow, even though the margin is melting back. A model of glacial retreat over the Long Island Lake area is represented in figure 15.

Figure 16 is a schematic diagram showing the effects of ice thickness on abrasion. At maximum thickness material is lodged onto the base of the glacier and little if any abrasion is accomplished. As ice thickness decreased, abrasion increased to a certain point until the friction between the particles and the bed is sufficiently lowered to retard the movement of a particle, thus reducing abrasion (Boulton, 1974). Other factors that affect abrasion are volume of basal debris, sliding of basal ice, transportation of debris downward towards bedrock, basal water pressure, relative hardness of rock particles and bedrock, particle characteristics and efficient removal of rock flour (Sugden and John, 1976). No single factor determines the rate or type of abrasion. Given the presence of basal debris, conditions most favorable for abrasion occur beneath warm-based glaciers.

(a)

(b)

Figure 14: Abrasion features in area, (a) striations and (b) chatter marks.



Glacial Retreat
ICE
freeze-
thaw
joint blocks
unit 1
unit 2
high %
of
unit 1
mixture
of
units 1 and 2
high %
of
unit 2
exfoliation and quarrying
contact

Figure 15

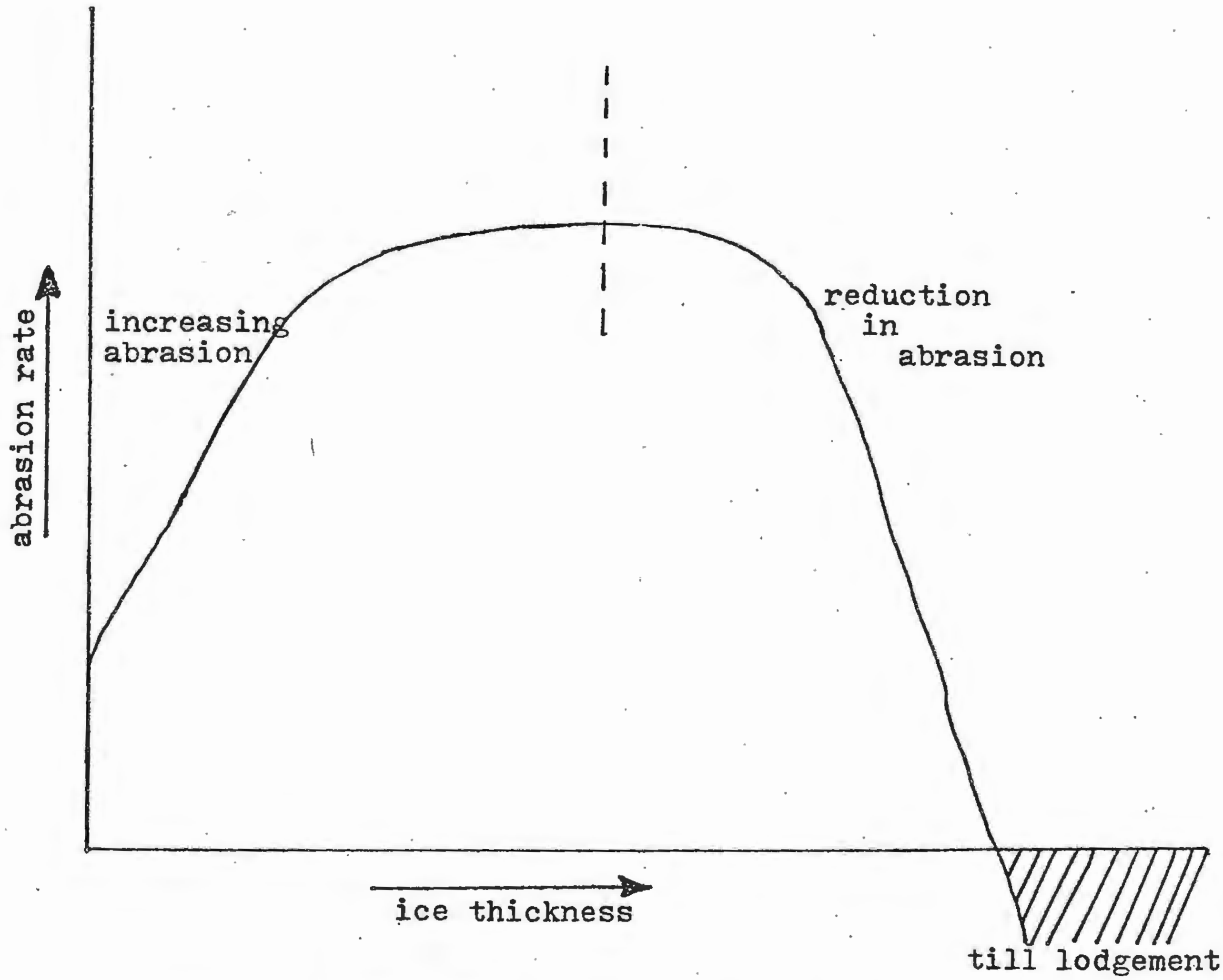


Figure 16: Schematice diagram showing abrasion rate vs ice thickness. (after Sugden and John, 1976)

As the ice margin approaches a particular source (such as unit 1 in Fig. 15), the material from unit one is removed by abrasion and plucking and remains in transport for only a short time before it is deposited. Outside of the margin, the composition of the till would at one time contain a high percent of unit 1. Further down glacier, the till would be composed of a mixture of unit 1 and 2. Moving further down glacier, the composition of the till would contain a high percent of unit 2. Thus, the percent of a particular bedrock source (unit 1) would decrease down glacier, as was the case in the distribution of clasts in till less than 1 meter. One must keep in mind that this relationship would only hold true if the ice were retreating at a constant rate, with no large scale stagnation.

Figures 7-10 showed an increase of granitic clasts in the localities underlain by the gabbro. This relationship would tend to disprove the theory previously mentioned. The increase in granite could be due to dilution, but what would be the source of dilution? Two factors could be involved that would increase the percent of granite. An unknown or buried granitic source could be supplying granitic clasts to the till. This factor is possible because there are ferrogranodiorite units exposed within the gabbro. Another possible factor might be dilution of the basal till by ablation till that contains a high percent of granite. The question may arise then why ablation dilution here and nowhere else in the area? A possible explanation for this relationship could be the affect of the upstream topography (Fig. 17). As the glacier flowed over the valley and ridge topography of the slate and diabase, the granite, which made up a large portion of the basal debris, topped the first ridge and continued to flow in a straight line as material above the base. Incorporated in this position the granite would be subject to less abrasion and the material could continue to flow above the base until it reached the margin and was deposited. Upon deposition, the granite would have a dilution affect on the composition of the till giving the till a higher percent of granite. Either case could explain the increase in granite. Only the first could be proved by drilling to see if a granitic body is buried by drift upstream from the localities where the increase takes place.

As a glacier thins, the margin can become cold-base as compared to warm-base in its thicker interior. Abrasion and quarrying would continue within the warm-base portion but at the margin, the glacier sole would become frozen to the bedrock interface and abrasion would be negligible.

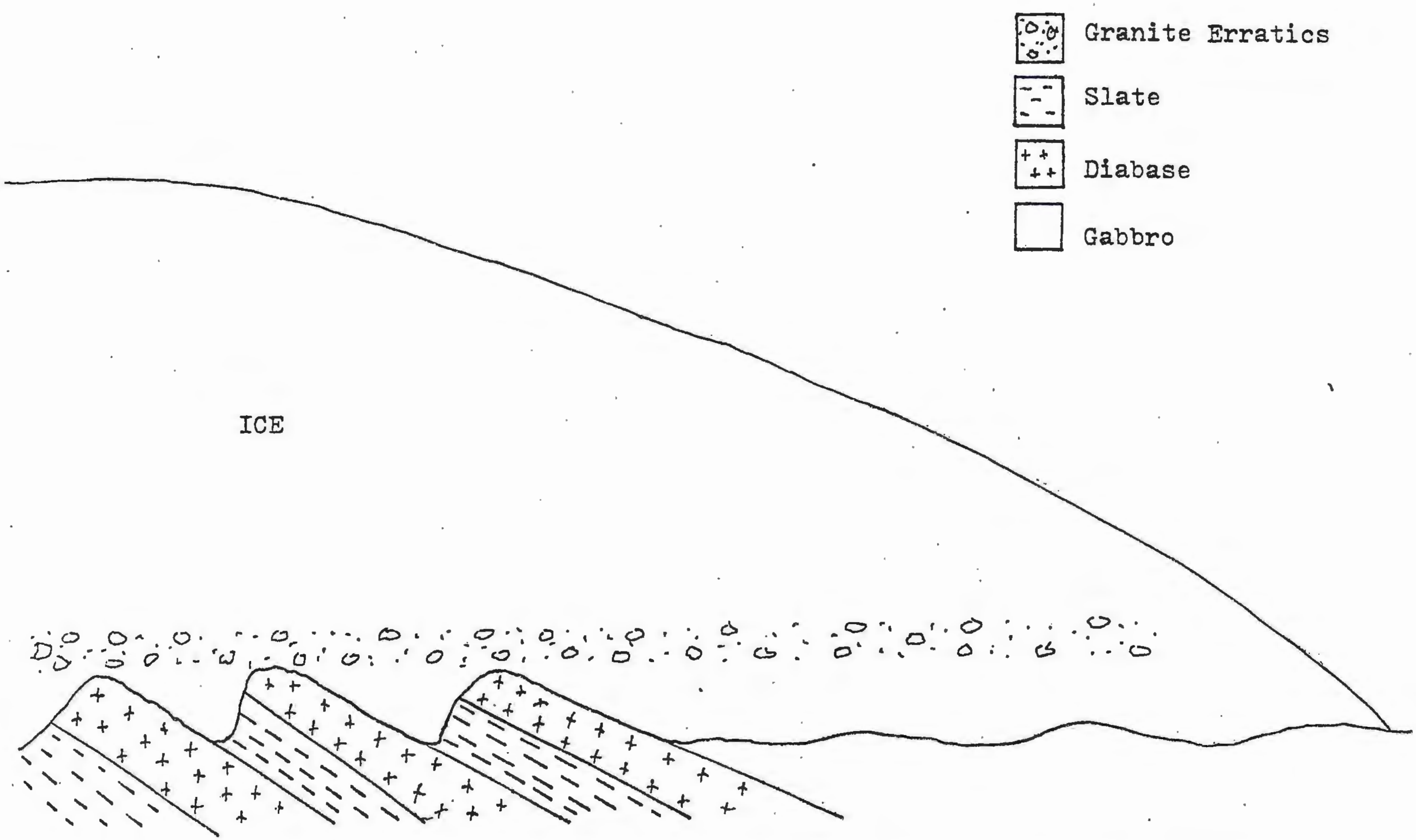


Figure 17: Diagrammatic cross section of glacier over slate and diabase.
(after Shilts, 1973)

A second process that could take place at the margin would be the fracturing of bedrock by the unloading of the overriding ice. Fractures form parallel to the face of unloading due to the release of stored strain energy (Lewis, 1954). With the existence of previous joint systems and newly developed exfoliation, large locks of bedrock rebound slightly above the surface. Each rebounded block would become an obstacle to the forward motion of the glacier. Pressure would increase at the contact between ice and block. The pressure increase would lower the melting point of the ice. Lowering of the melting point would enable the ice to melt, water to flow into the fractures, freeze and cause the blocks to fracture more.

During the summer months, as the margin returns to a warm-base, the ice in the fractures melts and more water flows into the fractures. During the winter months, the margin returns to a cold-base margin, the water would freeze and fracture the blocks more. Eventually the block would be fractured enough so that the glacier would be able to literally drag the large block (greater than 1 meter) out of position.

For these large blocks to be incorporated within the glacier, it is necessary for ice to exert a tractive force on the block. The greater the surface of contact between the ice and block, the greater the tractive force (Sugden and John, 1976). The smaller size fractions would not have the sufficient surface to allow further motion and so they would be deposited.

Sugden and John (1976) suggest that a thickness of 20 meters or more would be required to cause effective ice deformation around the blocks. Therefore, one could conclude that the removal of these large boulders is the result of the "last gasp" of the glacier, depositing the boulders on top of the smaller clasts. Evidence of this type of deposition in the area can be seen in figure 18. The boulders would be deposited close to their source because this activity of removing them takes place near the margin and the boulders remain in transport for only a short time. Thus, these boulders greater than 1 meter can be used to inferr contacts of the local or underlying bedrock.

Figure 18: Boulder greater than 1 meter on top of drift.

CONCLUSIONS

The glacial history of the Long Island Lake area is not as complex as other areas throughout Minnesota. Glacial erosion rather than glacial deposition has been the main factor affecting the distribution of clasts in till.

In the size fractions less than 1 meter in diameter, drift composition reflects the regional geology and not so specifically the local or underlying geology. Changes in composition and bedrock distribution are explainable in terms of the glacial history of the area and glacier physics, especially temperature changes during advance and retreat.

The following situations may explain the distribution of clasts in till: (1) as distance from a particular bedrock source becomes greater down glacier, the percent of those bedrock fragments in each size fraction less than 1 meter in diameter, decreases down glacier; (2) at sample sites within a particular bedrock unit, the percent of foreign bedrock fragments increase in the smaller size fractions; (3) the narrower the outcrop width, the more rapidly the composition percent of that bedrock type decreases down glacier; (4) clast composition is size fractions greater than 1mm, but less than 1 meter, relect the lithology of the regional bedrock but not necessarily the underlying bedrock; (5) clasts greater than 1 meter reveal the best relationship and are useful in inferring bedrock contacts within $\pm$ 60 meters.

The lack of local bedrock clasts in the smaller size fractions indicate either high resistance of local bedrock to crushing, or lack of opportunity for crushing because of short residence time in the glacial system (short distance transport). In either case, the fine-grained fraction therefore represents a contribution to the glacial load from a more distant source and the coarse-grained fraction represents a contribution to the glacial load from a local source.

TABLE I

Till composition

sample	total wt.	%sand	%silt and clay
4-6	95.17	96.25	3.75
4-3	89.63	83.25	16.75
28-2	96.53	56.28	43.72
28-3	91.50	83.05	16.95
28-6	92.19	88.76	11.24
3-1	101.05	81.84	18.16
3-8	90.45	72.84	27.16
3-5	96.64	91.91	8.09
27-2	102.15	92.67	7.33
34-1	96.91	75.95	24.05
10-3	91.83	88.23	11.77
10-4	93.28	86.07	13.93
23-2	90.46	76.45	23.55
23-1	101.90	95.37	4.63
19-1	91.84	72.43	27.57
19-2	95.39	76.34	23.66
30-1b	95.09	93.19	6.81
30-2	97.00	93.14	6.86
1-1	91.36	91.52	8.48
1-2	85.86	85.44	14.56
12-1	98.30	99.72	0.28
13-4	95.98	94.12	5.88
8-7	96.02	90.94	9.06

TABLE I (cont.)

Till composition

sample	total wt.	%sand	%silt and clay
8-6	100.95	84.60	15.40
29-2	98.39	87.49	12.51
29-1	93.48	87.94	12.06
5-3a	107.16	90.04	9.96
5-1a	94.86	98.09	1.91
5-1b	93.46	98.77	1.23
8-2	94.04	86.27	13.73

TABLE II							
Composition of Clasts in Till							
sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
4-6	1mm-2mm	30	0	10	0	60	0
	2mm-4mm	26	0	10	0	64	0
	4mm-16mm	29	0	24	0	47	0
	16mm-1m	24	4	24	0	48	0
	>1m	--	--	--	--	--	--
4-3	1mm-2mm	50	0	20	0	30	0
	2mm-4mm	64	0	10	0	26	0
	4mm-16mm	47	0	24	0	29	0
	16mm-1m	25	4	26	0	44	0
	>1m	--	--	--	--	--	--
28-2	1mm-2mm	90	10	0	0	0	0
	2mm-4mm	99	1	0	0	0	0
	4mm-16mm	100	0	0	0	0	0
	16mm-1m	68	32	0	0	0	0
	>1m	--	--	--	--	--	--
28-3	1mm-2mm	74	13	13	0	0	0
	2mm-4mm	75	11	14	0	0	0
	4mm-16mm	39	17	44	0	0	0
	16mm-1m	62	38	0	0	0	0
	>1m	0	100	0	0	0	0

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
28-6	1mm-2mm	75	12	13	0	0	0
	2mm-4mm	63	5	32	0	0	0
	4mm-16mm	36	23	41	0	0	0
	16mm-1m	64	36	0	0	0	0
	>1m	0	1	99	0	0	0
3-1	1mm-2mm	50	0	0	0	50	0
	2mm-4mm	38	0	2	0	60	0
	4mm-16mm	14	0	14	0	72	0
	16mm-1m	20	0	25	0	55	0
	>1m	0	0	0	0	100	0
3-8	1mm-2mm	50	0	0	0	50	0
	2mm-4mm	38	0	60	0	2	0
	4mm-16mm	36	0	36	0	28	0
	>1m	--	--	--	--	--	--
3-5	1mm-2mm	65	0	3	0	32	0
	2mm-4mm	50	0	16	1	33	0
	4mm-16mm	24	0	17	2	57	0
	16mm-1m	50	0	20	0	30	0
	>1m	--	--	--	--	--	--

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
27-2	1mm-2mm	30	20	50	0	0	0
	2mm-4mm	50	10	40	0	0	0
	4mm-16mm	38	0	62	0	0	0
	16mm-1m	25	12	40	0	23	0
	>1m	0	0	100	0	0	0
34-1	1mm-2mm	60	0	40	0	0	0
	2mm-4mm	50	0	50	0	0	0
	4mm-16mm	13	0	87	0	0	0
	16mm-1m	19	11	35	0	35	0
	>1m	0	0	0	0	100	0
10-3	1mm-2mm	10	0	0	0	90	0
	2mm-4mm	10	0	0	0	90	0
	4mm-16mm	0	0	0	0	99	1
	16mm-1m	5	0	30	0	65	0
	>1m	--	--	--	--	--	--
10-4	1mm-2mm	10	0	0	0	90	0
	2mm-4mm	10	0	0	0	90	0
	4mm-16mm	0	0	0	0	100	0
	>1m	--	--	--	--	--	--

TABLE II (cont.)							
Composition of Clasts in Till							
sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
10-2	1mm-2mm	10	0	0	0	90	0
	2mm-4mm	10	0	0	0	90	0
	4mm-16mm	0	0	0	0	99	1
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
23-2	1mm-2mm	13	0	87	0	0	0
	2mm-4mm	9	0	91	0	0	0
	4mm-16mm	7	0	93	0	0	0
	16mm-1m	10	0	90	0	0	0
	>1m	--	--	100	--	--	--
23-1	1mm-2mm	86	0	14	0	0	0
	2mm-4mm	62	0	33	0	0	5
	4mm-16mm	72	0	28	0	0	0
	16mm-1m	90	0	10	0	0	0
	>1m	0	0	100	0	0	0
19-1	1mm-2mm	20	0	80	0	0	0
	2mm-4mm	20	0	63	0	0	17
	4mm-16mm	14	0	86	0	0	0
	16mm-1m	10	0	50	40	0	0
	>1m	0	0	0	100	0	0

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
19-2	1mm-2mm	2	0	98	0	0	0
	2mm-4mm	11	0	83	6	0	0
	4mm-16mm	0	0	100	0	0	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
30-1b	1mm-2mm	35	0	10	55	0	0
	2mm-4mm	7	0	15	78	0	0
	4mm-16mm	6	0	2	92	0	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
30-2	1mm-2mm	16	0	4	0	80	0
	2mm-4mm	1	0	3	3	93	0
	4mm-16mm	4	0	0	3	93	0
	16mm-1m	--	--	--	--	--	--
1-1	1mm-2mm	9	0	4	0	87	0
	2mm-4mm	10	0	5	1	84	0
	4mm-16mm	13	0	19	3	65	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	100	--

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
1-2	1mm-2mm	53	0	1	0	46	0
	2mm-4mm	54	0	3	1	42	0
	4mm-16mm	8	0	4	4	84	0
	16mm-1m	60	0	20	0	20	0
	>1m	--	--	--	--	--	--
12-1	1mm-2mm	1	0	0	0	99	0
	2mm-4mm	2	0	0	0	98	0
	4mm-16mm	0	0	0	0	100	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
13-4	1mm-2mm	0	0	0	0	100	0
	2mm-4mm	0	0	0	0	99	1
	4mm-16mm	0	0	0	0	100	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
8-7	1mm-2mm	99	0	0	0	0	1
	2mm-4mm	98	0	0	0	0	2
	4mm-16mm	100	0	0	0	0	0
	16mm-1m	90	0	0	0	0	10
	>1m	100	0	0	0	0	0

TABLE II (cont.)							
Composition of Clasts in Till							
sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
8-6	1mm-2mm	99	0	0	0	0	1
	2mm-4mm	98	0	0	0	0	2
	4mm-16mm	94	0	0	0	0	6
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
29-2	1mm-2mm	78	32	0	0	0	0
	2mm-4mm	92	8	0	0	0	0
	4mm-16mm	95	5	0	0	0	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
29-1	1mm-2mm	100	0	0	0	0	0
	2mm-4mm	100	0	0	0	0	0
	4mm-16mm	95	5	0	0	0	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
5-3a	1mm-2mm	2	0	0	0	98	0
	2mm-4mm	5	0	0	0	95	0
	4mm-16mm	6	0	0	0	94	0
	16mm-1m	36	0	27	0	37	0
	>1m	--	-	--	--	--	--

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
5-1a	1mm-2mm	2	0	0	0	98	0
	2mm-4mm	5	0	0	0	95	0
	4mm-16mm	6	0	0	0	94	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
5-1b	1mm-2mm	2	0	0	0	98	0
	2mm-4mm	5	0	0	0	95	0
	4mm-16mm	6	0	0	0	94	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
8-2	1mm-2mm	1	0	0	0	99	0
	2mm-4mm	3	0	0	0	97	0
	4mm-16mm	5	0	0	0	95	0
	16mm-1m	--	--	--	--	--	--
	>1m	--	--	--	--	--	--
21-1	1mm-2mm	--	--	--	--	--	--
	2mm-4mm	--	--	--	--	--	--
	4mm-16mm	--	--	--	--	--	--
	16mm-1m	98	0	0	0	0	2
	>1m	100	0	0	0	0	0

TABLE II (cont.)

Composition of Clasts in Till

sample	clast dia.	%granite	%volcanic	%iron-fm	%rove	%gabbro	%other
16-1	1mm-2mm	--	--	--	--	--	--
	2mm-4mm	--	--	--	--	--	--
	4mm-16mm	--	--	--	--	--	--
	16mm-1m	96	0	0	0	0	4
	>1m	--	--	--	--	--	--
24-2	1mm-2mm	--	--	--	--	--	--
	2mm-4mm	--	--	--	--	--	--
	4mm-16mm	--	--	--	--	--	--
	16mm-1m	10	0	35	50	0	0
	>1m	--	--	--	--	--	--
27-1	1mm-2mm	--	--	--	--	--	--
	2mm-4mm	--	--	--	--	--	--
	4mm-16mm	--	--	--	--	--	--
	16mm-1m	18	0	47	0	35	0
	>1m	--	--	--	--	--	--
13-1	1mm-2mm	--	--	--	--	--	--
	2mm-4mm	--	--	--	--	--	--
	4mm-16mm	--	--	--	--	--	--
	16mm-1m	--	--	--	--	--	--
	>1m	100	--	--	--	--	--

REFERENCES CITED

Boulton, G. S., 1972, The role of thermal regime in glacial sedimentation. In Price, R. J. and Sugden, D. E.(eds) Polar geomorphology, Inst. Brit. Geogr. Spec. Pub. 4, p. 1-19.

Boulton, G. S., 1974, Process and patterns of glacial erosion. In Coates, D. R.(ed) Glacial geology, State Univ. of New York, Binghampton, p. 41-87.

Boulton, G. S. and Vivan, R., 1973, Underneath the glaciers: Geogr. Mag. 45 (4), p. 311-319.

Boye, M., 1950, Glaciaire et periglaciaire de l'Ata Sund nord-oriental (Groenland) (Paris; Expeditions polaires francaises, 1).

Cailleux, A., 1952, Polissage et surcreusement glaciaires dans l'hypothese de Boye: Rev. Geomorph. Dyn., 3, p. 247-257.

Carol, Hans, 1947, The formation of roches moutonnees: Jour. Glaciol., v. 1, p. 58-59.

Chamberlain, T. C., 1888, The rock-scorings of the great ice invasions: U.S. Geol. Survey 7th Ann. Rept., 1885-86, p. 147-248.

Cooke, H. C., 1937, Further note on northward moving ice: Am. Jour. Sci., v. 34, p. 221.

Dahl, R., 1965, Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway: Geogr. Annli. 47, p. 83-140.

Dreimanis, A., 1956, Steep Rock iron ore boulder train: Geol. Assoc. Canada Proc., v. 8, pt. 1, p. 27-70.

Dreimans, A. and Vagners, J., 1969, Lithologic relation of till to bedrock: Canada Natl. Acad. Sci. Pub. 1701, p. 93-98.

Dunquette, G., 1960, Preliminary report on Gould area: Quebec Dept. Mines Prelim. Rept. 432, p. 10.

Elftman, A. H., 1898, The geology of the Keweenawan area in northeastern Minnesota: Am. Geologist, 21: 90-109.

Embleton, C. and King, C. A M., 1975, Glacial Geomorphology, John Wiley and Sons, New York, p. 181-203.

Feirn, Wm. C., 1977, The stratigraphy and petrology of the Archean volcanic rocks at Jasper Lake, Eastern Vermilion District, Cook County, Minn.: unpubl. MS Thesis, Univ. of Minn.-Duluth, p.1-164.

Forbes, J. D., 1843, Travels through the Alps of Savoy (Edinburgh).

Gaigalas, A. I., 1964, Mineralo-petrograficheskii sostar moren pleistocena iugovostochnoi Litvy: Lietuvos TSR Mokslu Akad. Darbai, sec. B, v. 4 (39), p. 185-211.

Galibert, M. G., 1962, Recherches sur les processers d'erosion glaciaires de la Haute Montagne Alpine: Bull. Ass. Geogr. Francais 303/4, p. 8-46.

Gillberg, G., 1964, Till distribution and ice movements on the northern slopes of the South Swedish highlands: Geol. Foren. Stockholm Fork., v. 86, p. 433-483.

Gjessing, J., 1967, Potholes in connection with plastic scouring forms: Geogr. Annlr. 49A, p. 178-187.

Glen, J. W. and Lewis, W. V., 1961, Measurements of side-slip at Austerdalsbreen, 1959: J. Glaciol. 3 (30), p. 1109-1122.

Grout, F. F. and Schwartz, G.M., 1933, The geology of the Rove Formation and associated intrusives in northeastern Minnesota: Minn. Geol. Survey Bull. 24, p. 36.

Grout, F. F., Sharp, R. P. and Schwartz, G. M., 1959, The geology of Cook County, Minnesota: Minn. Geol. Survey Bull. 39, p. 12-77.

Hanson, G. N. and Malhotra, 1971, K-Ar ages of mafic dikes and evidence for low-grade metamorphism in northeastern Minnesota: Geol. Soc. America Bull.

Harris, S. E., 1943, Friction cracks and the direction of glacial movement: Jour. Geol., v. 51, p. 244-258.

Harrison, W., 1959, Petrographic similarity of Wisconsin tills in Marion County, Ind.: Indiana Geol. Survey Rept. Progress 15, p. 39.

Harrison, W., 1960, Original composition of Wisconsin till in central Indiana: Jour. Sed. Pet., v. 30, p. 432-446.

Hawkes, H. E. and Webb, J. S., 1962, Geochemistry in mineral exploration: New York, Harper and Row, p. 415.

Holmes, C. D., 1952, Drift dispersion in west-central New York: Geol. Soc. America Bull., v. 63, p. 993-1010.

Hope, R., Lister, H. and Whitehouse, R., 1972, The wear of sandstone by cold, sliding ice. In Price, R. J. and Sugden, D. E.(eds) Polar geomorphology, Inst. Br. Geogr. Spec. Pub. 4, p. 21-31.

Kvalheim, A., 1967, Geochemical prospecting in Fennoscandia: New York, Interscience, p. 349.

Lee, H. A., 1963, Glacial fans in till from the Kerkland Lake fault: Canada Geol. Survey Paper 63-45, p. 36.

Lister, H., Pendlington, A. and Chorlton, J., 1968, Laboratory experiments on abrasion of sandstones by ice: Int. Ass. scient. Hydrol. 79, p. 98-106.

Leverett, F., 1929, Moraines and shore lines of the Lake Superior region: U.S. Geol. Survey Prof. Paper 154-A, p. 72.

Lewis, W. V., 1954, Pressure release and glacial erosion: J. Glaciol. 2 (16), p. 417-422.

Matsch, C. L., 1971, Pleistocene stratigraphy of the New Ulm region, southwestern Minnesota (Ph.D. Thesis): Madsion, Wisconsin Univ., p. 78.

McDonald, B. C., 1966, Auriferous till in the Eastern Townships, southeastern Quebec: Canada Geol. Survey Paper 66-2, p. 51-54.

McDonald, B. C., 1967, Wisconsin stratigraphy and ice-movement directions in southeastern Quebec, Canada (abs.): Geol. Soc. America, Special Paper 115, p. 277.

Morey, G. B., Green, J. C., Ojakangas, R. W., Sims, P. K., 1970, Stratigraphy of the Lower Precambrian rocks in the Vermilion district, northeastern Minnesota: Minn. Geol. Survey Inv. 14, p. 33.

Morey, G. B., Weiblien, P. W. and Mudrey, M. G., 1971, Guide to the Precambrian rocks of northwestern Cook County as exposed along the Gunflint Trail: Ann. Inst. Lake Superior Geol., 17th, Duluth, Minnesota, p. 98-117.

Morey, G. B., Weiblien, P. W., Papike, J. J. and Anderson, D. H., 1969, Geologic Map of Long Island Lake quadrangle, Cook County, Minnesota: Minn. Geol. Survey open file map.

Potter, P. E. and Pettijohn, F. J., 1963, Paleocurrents and basin analysis: New York, Acad. Press Inc., p. 296.

Raukas, A., 1961, Mineralogica moren Estonii: Ecsti NSV Teaduste Akad. Toimetised X Koidi, Fuusik.-Matemat. ja Tehn. Teaduste Sec. Nr. 3, p. 244-258.

Rothlesberger, H., 1968, Erosive processes which are likely to accentuate or reduce the bottom relief of valley glacier: Int. Ass. scient. Hydrol. 79, p. 87-97.

Savvaitor, A. S., 1962a, Osostave melkozema morennykh otlozhenii v baseine r. Salaca, in I. Danilans (ed.), Questions on Quaternary geology, I: Akad. Sci. Latvian SSR, Inst. geol., Riga, p. 115-122.

Savvaitor, A. S., 1962b, Osoderzhanii trahelykh mineralov v morennykh suğlinkakh, in I. Danilans (ed.), Questions on Quaternary geology, I: Akad. Sci. Latvian SSR, Inst. geol., Riga, p. 123-128.

Shilts, W. W., 1973, Glacial Dispersal of rocks, minerals, and trace elements in Wisconsin till, southeastern Quebec, Canada: Geological Society of America Memoir 136, p. 189-219.

Sitler, R. F., 1963, Petrology of till from northeastern Ohio and northwestern Pennsylvania: Jour. Sed. Pet., v. 33, p. 365-379.

Stindule, A. V., 1964, On distribution of chemical elements in the morainic silt: State Committee of Geology, USSR, Institute of Geology, Riga, Questions of Quaternary Geology, III, p. 311-320.

Sugden, D. E. and John, B. S., 1976, Glaciers and Landscape, John Wiley and Sons, New York, p. 151-167.

Trainer, F. W., 1973, Formation of joints in bedrock by moving glacial ice: U.S. Geol. Surv. J. Res. 1 (2), p. 226-236.

Tricart, J. and Cailleux, A., 1962, Le modele glaciaire et nival. Sedes, Paris, p. 508.

Veyret, P., 1955 Le lit glaciaire: contradiction apparente des formes et logique reelle des processus d'erosion: Revue Geogr. alp. 43, p. 495-509.

Vivian, R., 1970, Hydrologie et erosion sous-glaciares: Revue. Geogr. alp. 58 (2), p. 241-264.

Weertman, J., 1961, Equilibrium profile of ice caps: J. Glaciol. 3 (30), p. 953-964.

White, G. W., Totten, S. M. and Gross, D. L., 1969, Pleistocene stratigraphy of northwestern Pennsylvania: Pennsylvania Geol. Survey Gen. Geol. Rept. G55, p. 88.

Willman, H. B., 1966, Mineralogy of glacial tills and their weathering profiles in Illinois, tp. II, Weathering profiles: Illinois Geol. Survey Circ. 400, p. 76.

Willman, H. B., Glass, H. D. and Frye, J. C., 1963, Mineralogy of glacial tills and their weathering profiles in Illinois, pt. I, Glacial tills: Illinois Geol. Survey Circ. 347, p. 55.

Winchell, A., 1888, Minn. Geol. and Nat. Hist. Survey, 16th Ann. Rept., for 1887, p. 253.

Wright, H. E. Jr., 1972, Quaternary history of Minnesota: Geology of Minnesota: A Centennial Volume, P. K. Sims and G. B. Morey, editors, p. 515-547.