ESKERS AND HEAVY MINERAL PROSPECTING,

NORTHEASTERN MINNESOTA

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ABSTRACT

Mineral exploration in heavily glaciated terrain is difficult because a mantle of glacial drift generally covers the bedrock. Eskers and the heavy minerals they contain were studied to (1) determine their potential use as a prospecting tool, and (2) better understand the dynamics of esker formation. Studies emphasized paleohydraulics, origin of esker sediment, lithology, and mineralogy.

Two main types of eskers are recognized in northeastern Minnesota on the basis of their morphology, sedimentology, and origin. Continuous eskers form as a single, continuous segment when an ice sheet is stagnant, or nearly stagnant. Meltwater flowing through an ice tunnel deposits sediment in both the tunnel and onto an adjacent outwash plain. Melting of the tunnel walls induces inflow of the ambient ice which leads to the influx of rock debris. Seasonal fluctuations of meltwater discharge leave a sedimentary sequence characterized by a wide variety of grain sizes (medium-grained sand to boulders) and bedforms (climbing ripples, massive beds, and planar, trough, and graded cross beds). Beaded eskers are a series of consecutive segments, or beads, that are separated by swamps or lakes, and whose trends follow the low ground between the drumlins of the Toimi Drumlin Field. A limited range of bedforms (massive beds and trough cross beds) and grain sizes (mostly boulders) are exposed in the beaded eskers. Other sedimentary features may be present, but they are covered by the surrounding swamp deposits and not exposed.

Individual segments of the beaded esker system probably form at the margin of an actively retreating ice sheet as an annual deposition event. Average distances between successive bead crests imply an annual retreat rate of 1200 feet (365 m) per year.

Stone counts, X-ray diffraction, and petrographic examinations of heavy mineral mounts were evaluated as drift prospecting tools. Similar results between stone counts in eskers and in the surrounding till indicate that the esker material is most likely derived from the basal ice debris. Concentration of the heavy mineral population by fluvial processes makes eskers and outwash better locations for sampling than till. A small split from each of the 97 bulk samples was analyzed by X-ray diffraction. As no more than 5 or 6 minerals could be identified from the charts, it does not appear to be an efficient method for prospecting. In contrast, petrographic examination of heavy mineral mounts gave a much better indication of minerals present. However, no economic indicator minerals were identified with either method. The petrographic studies were useful in differentiating glaciofluvial material deposited by the various lobes of ice. The St. Louis sublobe deposits, with a higher percentage of garnets, can be distinguished from the Rainy lobe and Superior lobe deposits, whose heavy mineral populations reflect the mafic bedrock over which the ice moved.

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I. INTRODUCTION

GENERAL STATEMENT

Mineral exploration in heavily glaciated terrain is difficult because of the mantle of glacial drift that covers the bedrock. Geophysical and geochemical prospecting have had limited success since each is restricted by several parameters such as geophysical signature of the orebody, drift thickness, clay content, and organic content.

Numerous attempts have been made to use the glacial drift to aid in the search for mineral prospects. Drift prospecting has become a proven technique for exploration in some areas, most notably in Canada and Finland. Several drift prospecting techniques have been used, including geochemical studies of till (Cohen and Stanley, 1982; Closs and Sado, 1979; Fortesque, 1983; and Shilts, 1973, 1984), glacial fans and boulder trains in till (Drake, 1983; Szabo and others, 1975; Lee, 1963, 1965), geophysical (Onesti and Hinze, 1970), and heavy mineral studies (Brundin, 1968; Brundin and Bergstrom, 1977; Lee, 1968; Dworkin and others, 1985).

Heavy minerals in eskers have been used as a successful drift prospecting tool in Canada by Lee (1968) but have remained untested in Minnesota. This thesis project was developed to evaluate the potential for drift prospecting in eskers in northeastern Minnesota. It was encouraged, and supported, by the Minnesota Department of Natural

Resources (DNR), which developed an interest in the potential for eskers in prospecting for mineral bedrock targets. A successful drift prospecting technique would be beneficial to a mineral exploration company because the glacial drift is often very thick and outcrops are scarce. The project involved sampling the sand and gravel in the eskers that overlie the 1,100 million year old Duluth Complex and the North Shore Volcanic Group, as well as the 2,000 million year old Thomson Formation, to determine whether (1) the drift contains any economic mineral indicators and (2) if so, determine the provenance of the minerals.

The study also involved general observations on morphology, sedimentology, and the origin of esker systems in northeastern Minnesota, including a general inventory. Several eskers were studied in detail to help understand the origin and paleohydraulics of different esker types in the field area.

The ultimate goal was to answer the questions: Are the esker sediments derived from distant or local sources? Is the material derived from the glacial load or eroded by the esker river from local bedrock? Are the detrital components in eskers, including heavy minerals, feasible for use as prospecting tools?

LOCATION

The field area (Figure 1) is located in the northeastern corner of Minnesota and covers approximately 2400 square miles, including part or

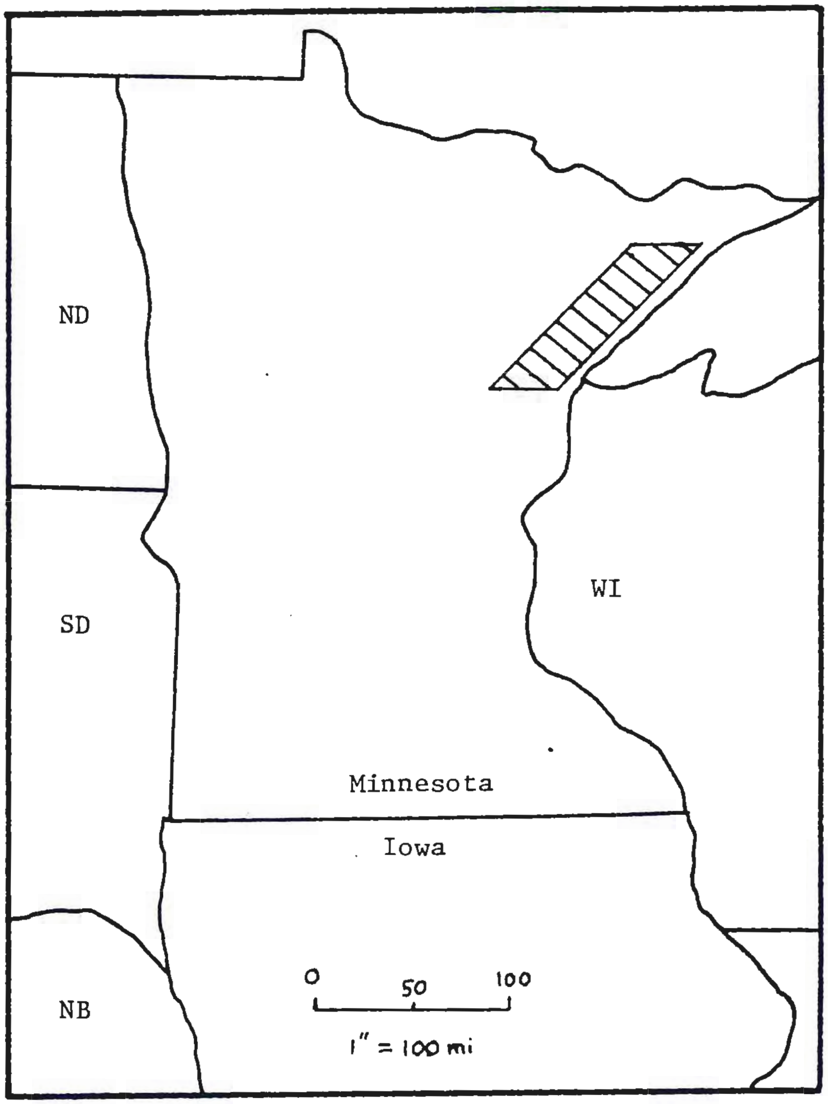


Figure 1. Location of study area, shown by cross hatching, northeastern Minnesota.

all of fifty U.S. Geological Survey 7.5 minute quadrangles. The area extends from north of Isabella, near the Lake-Cook County border southwestward to the Iverson area west of Cloquet. It is nearly 30 miles wide by almost 100 miles long.

FIELD METHODS

The field methods for studying the eskers involved two different approaches. The study was divided between sedimentological studies and drift prospecting studies.

Sedimentological studies: Several stratigraphic columns were constructed, and lithologies, grain sizes, and sedimentary structures were noted. The interpretation and classification of the sedimentary structures are after Miall (1978) as shown in Table 1.

Stone counts were performed at several locations to determine which size fraction (boulders (>1 foot) or pebbles (1-2 in.)) could be used as provenance indicators. A total of 30 boulder counts and 28 pebble counts were done. One hundred boulders were counted at each location, and their lithologies were recorded in the field. One hundred pebbles were collected and taken back to the lab, washed and identified for each sample. Several boulder counts were done at different locations on the same esker to study lithologic changes along the esker.

Drift prospecting studies: Gravel pits and road cuts provided the best exposures of the esker material and were most often used as sample

Facies Code	Lithofacies	Sedimentary structures	Interpretation
Gms	massive, matrix supported gravel	none	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits
Gt	gravel, stratified	trough crossbeds	minor channel fills
Gp	gravel, stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (l. and u. flow regime)
Sl	sand, fine	low angle (<10°) crossbeds	scour fills, crevasse splays, antidunes
Se	erosional scours with intraclasts	crude crossbedding	scour fills
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including eta cross-stratification	scour fills
Sse, She, Spe	sand	analogous to *Ss, Sh, Sp*	eolian deposits
Fl	sand, silt, mud	fine lamination, very small ripples	overbank or waning flood deposits
Fsc	silt, mud	laminated to massive	backswamp deposits
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits
Fr	silt, mud	rootlets	seatearth
C	coal, carbonaceous mud	plants, mud films	swamp deposits
P	carbonate	pedogenic features	soil

Table 1. Classification scheme of sedimentary structures, after Miall (1978).

collecting sites. Eskers could not be sampled from the top or side in most cases because of the difficulty of digging through a gravel- and boulder-rich root zone. This root zone is a result of the mixing of the top 4-5 feet of material by trees being blown over after they die or are exposed to a strong wind. Continuous slope wash since the last ice retreated has resulted in the removal of most of the fine-grained material to produce the present bouldery lag deposit.

A total of 97 samples were collected during the summer of 1984. In some eskers, such as the Cloquet esker, four samples were taken across the exposed face, while in others several samples were taken along the trend of the esker.

The sample was collected from a vertical channel 10 feet long (5 feet long if the exposures were limited) and 1-2 feet wide that was dug into the esker face. Each sample would weigh between 600 and 800 pounds, and would nearly fill a 50-gallon barrel. Two or three samples could be collected in a day, although production rate was variable, depending upon the extent of the exposure.

The samples were transported and stored in old 50 gallon paint barrels loaned to the DNR by the St Louis County Highway Department. The samples were stored at the St Louis County Highway Maintenance garage near Pike Lake, Minnesota; the St. Louis County Highway Maintenance garage in Brimson, Minnesota; and the Babbitt, Minnesota Water Works Department. The samples from Pike Lake and Brimson were taken to the Arrowhead gravel pit three miles north of Twig, Minnesota where an adequate supply of water was available to process the samples. The samples at Babbitt were processed on site.

Each sample was jigged and concentrated with a hydromatic jig. A flow sheet for the sample processing is shown in Figure 18. Three to five gallons of concentrated sample were removed from the jig and used for the laboratory studies.

LABORATORY METHODS

The 3-5 gallon concentrated sample was processed by Dennis Martin at the DNR office in Hibbing, and a 100 g split was used for the optical studies and the X-ray diffraction studies of this project. A portion of this 100 g sample was used in a heavy mineral separation for optical examination. A total of 15 samples were point-counted: 9 eskers, 3 drumlins, 1 outwash, and 2 bedrock.

This 100 g split was further split to approximately 10 g for the X-ray diffraction studies, and the magnetic minerals were removed with a hand-held magnet. Sample weights and percentages of magnetic minerals were recorded. This small split was then powdered with a mortar and pestle, mounted as a slurry on a glass slide, and X-rayed on the Siemens X-ray diffractometer at UMD. The results were interpreted with a search manual and X-ray diffraction tables.

II. REGIONAL GEOLOGY

BEDROCK LITHOLOGY

The study area is underlain by several different rock types, all Precambrian in age, including the Thomson Formation, basalts and felsites of the North Shore Volcanic Group, and the Duluth Complex (Figure 2). The distinctive bedrock types are reflected in the color, texture, and stone lithology of the overlying drift.

Thomson Formation. The Thomson Formation consists of a metasedimentary sequence of interbedded slates and greywackes that crop out in the south and southwestern section of the field area. The formation crops out locally along several abandoned drainage channels that served as outlets for Glacial Lake Upham, and more notably, near the town of Thomson, where the present day St. Louis River has removed the overlying drift and flows over bedrock. The sediment of the formation was deposited in the 2,000 million year old Animikie Basin. Subsequent deformation has folded the rocks into large open synclines and anticlines in the field area. A good summary of the rocks is given by Schwartz (1942), Morey and Ojakangas (1970), and Wright and others (1970).

North Shore Volcanic Group. The North Shore Volcanic Group is a 1,100 million year old sequence of lava flows and interflow sediments. The rocks are well-exposed along the north shore of Lake Superior where they dip 8 to 10 degrees towards the lake. The rocks contain the full range of

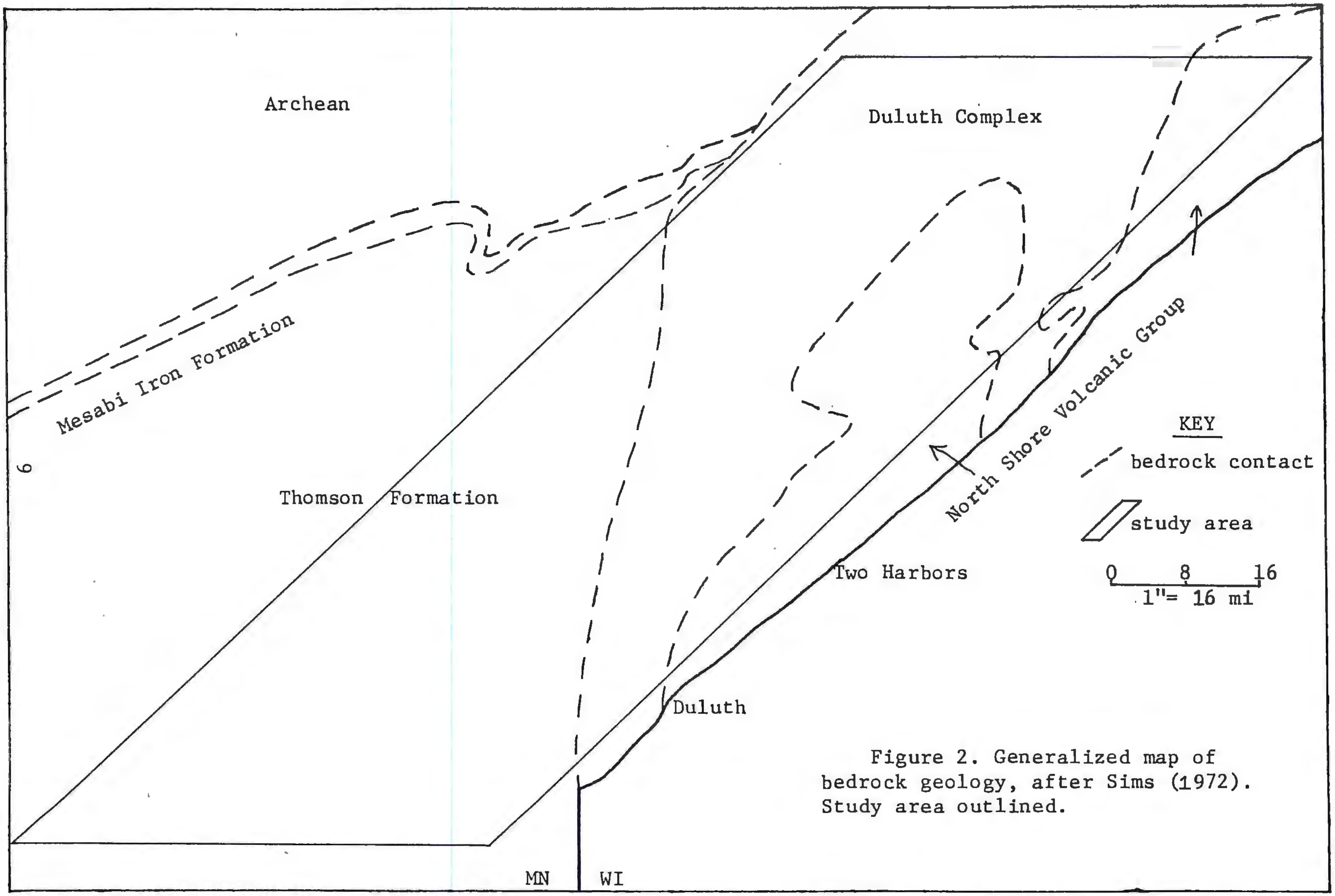


Figure 2. Generalized map of bedrock geology, after Sims (1972). Study area outlined.

compositions from primitive Al-rich olivine tholeiites to rhyolites. These Keweenawan plateau lavas were produced in response to tensional rifting of the North American continent (Green, 1979). Several other authors have studied this group, including Sandberg (1938), Grout and Schwartz (1939), Schwartz (1949), and Grout and others (1959).

Duluth Complex. The major portion of the field area is underlain by the 1,100 million year old intrusive Duluth Complex. This formation crops out in an arcuate pattern extending from Duluth northeastward nearly to the northeastern tip of Minnesota, a distance of about 150 miles. Except at Duluth, where it is underlain and overlain by the lava flows of the North Shore Volcanic Group, the complex was intruded along an unconformity between the overlying volcanics and the underlying older rocks of Early and Middle Precambrian age (Phinney, 1972).

Detailed descriptions of the complex have been given by Taylor (1964), Weiblen (1965), Phinney (1972), and Bonnichsen (1972b). Sims and Morey (1972) have presented a generalized discussion of the stratigraphic setting, and Weiblen and Morey (1980) have given an up-to-date summary of the geology of the complex.

The Duluth Complex comprises a variety of intrusions including anorthosite, troctolite, gabbro, granodiorite, and granite, some of which appear to have been feeders for the Keewanawan flood basalts found along the north shore of Lake Superior (Naldrett, 1981).

Extensive low-grade sulfide deposits along the western margin of the complex, primarily consisting of pyrrhotite, chalcopyrite, cubanite, and pentlandite, are of interest as potential ores of copper and nickel (Bonnichsen, 1972a).

BEDROCK TOPOGRAPHY

Differential erosion of the underlying bedrock caused the formation of preglacial lowlands which, in turn, controlled the flow directions of the various lobes of ice in northeastern Minnesota.

The Superior lobe was localized by poorly-resistant Late Precambrian red sandstone and shale. The lobe was rooted in the Lake Superior basin, a large syncline of sandstone and shale bounded by resistant volcanic rocks on the north side and by sandstone and volcanics on the Bayfield and Keweenaw Peninsulas on the south side. The basin is the deepest lowland of the Great Lakes region, and it provided a reservoir of ice that spread far southwestward into southern Minnesota and north-central Wisconsin (Wright and others, 1973.)

The main topographic trough of the western Lake Superior basin terminates southwestward near Sandstone, Minnesota, where bedrock exposed at the surface forms a divide whose south side slopes gradually southward to the Minneapolis lowland (Wright and others, 1973).

The Des Moines lobe filled a lowland cut in west-dipping Cretaceous shales along the Minnesota-Dakota border and followed southeastward along the Minnesota River valley. The St. Louis sublobe of the Des Moines lobe branched off and flowed eastward into the Red Lakes lowland. The advance continued to fill this lowland and spread across the state and into the western edge of the field area, where it overlapped the Rainy lobe deposits (Wright and others, 1973).

The Rainy lobe flowed from the northeast to the southwest parallel to the north shore of Lake Superior. The resulting drift covers the north shore highlands, which are underlain by the Duluth Complex and, on the eastern edge, the North Shore Volcanic Group.

QUATERNARY GEOLOGY

The glacial history of northeastern Minnesota was first outlined by Leverett (1932), and more recently refined considerably by Wright and others (Wright and Ruhe, 1965; Wright and Watts, 1969; and Wright, 1972, 1973).

Lowlands channeled the lobes of ice that protruded from the Laurentide ice sheet, especially when the ice was thinner during the waning stages of the Wisconsin Glaciation. The ice lobe in each lowland produced a glacial drift of distinctive color, texture, and stone content, permitting the correlation of ice advances of different lobes with one another (Wright, 1972).

Three lobes of ice (Figure 3) produced the surface features that are seen in the field area today, including drumlins, outwash plains, moraines, tunnel valleys, and eskers. These were the Superior lobe, the Rainy lobe, and the St. Louis sublobe of the Des Moines lobe.

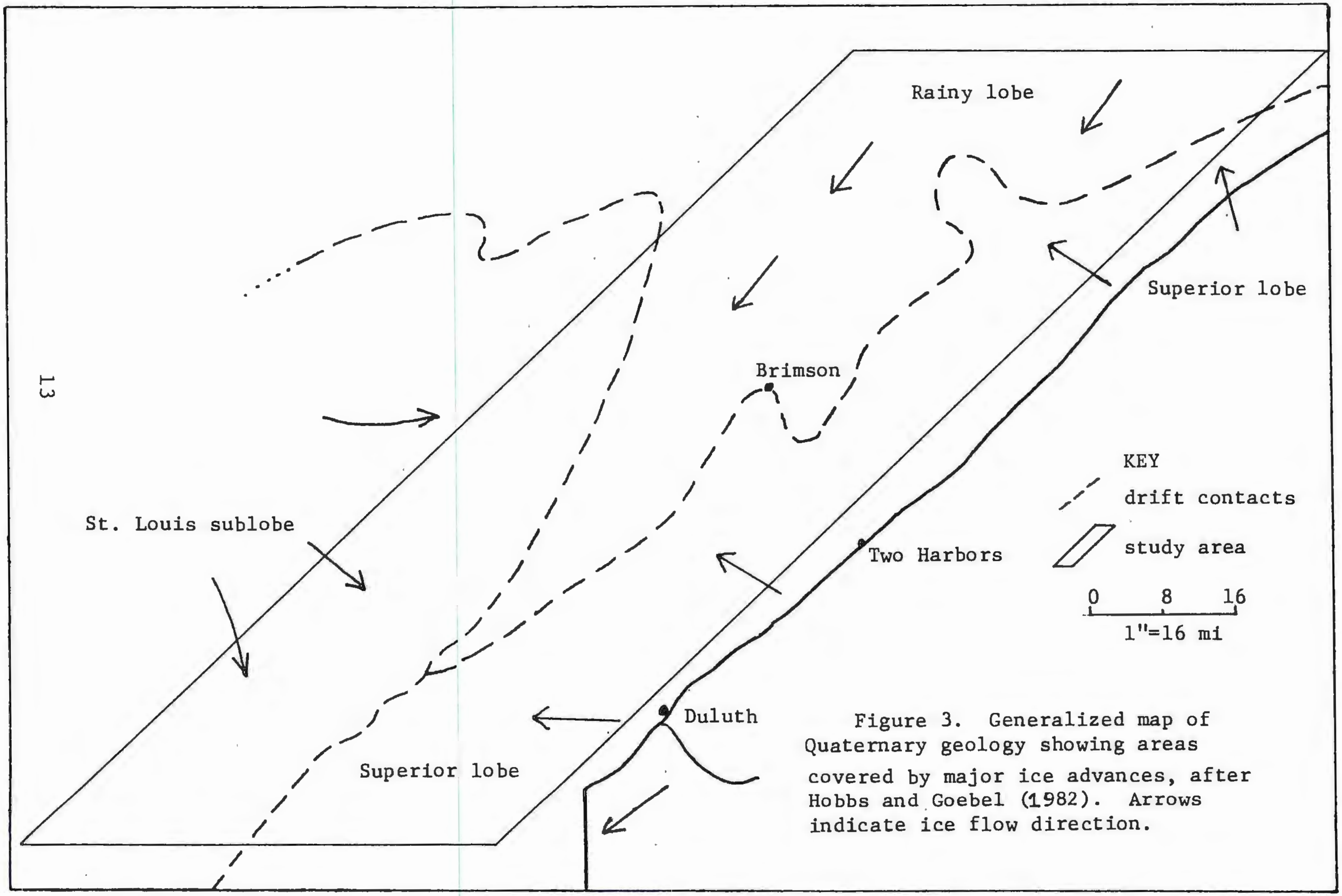


Figure 3. Generalized map of Quaternary geology showing areas covered by major ice advances, after Hobbs and Goebel (1982). Arrows indicate ice flow direction.

The Superior lobe produced a till with a distinctive red color, derived from the late Precambrian red sandstone and shale that form the bedrock southwestward from Duluth and underlie most of the Lake Superior basin itself (White, 1966). Other rock types, derived largely from the north shore of Lake Superior, are red and purple felsite as well as basalt, which includes a distinctive amygdaloidal form and a distinctive variety of banded agate as one type of amygdule filling. The till is generally sandy, although where proglacial lakes were overridden, it is silty or clayey (Wright, 1972).

The Superior lobe moved west and southwest out of the Lake Superior basin at least four times during the Wisconsin Glaciation. These advances and retreats, or phases, include (from oldest to youngest) the St. Croix phase, Automba phase, Split Rock phase, and the Nickerson phase. During the time of maximum southern advance of the St. Croix phase, the Superior lobe extended southwestward across a bedrock divide near Sandstone in Pine County and into the Minneapolis basin (Wright, 1972). Deposits from the Automba phase overlie the St. Croix phase deposits and, in northern Minnesota, form the Highland Moraine and the Mille Lacs Moraine. The maximum extent of the Split Rock phase is evidenced by the Barnum Till (Baker, 1964) and a series of eskers, outwash fans, and ice contact slopes southwest of Cloquet, Minnesota. The final advance of the Superior lobe, the Nickerson phase, advanced as a narrow lobe almost to Cloquet, where the ice reached an elevation limit of 1200 ft. (360 m).

The other principal lowland of the north, the Red River valley, channeled the Des Moines lobe southward to central Iowa from the Paleozoic carbonate terrain of Manitoba and the Cretaceous shale of northwestern Minnesota. Its St. Louis sublobe protruded eastward across the Red River Lowland almost to Lake Superior. Near its terminus, this lobe also carried reworked lake beds as part of its load, producing a calcareous, fine-textured till ranging in color from light brown to reddish-brown (Wright, 1972). This drift also contains a small percentage of Cretaceous shale fragments, as well as Paleozoic limestone and dolomite from the Winnipeg lowland.

In the upland area between the drift of the Superior lobe and the drift of the St. Louis sublobe are the Rainy lobe deposits. The Rainy lobe advanced from the northeast across the Rainy River and the Mesabi Iron Range, and flowed southwestward parallel to the north shore of Lake Superior. Its drift is brown to gray, non-calcareous, and sandy to stony, largely because of the high content of gabbro or other crystalline rocks from which most of it was derived (Wright, 1972).

The oldest Wisconsin drift exposed in the field area with extensive surface expression is that underlying the Toimi Drumlin Field of the Rainy lobe. This geomorphic feature consists of about 1400 drumlins trending southwest, covering parts of eastern St. Louis and western Lake county. The drumlin field is 70 miles long and up to 25 miles wide (Wright, 1972). Individual drumlins are generally 1-2 miles long, 1/4 mile wide, and 30-50 feet high. Most are symmetrical in profile parallel to the long axis, although a few are not, displaying the characteristic feature of a steeper, higher end in the up-glacier direction. The drumlins are composed of gray, sandy, stony till, rich in fragments of the Duluth Gabbro or its differentiates (anorthosite, red syenite, and diabase) which form the bedrock of much of the area beneath the drumlin field. Huge boulders of gabbro commonly dot the surface (Wright, 1972).

The Toimi Drumlin Field is buried on the southeast and south by the Highland moraine and outwash associated with the advance of the Superior lobe during the Automba phase. On the west the drumlin field is buried by the generally thin drift of the St. Louis sublobe and by sediments of glacial Lake Upham, but many of the drumlins maintain palimpsest forms that show through the blanketing drift.

Radiocarbon dates indicate that the entire sequence of ice sheet digitations that produced the various lobes of ice and resulting geomorphic features occurred during late Wisconsin time. The Rainy lobe drift was deposited contemporaneously with the St. Croix phase of the Superior lobe advance, approximately 20,000 years ago. The other three advances of the Superior lobe have been dated as occurring between 20,000 to 10,500 years ago (Wright and others, 1973).

III. ORIGIN OF ESKERS

GENERAL STATEMENT

Eskers have been well-documented and studied in glaciated parts of the world by numerous authors (see Flint, 1971, p. 214-218, and Embleton and King, 1975, p. 467-484). Included in this work are studies on the transport distance for material in the eskers, nature of esker sedimentation, and paleohydraulics, all of which are related to the origin of eskers.

Hummel (1874) was the first of several authors to postulate a theory for the origin of eskers when he pointed out that most eskers are the deposits of glacial streams confined by walls of ice and left as ridges when the ice disappeared. The theory has remained basically the same over time, but it has expanded significantly (Lewis, 1947; Meier, 1951; Stokes, 1958; Sugden and John, 1976)

After studying eskers in Finland, Tanner (1937) concluded that they must have been formed in open channels on the ice surface and then let down, or superimposed, on the underlying topography as the ice wasted away.

Price (1973, p. 141) pointed out that the cross-sectional shapes of the tunnels plays an important part in determining the final cross-sectional shape of the esker, as well as its internal characteristics. He also thought that the form, disposition, and internal characteristics of eskers cannot reveal whether the initial deposition took place in the supra-, en-, sub-, or proglacial environment.

Banerjee and McDonald (1975), in a discussion of the nature of esker sedimentation, maintained that both the nature of the conduit through which the esker stream flowed and the site of deposition control esker sedimentation. These two factors can commonly be determined from the sedimentary succession. Interaction of these two factors permits definition of three different models of esker sedimentation: open channel, tunnel, and deltaic (Table 2).

PALEOHYDRAULICS

Eskers indicate the position of the major route by which meltwater and glaciofluvial debris is transported from within the confines of the glacier system to achieve output at the glacier margin. The concept of a water table developing in a glacier was discussed by Sugden and John (1976, p. 288). They maintained that the water migrated downward through a vadose zone under the influence of gravity to the phreatic zone where the meltwater flowed under hydrostatic pressure. They also believed pressure could be built up by constrictions developing in the tunnel as a result of ice movements. Other authors who support and discuss the water table concept include Shreve (1972, 1985), Vivian (1970), Iken (1972), Sissons (1967), and Rothlisberger (1972).

Wright (1973), studying the Superior lobe, mentioned the formation of

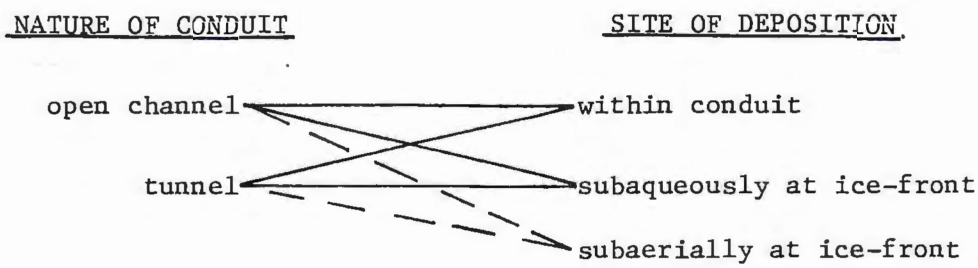


Table 2. Models of esker sedimentation, after Banerjee and Mcdonald (1975).

wide, subparallel tunnel valleys cut into the underlying till and into bedrock by subglacial streams driven to high velocity under the hydrostatic pressure resulting from the load of many hundred meters of active ice. Subsequent stagnation and ablation of the ice exposed the tunnel valleys to atmospheric pressure and converted the subglacial streams from major erosional streams to small depositional streams, which formed discontinuous eskers along many of the tunnel valleys.

Hooke and others (1985) suggested, from their studies on the Bondhusbreen outlet glacier in Norway, that the location of subglacial water courses changed seasonally, and that the conduits can temporarily be dammed.

It is now widely accepted (Haefeli, 1970; Rothlisberger, 1972; Shreve, 1972; Hodge, 1974) that englacial and subglacial water conduits are smallest in the early spring after closing by plastic deformation during winter when discharges are low. As surface melting accelerates in the spring, discharges increase and passages are enlarged by melting. Energy needed for this melting is produced both from heat carried by water generated from surface melting and by conversion of potential energy to heat as the water falls in elevation (Hooke and others, 1985). Due to this expansion and contraction of the meltwater conduits, water can continue to flow during the winter as it is slowly forced out of the channels and cavities as lowering of the water pressure allows them to squeeze shut.

Recent hydrologic work by Shreve (1972, 1985) has contributed important information on the study of water under glaciers and the formation of eskers with respect to the meltwater. He compared the water-filled tunnels along the beds of ice sheets to phreatic caverns in limestone (1985, p. 9), with two special conditions that make their behavior unique, and which bear strongly on the eskers that develop in them.

The first condition is that the water pressure in such tunnels is governed primarily by the weight of the overlying ice (Shreve, 1972). Tunnels beneath a hundred meters or more of ice can significantly expand or contract in at most a few days in response to an increase or decrease in the water pressure. This expansion or contraction lowers or raises the pressure by increasing or decreasing the tunnel capacity until the internal and external pressures balance, that is, until the water pressure in the tunnel equals the glaciostatic pressure in the surrounding ice. As a result, the water-filled tunnels adjust in size to transmit exactly the amount of water supplied. An important corollary of this adjustment is that water completely fills subglacial tunnels except locally where the overlying ice is thin, or temporarily, when the water supply suddenly drops (Shreve, 1985).

The second condition of water-filled tunnels is that melting of the tunnel walls, which is almost entirely due to viscous heating of the flowing water, tends to enlarge the tunnel, causing the water pressure to drop and inducing inflow of the surrounding ice. The rate of melting can even be negative, that is freezing can occur, accompanied by ice flow away from the tunnel. With melting of the walls, the shape of the tunnel is sharply arched, while freezing of the tunnel walls will give a shape that is wide and low.

The second condition primarily governs the form, composition, and structure of the eskers, whereas the first primarily governs their paths (Shreve, 1985).

The rate of freezing and melting of the tunnel walls strongly influences the form, composition, and structure of the esker because it controls both the shape of the subglacial tunnel and the influx of rock debris. This also has implications for drift prospecting, as it bears on the origin of the material. A more complete discussion follows in the drift prospecting section.

Little work has been done on eskers in northeastern Minnesota, although Sharp (1953) briefly mentioned eskers in his work on the glacial deposits of Cook County. Wright (1973) discussed the origin of eskers and their relationships to tunnel valleys in east-central Minnesota. He concluded (1973, p. 272) that the tunnel valleys were formed by subglacial streams under high hydrostatic pressure caused by the weight of the overlying ice. Thinning of the ice reduced the hydrostatic pressure and opened the tunnels, whereby the streams shifted from an erosional to a depositional habit, producing eskers. He attributed the gaps in the eskers to represent sites of nondeposition where water velocity was locally great enough to transport the sediment.

SUMMARY

Work by numerous authors on many different eskers has shown they can form under several different conditions that are related to tunnel shape, position of meltwater stream (en-, supra-, sub-, or proglacial), and the conditions of water in the ice tunnels.

Observations from this study show that eskers can form in ice in which the ice margin is slow-moving, with a net retreat of the ice margin, or the margin has undergone large scale stalling. The esker morphology, length, paleohydraulics, sedimentary structures, adjacent glacial features and topographic relationships contribute evidence to support this conclusion. This wide range of conditions under which eskers can form gives rise to a variety of esker types that are found in northeastern Minnesota, which are discussed in the following chapters.

IV. ESKER TYPES IN MINNESOTA

GENERAL STATEMENT

Many different types of eskers have been described. DeGeer (1910) was one of the first to describe beaded eskers, a linear ensemble of short, glaciofluvial segments, or beads, that comprise some esker systems in Scandinavia. Banerjee and McDonald (1975) also described beaded eskers. Lewis (1947) reported on an esker in the process of formation in Norway, and a long, nearly continuous esker was studied by Lee (1965) near the Kirkland Lake-Larder Lake gold belt, near Munro, Ontario.

Several types of eskers occur in northeastern Minnesota. They are either continuous, beaded, or small, discontinuous segments. The continuous eskers and beaded eskers are more numerous and extensive than the smaller segments and therefore more important with respect to drift prospecting. The shorter segments were not studied in detail for this project.

CONTINUOUS ESKERS

Characteristics

The best examples of continuous eskers are associated with the Superior lobe during the Split Rock phase. Five northwest-trending eskers merge into coalescing outwash fans southwest of Cloquet. The eskers are short (1-2 miles) perhaps because their headward ends may have been truncated by the post-glacial erosional channels of the diverted St. Louis River, but more likely because the eskers may represent the downstream ends of major subglacial tunnel valley streams emerging from under the Superior lobe (Wright, 1972, p. 533).

The eskers are all sharp-crested, and at least one of them is appended by smaller, subparallel branch or tributary eskers. These branch eskers are best seen near the esker that crosses Section 14, T. 48 N., R. 18 W. (Iverson Quadrangle).

Three of the eskers are separated by a distance of one mile, whereas the other two are about three miles apart. They are up to 120 feet high. Two of them show ice block depressions near the crests. The width of the eskers varies from 200 to 400 feet, with one exception: the esker in Section 12, T. 48 N., R. 18 W. (Iverson Quadrangle) is nearly 1200 feet wide. Outwash plains and ground moraine surround the eskers.

Continuous eskers are also associated with the Rainy lobe. The Caribou Lake esker (Sec. 11 and 14, T. 51 N., R. 16 W., Twig Quadrangle) is a single, sharp-crested ridge, one mile long that merges into an outwash plain. In one place the esker ridge expands to a width of 500 feet and is pitted with a large ice block depression. Along the rest of its course the esker is less than 200 feet wide. The maximum height is 70 feet. The esker is situated on higher ground rather than in topographic depressions like the beaded eskers. It is surrounded by Superior lobe deposits that include both outwash, to the north and south, and hummocky, ice-stagnation topography to the east.

A possible model for the origin of continuous eskers can be developed based on geomorphic and topographic evidence, along with field relationships of the glacial deposits. The sedimentological evidence, discussed in the next section, also contributes support for this model.

The eskers associated with the Superior lobe probably formed at the ice terminus after the lobe had ceased forward motion during the Split Rock advance. Little internal ice motion was taking place as indicated by the absence of a terminal moraine. If the eskers were constructed over a period of years, then some minor internal motion of the ice may have taken place as the ice adjusted to the seasonal changes in the water volume within the esker tunnels.

The Cloquet moraine borders the eskers on three sides, and the Cloquet outwash plain is located in front of them. The meltwater streams that formed the eskers dumped their sediment load into coalescing outwash fans at an elevation of 1250 to 1300 feet.

THE CLOQUET ESKER

Location and morphology

The Cloquet esker is located just southwest of the town of Cloquet, Minnesota. It is currently being mined for sand and gravel and, as a result, a well-exposed cross-section across the esker trend was available for examination.

The esker has fairly steep sides and a single sharp crest, that in one place meanders several hundred feet. It is one continuous segment just under 1 mile in length, 100 feet high, and 300 to 400 feet wide. The trend of the esker is N. 37 W., and the meltwater that deposited the sediments flowed in that same direction. It is flanked laterally by moraine topography and outwash plains on the southwest and by a large kame on the northeast. The esker itself merges into an outwash plain sloping to the northwest. A swamp containing Otter Creek is at the head of the esker.

Sedimentology

Detailed studies of the internal characteristics of the Cloquet esker revealed a wide range of sorting, grain sizes, and sedimentary structures which, in turn, indicate fluctuating paleohydrological conditions during deposition.

Figure 4 shows a photograph of the exposed section across the trend of the esker, and Figure 5 is a sketch made from the photograph to clarify and delineate the sedimentary units. A general lack of faults or slump structures in the sediments implies a subglacial origin for the esker because such structures are commonly associated with ice-cored sediments that have been disturbed as underlying ice wasted away.

Data on the grain sizes and sedimentary structures in the exposed section have been compiled into a stratigraphic column (Figure 6) and interpreted after Miall (1978). Grain sizes and sedimentary structures range from medium to very coarse, well-sorted sand in the lowermost trough

Figure 4. Photograph of the exposed cross section through the Cloquet esker. Flow direction is toward the viewer.

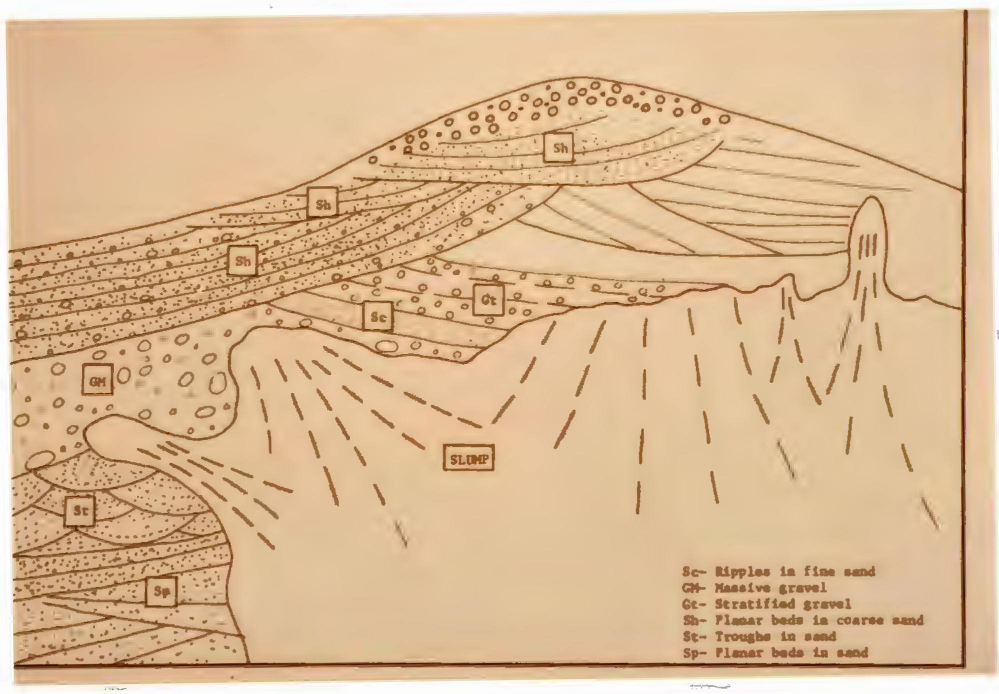
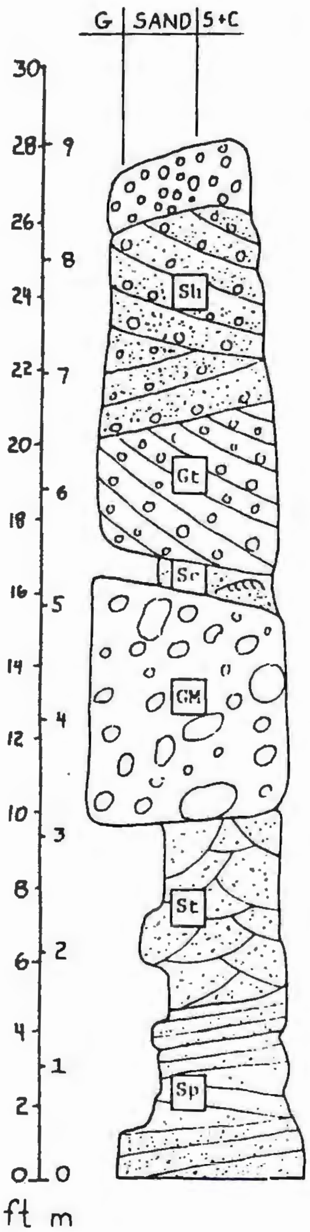


Figure 5. Photograph of a sketch drawn from the above photo (Figure 4).

STRATIGRAPHIC COLUMN FOR THE CLOQUET ESKER



LITHOFACIES	SEDIMENTARY STRUCTURES	INTERPRETATION
OVERBURDEN	NONE	ROOT ZONE
VERY COARSE SAND AND PEBBLES	PARALLEL LAMINATION PLANE BEDS	PLANAR BEDS (UPPER AND LOWER FLOW REGIMES)
STRATIFIED GRAVEL	LARGE SCALE TROUGHS	MINOR CHANNEL FILLS
FINE GRN. SAND	CLIMBING RIPPLES	CREVASSE SPLAY
MASSIVE OR CRUDELY BEDDED GRAVEL	HORIZONTAL BEDS LARGE TROUGHS	CHANNEL LAG
MEDIUM TO VERY COARSE SAND	TROUGHS	DUNES (LOWER FLOW REGIME)
MEDIUM TO VERY COARSE SAND	PLANAR CROSS BEDS	SAND WAVES (LOWER FLOW REGIME)

Figure 6. Stratigraphic column for the Cloquet esker. Interpretations after Miall (1978).

cross-beds and planar cross-beds, to massive gravel with clasts up to two feet in diameter, to large-scale troughs of gravel to large-scale troughs of very coarse sand and pebbles.

The uppermost unit of the esker (Sh) is trough cross-bedded, very coarse sand and gravel, and is similar to the "anticlinal" bedding described by Flint (1971, p. 215), Embleton and King (1975, p. 484), and Shreve (1985). The term is somewhat misleading because the beds have not been folded into an anticline, but merely dip away from the axis of the esker. As Shreve (1985) notes, this is a commonly observed feature and has frequently been attributed to slumping toward the sides in response to loss of support when the enclosing ice melted (Flint,1971, p. 215; Embleton and King, 1975, p. 484), although there are alternative explanations (Sharp, 1953, p. 872; Flint, 1971, 215-216). The latter authors attribute the anticlinal bedding to primary deposition. A further explanation for the anticlinal bedding is given by Shreve (1985) in his discussion of sharp-crested eskers in Maine. Wall melting, and hence water flow, must be greatest near the crest, where the bulk of the debris is deposited and then moved forward and downward along the flanks.

This forward and downward movement of the very coarse sand and pebble fractions could explain the large-scale troughs that parallel the steep sides of the Cloquet esker.

The unit labeled (Gt) is composed of large scale troughs of gravel that may have formed in a manner similar to the overlying unit, with the sediment being carried forward and downward by meltwater moving under fairly high velocity.

Climbing ripples, in the unit labeled (Sc), and shown in the photograph in Figures 4 and 5, are of well-sorted, medium- to coarse-grained sand. In Miall's (1978) interpretation, they infer the presence of a crevasse splay, or an area of overbank flooding in a deltaic environment. Since this is not the case here, a better interpretation might be that there was more sand in the stream than could be transported, and the sediment load was rapidly deposited. Two factors could help account for this: (1) a large amount of sand was dumped into the meltwater stream in a short amount of time, and (2) the meltwater stream lost its transporting capacity relatively quickly.

The massive gravel unit (Gm) is also well-sorted as most of the finer-grained material has been washed away. This unit was deposited by a much higher velocity stream than the one which deposited the underlying sand units. The change between the underlying sand unit (Sc) and this unit (Gm) could represent a period of time during which an increased flow velocity gave the meltwater stream the power to channel, scour, and erode existing bedforms. A subsequent decrease in velocity would have allowed deposition of the sediment load as the massive, well-sorted, coarse-grained gravel unit that is presently exposed in the esker.

The lowermost unit exposed in the esker is well-sorted trough (St) and planar cross-bedded sand (Sp). The upward change in the vertical sequence from planar to trough cross beds with little or no change in grain size, could imply a slight increase in flow strength as the sediments were accumulating (Figure 7). Minor channel lags of pebble size material are seen at the base of some of the troughs.

Lithology

The lithologies of the material in the Cloquet esker are dominantly red sandstone, massive basalt, amygdaloidal basalt, and gabbro, with lesser amounts of granite, gneiss, and slate. Lake Superior agates are fairly common.

The gabbro, granite, and gneiss were probably derived from the underlying Rainy lobe material (Independence Till of Wright and others, 1970), although some gabbro may have been derived from the Duluth area by Superior lobe advances. These most likely accumulated in the esker through a variety of paths. The Superior lobe overrode deposits of the Rainy lobe in this area, and some blending of the tills could have taken place.

Origin of Esker Sediment

As the ice stagnated and began ablating, a network of meltwater channels developed within the glacier that carried water toward the glacier terminus. This water could have transported material as it migrated along a network of passages and channels, as described by Shreve

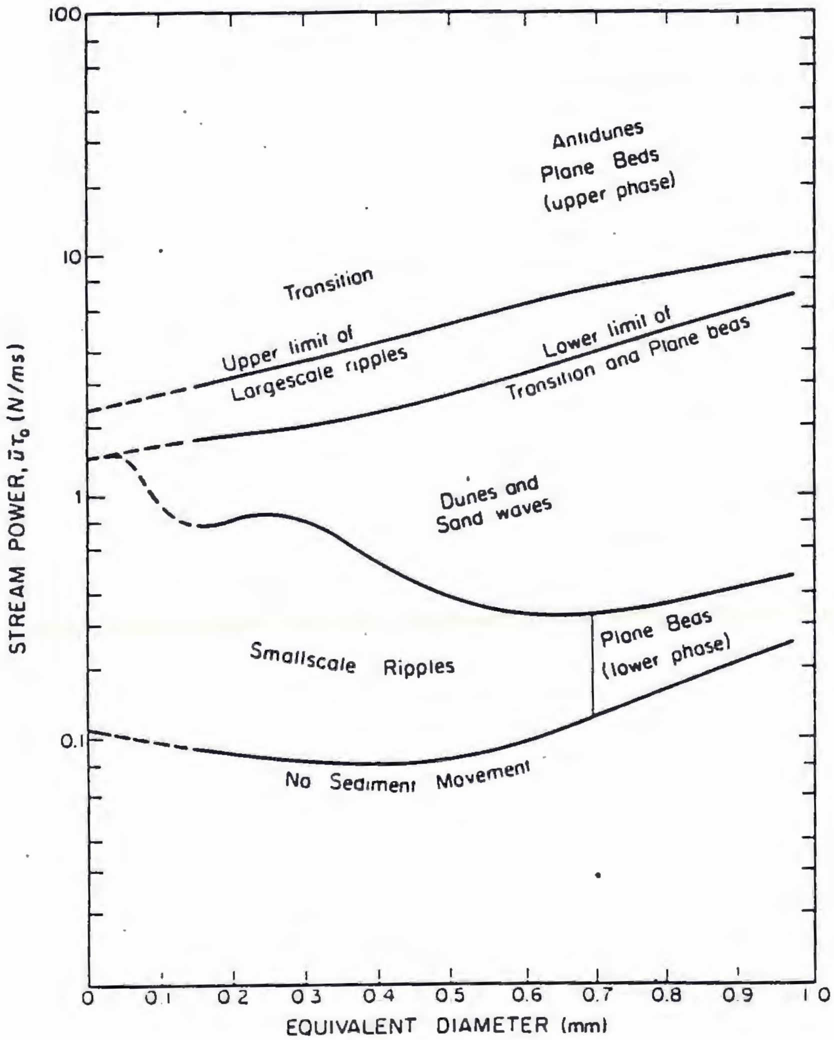


Figure 7. Hydraulic criteria for bedforms based on stream power, after Allen (1968).

(1972), and carried that sediment into the main tunnel where deposition ultimately took place.

The esker material may have been derived from one or more of several possible sources that include: (1) supraglacial material, (2) sediment derived from the bedrock beneath the meltwater stream by fluvial erosion, (3) drift directly under the ice that could be eroded, and deposited by the meltwater stream, (4) englacial material, and (5) material within the ice, near its base (basal debris).

The lack of a till cap on the esker indicates relatively clean ice above the esker tunnel. Therefore the supraglacial environment contributed little material to the esker.

Little evidence is seen that would indicate subglacial meltwater erosion of either the underlying Independence Till or the local bedrock took place. No topographic evidence exists that would imply channeling of the Independence till, or bedrock, although deposits from the Nickerson phase advance may have covered these. The mixed lithology of the esker boulders (characteristic Rainy lobe material, such as gabbro and granophyre, and diagnostic Superior lobe material, such as red sandstone, amygdaloidal basalt, and Lake Superior agates) indicates the meltwater erosion of the Independence Till was not a dominant influence on the esker composition.

Englacial sediment, while it may have contributed some material to the esker, does not seem to be a major contributor since it is generally least like the locally-derived material, except where thrusting occurs at the ice margin.

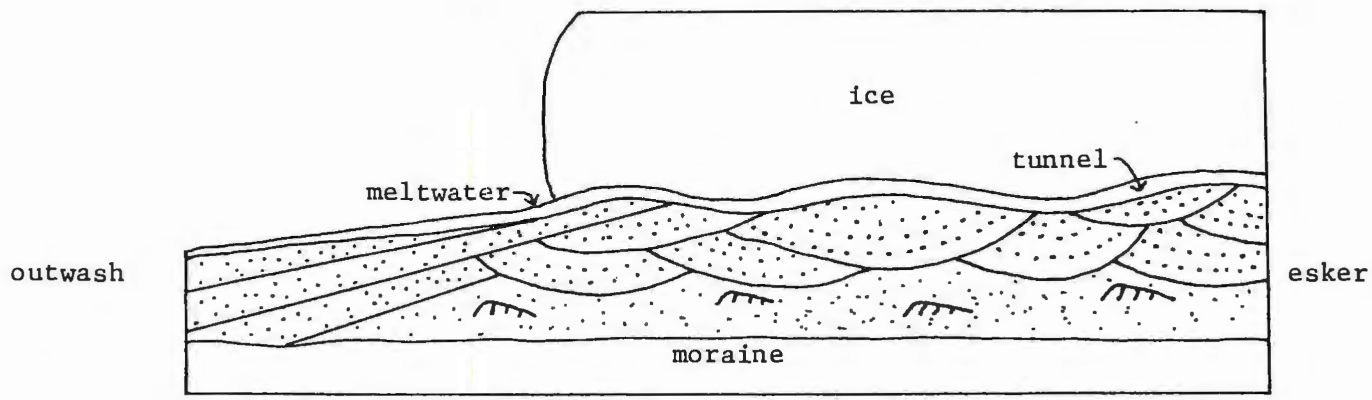
The most likely source for the esker material is the basal ice debris. This zone would contain the highest percentage of locally-derived material that was eroded during the advance of the Superior lobe, as well as material from the underlying Independence Till that was incorporated into the glacial load.

Since the ice tunnel was formed at the base of the ice (as shown by the well-preserved sedimentary structures), the basal debris would have been a nearby, readily available source of sediment. This basal debris appears to be the most reasonable source, although the other sources mentioned could have contributed minor amounts.

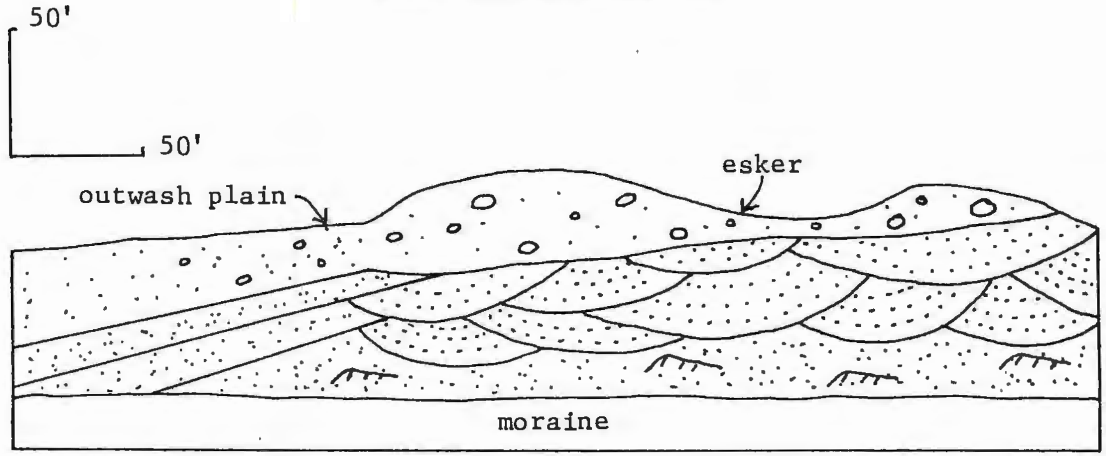
It also appears that the esker accreted concurrently with the deposition of the adjacent outwash plain, because the Cloquet esker is at the same elevation or slightly higher. This would agree with similar observations on glacial features in Alaska that "deposition appears to have been related to building of ice contact outwash fans at an earlier, stabilized position of the glacier front" (Washburn, 1941, p. 222) .

The spacing between the eskers, 1 to 3 miles, could establish the "drainage basins" for the meltwater that supplied the esker-building streams. Changing locations of subglacial water courses observed by Hooke and others (1985) could account for the deposition of the branch eskers.

The top sketch in Figure 8 is drawn parallel to the long axis of the esker, showing the meltwater stream flowing under the ice, and depositing sediment in the tunnel as well as on the outwash plain. The bottom sketch



Esker during formation



Present topography

Figure 8. Hypothetical model of a continuous esker showing meltwater flowing through a subglacial tunnel and depositing sediments in an esker and onto an outwash plain (top), and the present, exposed topographic relationships (bottom).

Figure 9. Well preserved graded, planar cross beds in the Cloquet esker.

Figure 10. Well preserved climbing ripple sequence in the Cloquet esker.

shows the esker and outwash plain as they look today.

Summary

The Cloquet esker was deposited subglacially, as shown by the well-preserved sedimentary structures (Figures 9 and 10). Delicate features like these would not have survived had they been deposited supraglacially or englacially, and subsequently lowered to the ground as the underlying ice ablated.

The presence of an adjacent outwash plain rather than a terminal moraine indicates the ice was nearly stagnant (or at least not actively advancing) rather than actively conveying material to the glacial terminus, and thus the esker formed as a late-stage event.

The material in the esker could have been derived from a number of different sources that include supraglacial material, meltwater erosion of the underlying bedrock and the Independence till, englacial debris, and the debris-rich basal ice zone. The lack of meltwater channels, combined with the mixed lithology (indicator clasts from both the Rainy lobe and the Superior lobe), as well as the high percentage of locally derived material indicate that the esker material was derived from the basal debris of the Superior lobe.

Wright (1972) proposed that the eskers were the downstream ends of major subglacial tunnel valley streams emerging from under the Superior lobe, that deposited their sediment load after the stagnation and ablation of the ice exposed the tunnels to atmospheric pressure and converted the subglacial streams from an erosional mode to a depositional one.

Another possibility, based on work for this study, can be developed. There is no topographic evidence to suggest high velocity meltwater streams were eroding tunnel valleys in this area, although the argument could be made that the deposits from the Nickerson phase of the Superior lobe advance would have covered, and filled, these tunnel valleys. However, the esker lithology is dominantly Rainy lobe and Superior lobe material, and not local bedrock from the Thomson Formation, which implies subglacial meltwater streams under high hydrostatic pressure were not eroding the local bedrock.

The shape of the esker, sharp-crested with steep sides, is the result of a tunnel that was sharply arched, due to melting of the tunnel walls as proposed by Shreve (1985). In-flowing of ice towards the tunnel, to accomodate the wall melting, would carry debris from the basal ice into the tunnel where it could be transported and deposited as the esker.

The formation of the esker probably took place over a period of time, of at least one season, but more likely over a number of years as the ice gradually wasted away. This would allow numerous opportunities for the esker to be eroded, scoured, and built up again in the meltwater tunnel, finally to be left as a continuous esker after the meltwater supply lost the competence to erode and transport sediment.

Anticlinal bedding, seen near the esker crest, could result from the sediment being deposited into the tunnel near the esker crest and moved forward and downward along the flanks.

Work by Hooke and others (1985) has contributed information about glacial meltwater discharge that could help explain some of the features seen in the esker. They noted a wide variation in the amount of water discharged through subglacial tunnels on a daily basis, as well as on a seasonal basis, with occasional unusual discharge events. These unusual events involved a sharp drop in discharge followed, within an hour, by a period of high discharge. This was attributed to the damming and subsequent bursting of upstream conduits, perhaps due to a collapse of an ice tunnel.

These large changes in fluvial discharge from a modern example in Norway could help to explain the variations in grain size, changes in sedimentary structures, and subsequent changes in the flow regime recorded by the Cloquet esker.

The numerous, abrupt changes in grain size indicate the water velocity varied considerably during esker deposition. Each individual unit is truncated and cross-cut by the overlying unit. It is interesting to note that the erosional gaps could imply longer periods of time than are represented by the depositional events.

BEADED ESKERS

Characteristics

Beaded eskers are the most common type of esker in the study area. These are most commonly, but not always, found associated with glacial deposits left by the Rainy lobe. They generally lie between and parallel to the drumlins in the Toimi Drumlin Field. The beaded esker systems are longer than the continuous eskers, as much as 10 to 12 miles in length. They have an exposed height of 20 to 80 feet. The crests of the beads are fairly sharp.

There are approximately 32 beaded eskers associated with the Rainy lobe and three with the Superior lobe. The lateral distance between the beaded esker systems is two to four miles.

The beaded eskers are characterized by a series of consecutive segments, or beads, that are separated by swamps or lakes. The beads average about one-quarter mile in length, with a range between a few hundred feet to a mile in length. The gaps between the back of one bead and the front of the next bead average 200-400 feet. Most of the beaded eskers follow the low ground between the drumlins, but in Section 31, T. 55 N., R. 14 W. (Comstock Lake Quadrangle) a beaded esker crosses a low divide of slightly higher ground. This is also the only place where a beaded esker bifurcates for a short distance before returning to the common single ridge form.

Most of the beaded eskers are fairly straight, although their trends may wander from side to side of the valley between the drumlins. The Hulligan Lake esker, described in detail in the next section, does show a large meander of nearly three quarters of a mile around Hulligan Lake (Sec. 2, T.54 N., R.14 W., Boulder Lake Reservoir Northeast Quadrangle).

Origin of Beaded Eskers

From recent observations of glaciers it is now known that eskers can form in the following ways (Saunderson, 1975): 1) sedimentation within a subglacial tunnel, 2) sedimentation in supraglacial stream channels with subsequent lowering to the ground surface as the ice melts, and 3) transport of englacial debris along shear planes toward an englacial tunnel and reworking of this debris by meltwater in the tunnel. A fourth type of environment, explainable in terms of a modified subglacial theory, also needs to be considered. The most explicit statement of this hypothesis was made by De Geer (1910, 1940), who found that esker gravels and varves commonly were located adjacent to each other and therefore must be genetically related. He traced a lateral change from esker gravels into varve couplets, and these couplets became finer-grained in a distal direction. De Geer concluded the esker gravels and varve couplets represented different facies of the same time-stratigraphic unit. The coarse esker gravels were thought to be deposited at the exit of a subglacial tunnel where it fed into a standing body of water. The decreasing competency of the flow in the distal direction would be accompanied by sedimentation of progressively finer-grained material in a glaciolacustrine environment, producing a continuous gradation from gravel to clay (Saunderson, 1975). De Geer (1940) also considered the formation of each bead to be an annual depositional event that took place as the ice margin retreated.

If the beads do represent an annual depositional event, then the meltwater tunnel could have expanded or contracted in response to the water supply. Water would drain from the ice sheet during the winter months, but sediment deposited in the tunnels could act as porous conduits for new meltwater the following year, thereby reestablishing the drainage network.

One line of evidence for the annual periodicity of the beaded eskers in the study area is the distance separating the crests, or high points, of the beads. This point was chosen rather than the front or back of the bead because (1) it may have formed during peak summer run-off and (2) the genuine front or back may be mantled by the surrounding swamp and not exposed. The average distance between the crests of 22 beads is 1200 feet, or 365 meters. This is in close correlation with the radiocarbon dating of continental ice sheet retreat from the U.S.-Canada border to the St. Lawrence lowland, a distance of 100 km (62 miles) in 400 years, which gives an average retreat rate of 250 meters (820 feet) per year (Gadd and others, 1973).

The beaded eskers between the Toimi Drumlins could have formed in a manner similar to the De Geer hypothesis; unfortunately, none of the exposed cross-sections have shown any type of distal fining or interfingering of the sediments with lake clays or varves. Therefore, if such a relationship exists, it is not exposed.

Some of the swamps have ponds in the middle, indicating the progression of lateral infilling of lakes. The sediments in such swamps and lakes are as much as 40 feet thick (Wright, 1972, p. 566). Therefore, the drumlins could have at least an additional 40 feet added to the exposed height. This could make the eskers nearly twice as high as they seem to be now, and thus difficult, if not impossible, to see the sediments deposited in the low areas between the beads. Fanning or broadening of a delta-like deposit is not seen, nor are any of the interfingering of gravels and clays, since the tops of the eskers are all that is exposed.

At least one of the beaded eskers, the Sullivan Lake esker (T. 56 N., R. 11 W., Kane Lake Quadrangle), lies in what appears to be a tunnel valley. This esker could have formed in a manner similar to that proposed by Wright (1973) but evidence from this study suggests that it formed under different circumstances. This is the only tunnel valley that contains a beaded esker. Most of the other Rainy lobe eskers are located in topographic lows between the drumlins and the majority of these do not appear to be tunnel valleys. The regular spacing between many of the segments in most of the beaded eskers is probably due to the annual retreat-deposition cycle proposed by De Geer (1910), rather than by erosional gaps, or sites of non-deposition, as proposed by Wright (1973). The beaded eskers probably formed in the pre-existing topographic lows as meltwater was channeled by the underlying topography, and in at least one case, the topographic low happened to be a tunnel valley.

THE HULLIGAN LAKE ESKER

Location and morphology

The Hulligan Lake esker is located 25 miles north of Duluth, where it crosses St. Louis County 4. Several access points are available to study the esker at different locations along its length. The Hulligan Lake esker is one of several beaded eskers in the study area.

The esker can be traced for 12 miles across the Boulder Lake Northeast and the Comstock Lake 7.5 minute topographic quadrangles. The beads are shaped like elliptical domes 300-500 feet long by 100-150 feet wide and can be as long as one mile. The height of the beads varies from 25 feet to 45 feet above the neighboring swamp. Successive beads are separated by 250-2500 feet of swampland. There are 39 beads in the esker. The swamps and low ground that surround the beads are, in turn, bordered by the southwest-trending Toimi Drumlin field. The trend of the esker, and the drumlins, is N. 45 E. A large meander can be seen in the esker in Section 2 (T. 54 N., R. 14 W.).

Sedimentology

Studies of the Hulligan Lake esker could not be made with the same amount of detail as for the Cloquet esker. However, the availability of numerous access points, combined with several small excavations made during the sampling period, and observations in one abandonded gravel pit give some insight into the conditions under which the esker was deposited.

Examinations at the four sample locations, and the abandoned gravel pit, show that a limited variety of grain sizes are present in the esker. Sketches of these locations and their positions along the esker are shown in Figure 11.

With one exception, all of the exposures consist of well-sorted, cobble- to boulder-sized material, that is subrounded to rounded. The boulders, which appear to be crudely cross-bedded in one place, reach up to 1.5 feet in diameter. A minor sand lens, seen in one place (#58 on Figure 11) implies some changes in the current velocity.

The exposure that is not all bouldery material, labeled #52, has a base of 4 inch cobbles that is overlain by nearly 4 feet of 1 inch gravel and poorly sorted, coarse sand.

As with the Cloquet esker, the grain sizes and sedimentary structures seen in the exposures are interpreted after Miall (1978). Most of the sections consist of massive or crudely bedded gravel (Gm) that could represent horizontal beds or large troughs deposited as channel lags. The poorly sorted sand and gravel unit in #52 (Gt) may have been minor channel fillings.

The gravel pit shown on Figure 11, was abandoned several years ago and, as a result, offered a poor exposure of the esker face. The material had slumped and any sedimentary structures that may have been there were not exposed. The size of the material in the pit ranges from cobbles to large boulders. This is similar to most of the previously described sample locations. Some finer-grained material, sand to gravel size, must have been present in the pit to make it a feasible source of road-building material.

Lithology

The major rock types found in the esker are gabbro and granophyre,

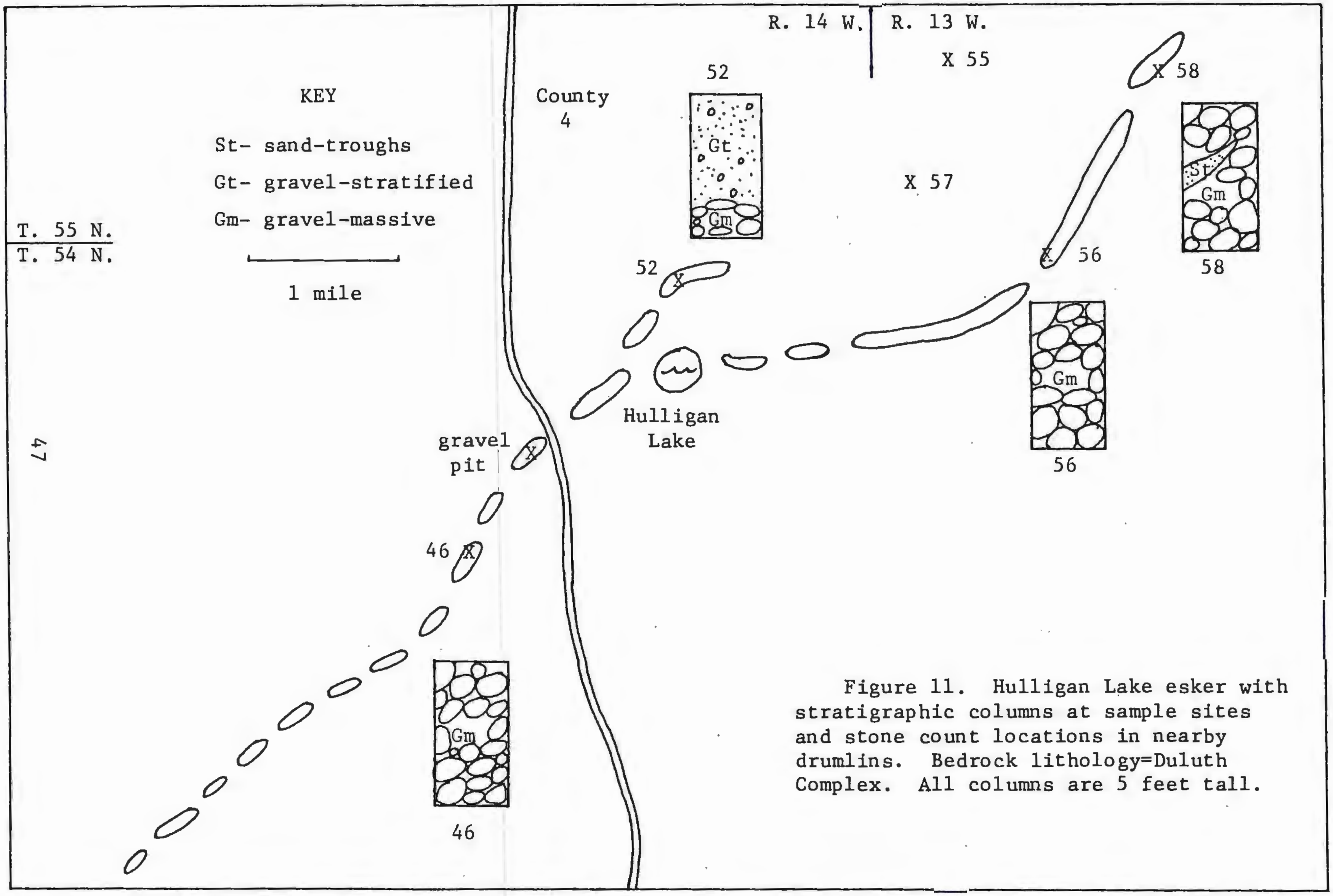


Figure 11. Hulligan Lake esker with stratigraphic columns at sample sites and stone count locations in nearby drumlins. Bedrock lithology=Duluth Complex. All columns are 5 feet tall.

with lesser amounts of granite, gneiss, metavolcanics, metasediments, and basalt. The gabbro and granophyre were derived from the underlying Duluth Complex, while the other components came from up-ice locations such as the greenstones in the Vermilion district and the Giants Range batholith. The unaltered- to weakly-altered basalt was most likely derived from the North Shore Volcanic Group.

Origin of Esker Sediment

The relatively homogeneous bedrock of the Duluth Complex and the lack of an overlying till with a different lithologic composition makes the origin of the clasts in the Hulligan Lake esker more difficult to determine than the clasts in the Cloquet esker. Several sources could have contributed material including (1)supraglacial debris, (2) englacial debris, (3) meltwater erosion of the subglacial till, (4) meltwater erosion of the underlying bedrock, and (5) basal debris.

As with the Cloquet esker, no till cap was seen, implying that the overlying ice was fairly clean, and supraglacial material was not a major source of esker sediment. Englacial debris could account for the presence of granite, gneiss, metavolcanics, and metasediments that have been transported farther than the gabbro, and also make up a smaller percentage of the esker material.

Meltwater erosion of the subglacial till did take place (as shown by the tunnel valley that contains the Sullivan Lake esker) and may or may not have contributed material to the esker, although the beaded eskers appear to be late-stage deposits that could have formed as the ice sheet was retreating. The contribution from this source is difficult to determine. Furthermore, there is no evidence that the bedrock was eroded by the meltwater stream.

Basal debris appears to be a probable source for most of the esker sediment. The basal zone of the ice would be enriched in local bedrock, which, in turn, would provide a large amount of sediment from which the meltwater could derive the esker-building material. This would leave an esker with clasts of a lithology similar to that of the surrounding till, as well as the local bedrock. Further support could be given to this theory if the drumlins were formed by erosion, as proposed by Whittecar and Mickelson (1979), rather than by deposition. Such an origin would require entrainment of significant volumes during drumlin formation, and subsequently, that there would be a large amount of basal and englacial sediment available for esker-building processes.

The similar results of the boulder counts done in the esker sediment and the adjacent till seem to imply that the esker material could have been derived from the basal ice debris, which would have lithologies similar to those in the till. This would agree with the results presented by Hellaakoski (1931) in his studies of an esker near Laitila, Finland. He noted, based on several boulder and pebble counts, that the morainic drift is the source of the material in the esker. He also concluded that the esker sediment had been transported about four kilometers down-ice from its parent drift as shown by stone counts and degree of rounding.

Summary

The path of the esker, channeled into the low ground between the drumlins, could imply that underlying topography was an important factor in determining the course of the meltwater stream. It also supports the idea that the esker formed subglacially. The esker in Section 31 (T. 55 N., R. 14 W., Comstock Lake Quadrangle) that crosses a low divide of slightly higher ground and bifurcates, shows that hydrostatic pressure may have exerted some control on the paths of the beaded eskers, and may also have been responsible for the large meander in the Hulligan Lake esker.

For most of its length, the beaded esker is surrounded by swamps, or low ground, that occupy the areas between the drumlins. Some of these host small ponds that could be remnants of small proglacial lakes that have been filled with up to 40 feet of clays and organic material. Hulligan Lake, around which the Hulligan Lake esker meanders, is probably a remnant of a much larger lake that occupied the low ground between the drumlins.

The coarse bouldery units seen in several places along the strike of the Hulligan Lake esker could support the De Geer theory for the origin of beaded eskers. If, as proposed, the visible part of the esker is the top of a larger, partly covered beaded segment, then it most likely was deposited by the peak summer runoff. This could account for the large boulders seen at the sample locations. Interfingering of the esker material with lake sediments, if present, is not exposed, and further work with excavations or drilling would be needed to confirm or reject the hypothesis.

The source of the sediment in the beaded eskers, while not pinpointed the way the Cloquet esker source was, was most likely derived from the basal debris of the Rainy lobe. Englacial debris, and subglacial meltwater erosion of both the underlying till and the local bedrock may also have contributed sediment, although they probably were not major sources.

V. DRIFT PROSPECTING

INTRODUCTION

Many workers have used several techniques in the study of glacial drift as a prospecting tool. These studies have attempted to answer a number of questions that include: How far has the material contained in the drift been transported? Do geochemical studies of till aid in prospecting? Is the material found in eskers contributed by meltwater erosion of the bedrock, or is it from the glacial load?

One of the earliest workers was Stone (1899), who observed that fragments of overridden bedrock enter the composition of an esker within less than one mile from the outcrop. He also noted that in some large eskers, such as the Katahdin esker in Maine, material seemed to be transported farther than in smaller eskers.

Drake (1983) noted that glaciers produce boulder trains, ore trails, and element fans when they override ore bodies or distinctive lithologies. His studies showed that the lithic, mineral, radioactive, element, and magnetic distributions in till away from known sources formed a three-dimensional configuration, with shapes resembling smoke plumes drifting laterally.

Magnetic observations by Onesti and Hinze (1970) over two eskers and the adjacent till plains showed a distinct difference in the magnetic intensity between the two, with the esker, in each case, having a much higher reading than the till. They attributed this to variations in the concentration of magnetic minerals, which, in turn, was a result of the mode of transportation of the materials.

Glacial till around the Mt. Pleasant Mo-W-Bi-Cu-Sn-Zn mineralized zone in New Brunswick was studied by Szabo, Govett, and Lajtai (1975). They found that dispersion trains of Cu, Pb, and Zn in the fine fractions could be traced for 2-5 km from the mineralized source, while the coarser fraction extended up to 16 km. They also found that studies of pebble dispersion in the glacial transport direction indicate that once a contact is crossed, the contribution of the underlying bedrock to the pebble counts depends greatly on the size fraction observed. The 90% composition is reached within 3 km in the greater than 5.1 cm fraction, but the same contribution in the 1.9-3.8 cm fraction is not matched until about 13 km from the contact. Boulders from the underlying bedrock constituted as much as 80% of the total count just a short distance from the contact.

Everson (1977) achieved similar results from his studies of various size fractions contained in the drift in the Long Island Lake Quadrangle in northern Minnesota. He found boulders greater than 1 meter to be within ± 60 meters of bedrock contacts. The fine-grained fraction (less than 1 meter) reflected the regional geology more than the local, or underlying bedrock.

In his study of the Laitila esker in Finland, Hellaakoski (1931) compared various size fractions of material in a moraine to those in an esker, which trended across the moraine and under which there was fairly good bedrock control. He concluded the esker material was derived from the moraine and subsequently transported a distance of nearly 4 km in the esker.

Chemical analyses of the -0.037 mm size fraction of 109 till samples investigated by May and Dreimanis (1973) showed that the Erie-Ontario lobe tills may be distinguished from the Huron-Georgian Bay lobe tills by a higher content of Ni, Cu, Zn, and Cr.

Three different techniques were used during this study to try to determine provenance for the esker material and to investigate heavy mineral suites that could indicate overridden bedrock that might have economic potential: (1) stone counts; (2) X-ray diffraction of heavy mineral mounts; and (3) optical examination of heavy mineral mounts.

STONE COUNTS

General statement

The purpose of the stone counts was to see whether boulders or pebbles could be used as provenance indicators. Stone counts are useful since they can be done easily and fairly quickly in the field. It was hoped that the dominant lithology recorded in the stone counts would give important information regarding up-ice bedrock lithology.

A total of 58 eight stone counts were performed including 30 boulder counts and 28 pebble counts. The lithologies of the boulders and pebbles were studied in eskers, outwash, and till from each of the three lobes of ice that deposited drift in the study area. The results have been tabulated and are displayed in three tables, one for each drift sheet: Rainy lobe, Table 3; Superior lobe, Table 4; and the St. Louis sublobe, Table 5. Sample numbers and locations are plotted on Plate 1 (back folder), as well as in Figures 11 and 12 (for the Rainy lobe), 13 and 14 (for the Superior lobe), and 15 (for the St. Louis sublobe), along with the bedrock geology and the generalized glacial geology.

One hundred boulders were counted at each location and their lithologies were recorded in the field. One hundred pebbles were collected at each location, and taken back to the lab, washed, and identified.

As work progressed it became apparent that not only were boulders easier to count and identify than pebbles, but they may also be more useful. Their lithologies could be determined in the field, samples did not need to be carried back to the lab for preparation, and the boulders are potentially better provenance indicators because the larger material is less likely to be carried as far by the esker-building streams. Thin-sections were prepared and examined with a petrographic microscope for six boulders that were difficult to identify because of their fine grain size. The thin-sections examined were all basalt.

The results of the stone counts are presented in three groups based on the parent drift. The groups will be discussed separately.

<u>Rainy Lobe Deposits</u>: The 30 stone counts done in the Rainy lobe drift

include 14 pebble counts (4 outwash, 4 eskers, and 6 till), and 16 boulder counts (2 outwash, 8 eskers, and 6 till). These counts include work done on, and around, the Hulligan Lake esker. Both the esker and the surrounding drift overlie the Duluth Complex, which is the dominant up-ice lithology for almost 90 miles. Another esker, seen on the Comstock Lake Quadrangle (T. 54 N., R. 15 W.) was also included in the counts. The sketch in Figure 12 shows the relationships between the eskers, drumlins, and sample locations.

The dominant lithology, gabbro, combined with granophyre, comprises a large percentage of the boulder counts (till 68-86%, esker 54-88%, and outwash 73 and 74%) while smaller percentages, with wider ranges, occur in the pebble size fraction (till 25-55%, esker 28-43%, and outwash 17-38%).

It appears the boulder fraction gives a better indication about the underlying bedrock lithology than does the pebble fraction. The pebble percentages may be diluted from material carried from locations up-ice, as shown by a higher percentage of metasediments and metavolcanics, that may have been derived from the Archean greenstone belts.

These results agree with those of Everson (1977), who noted that coarser material in his study area had been transported shorter distances than the finer material, and that the finer material was more diluted by up-ice lithologies.

The close agreement between gabbro and granophyre percentages seen in the till and in the eskers could imply that the bulk of the esker material

LITHOLOGY	29 PC out.	30 BC out.	31 BC esker	32 PC esker	33 BC till	34 PC esker	35 BC esker	36 BC out.	37 PC out.	38 PC till	39 BC till	40 PC out.	41 PC out.	42 PC till	43 PC till	44 BC till	45 PC till	46 BC esker	47 PC esker	48 PC esker	49 BC esker	50 PC esker	51 BC till	52 BC esker	53 BC till	54 PC till	55 BC till	56 BC esker	57 BC till	58 BC esker
granophyre	6	10	21	5	7	5	10	8	13	12	15	13	7	9	6	7	19	6	11	5	15	7	7	14	11	7	12	12	8	15
basalt	27	13	14	10	-	35	8	7	34	45	39	41	23	42	23	3	28	5	51	42	10	28	-	6	8	27	6	1	6	2
gabbro	11	63	33	70	72	35	64	66	25	13	40	16	31	25	35	79	31	74	30	23	41	36	72	50	66	38	56	76	64	59
sandstone	7	-	-	-	-	3	-	-	2	12	-	-	2	1	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
granite	2	8	10	4	9	3	13	5	8–	2	-	9	6	2	8	9	7	5	4	12	14	8	9	14	7	4	22	9	20	12
gneiss	-	4	7	5	-	-	-	3	3	3	-	-	-	5	7	2	-	1	-	3	2	2	-	2	2	-	2	2	2	5
black slate	6	2	3	2	4	15	4	-	6	-	-	2	9	-	-	-	-	-	-	4	16	17	4	-	-	-	-	-	-	-
greywacke	25	-	-	1	3	-	-	2	4	6	-	13	17	13	14	-	11	2	3	8	-	-	3	3	2	18	2	-	-	-
iron formation	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	1	-	-	-	1	-	2	-	-	-	-	-	-
quartzite	3	-	5	-	-	1	-	-	-	-	-	-	-	-	-	-	2	-	-	1	-	-	-	-	-	-	-	-	-	-
conglomerate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-
metavolcanics	9	-	-	-	2	-	-	9	3	-	4	2	2	-	5	-	2	1	-	-	-	1	2	8	4	3	-	-	-	7
diabase	-	-	6	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
agate	-	-	-	-	-	-	-	-	-	4	2	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
rhyolite	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
unknown	2	-	1	-	3	3	1	-	-	1	-	-	3	3	2	-	-	2	1	3	-	-	3	-	-	1	-	-	-	-

Table 3. Results of stone counts from the Rainy lobe drift. PC= pebble count, BC= boulder count, Out.= outwash. Sample numbers correspond to locations on Plate 1 (back folder).

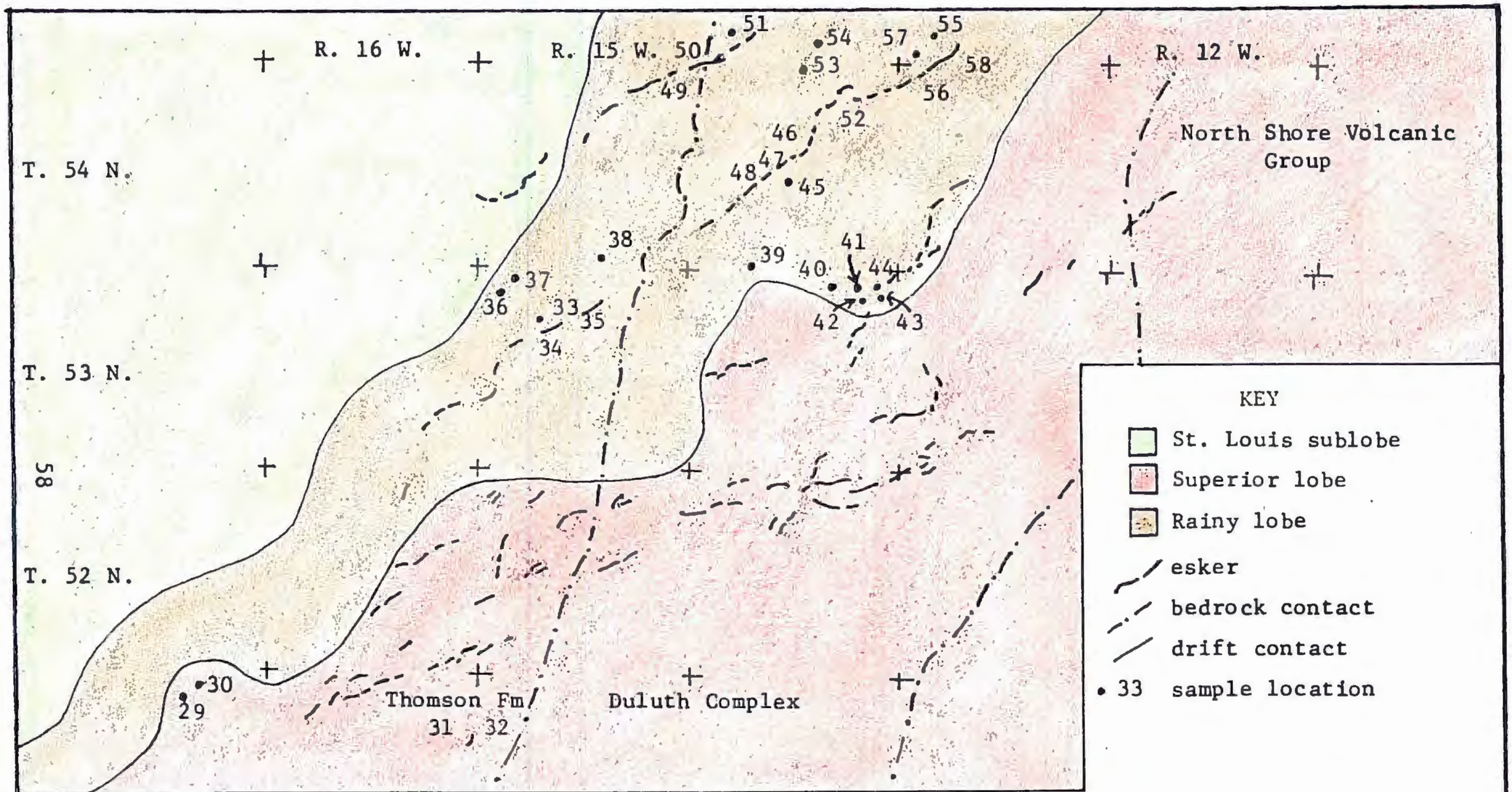


Figure 12. Relationships between eskers, bedrock geology, glacial geology, and sample locations for stone counts in the Rainy lobe drift.

was derived from the basal ice load, or perhaps, eroded from the underlying drumlins by the meltwater stream. There is no indication that the esker gravel is enriched in local bedrock by subglacial fluvial erosion.

It is interesting to note the lithologic changes in the Hulligan Lake esker as it trends across the area. Gabbro comprises 59 to 76% of the boulders in the farthest upstream counts. This abundance decreases to 50% of the count at the middle location, and increases back to 74% for the last (farthest downstream count). The variation in lithologic percentages is a reflection of the inhomogeneous nature of the debris contained in the basal ice, which in turn, is caused by the mixing, blending, and shearing of different rock types that were incorporated into the glacial load. When the gabbro numbers are combined with the granophyre numbers, the proportion in all four counts is very close to 75% for the Duluth Complex boulders (counts 46, 52, 56, and 58).

The boulder counts done in the nearby drumlins (counts 55 and 57) give results that are very similar to those from the Hulligan Lake esker. Gabbro totals combined with granophyre totals are close to 75% in both counts.

Two beaded eskers, in the Comstock Lake Quadrangle, were studied by stone counts, and lie close to, or down-ice from the bedrock contact between the Thomson Formation and the Duluth Complex. One boulder count and one pebble count was done on each of the two eskers. The sketch in Figure 13 shows the relationships between the eskers and the bedrock contact.

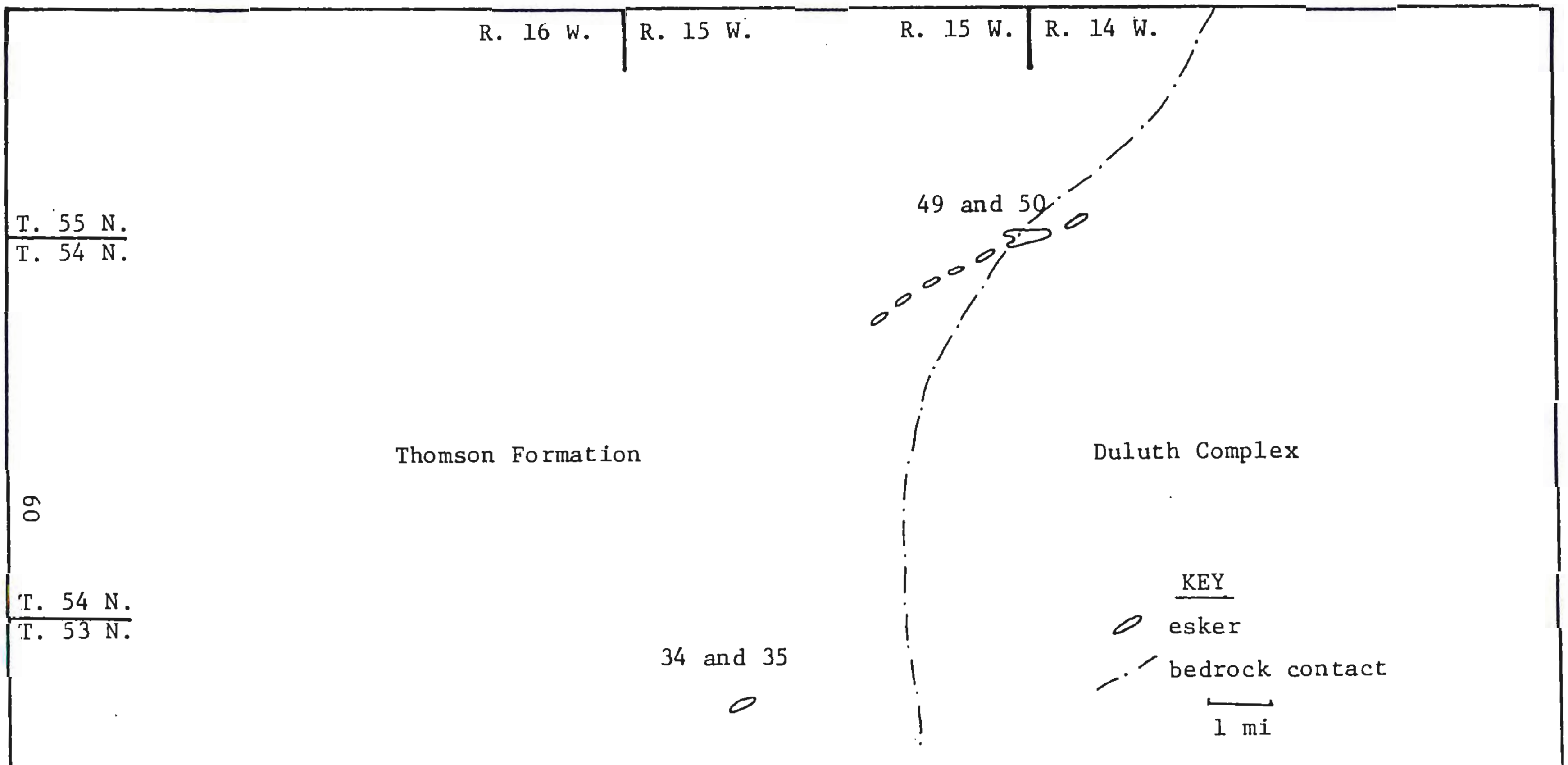


Figure 13. Relationship between eskers, bedrock lithology, and stone count locations near a bedrock contact between the Duluth Complex (east side) and the Thomson Formation (west side).

The counts labeled 49 and 50 are from an esker that lies very close to the bedrock contact, and results show some slate in the boulder- and pebble-size fractions. These percentages, while low, are still higher in slate than up-ice stone counts (over the Duluth Complex), so the slate is most likely derived from the underlying Thomson Formation. The close agreement between the slate percentage in the boulders (16) and the pebbles (17) gives little indication as to which size fraction would be a better provenance indicator.

Counts 34 and 35 are from a short bead segment further down-ice than counts 49 and 50, and also further down-ice from the bedrock contact. The slate percentage in the pebble fraction (15) is much higher than in the boulder fraction (4).

It should be noted that the boulders in both eskers show a higher percentage of gabbro plus granophyre than the pebbles do, thereby giving a better indication of the proximal up-ice bedrock lithology. The same relationship (of boulders giving a better idea about the up-ice lithology, using gabbro and granophyre as an indicator) does not hold true when slate is used as an indicator. There are more pebbles of slate than boulders of slate. This could be a result of the slate possessing a higher degree of "crushability" than the intrusive rocks, and thereby having an increased rate of comminution.

Superior Lobe Deposits: The 16 stone counts done in the Superior lobe drift include 8 pebble counts (2 esker, 1 till, and 5 outwash), and 8 boulder counts (5 esker, 1 till, and 2 outwash). See Figure 14.

LITHOLOGY	1 PC esker	2 BC esker	3 BC till	4 PC out.	5 PC out.	6 BC out.	7 PC esker	8 PC out.	9 BC esker	10 PC out.	11 BC out.	12 PC till	13 PC out.	14 BC esker	15 BC esker	16 BC esker
granophyre	2	4	14	–	–	27	9	–	10	2	–	5	6	33	51	64
basalt	31	33	21	53	43	49	26	23	10	27	2	54	59	44	17	2
gabbro	15	9	15	6	8	6	7	14	18	13	14	15	21	15	27	32
sandstone	19	23	2	15	7	2	19	15	7	7	6	2	1	2	–	–
granite	4	5	14	8	12	19	9	17	18	10	27	7	–	3	1	1
gneiss	–	2	10	–	4	–	4	4	6	1	5	–	2	–	1	1
black slate	12	24	24	4	14	2	6	4	31	2	14	2	–	3	–	–
greywacke	13	–	–	6	–	–	12	12	–	17	6	3	9	–	–	–
iron formation	–	–	–	–	–	–	–	–	–	–	2	–	–	–	–	–
quartzite	2	–	–	3	2	–	–	–	–	–	–	–	–	–	–	–
conglomerate	–	–	–	–	–	–	–	–	–	2	3	–	–	–	–	–
metavolcanics	–	–	–	1	–	–	–	–	–	11	–	–	–	–	1	–
diabase	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–
agate	–	–	–	–	–	–	–	2	–	6	–	2	–	–	–	–
rhyolite	–	–	–	–	6	–	2	3	–	2	2	4	2	–	–	–
unknown	2	–	–	4	4	–	6	6	–	–	–	6	–	–	–	–

Table 4. Results of the stone counts from the Superior lobe drift. PC= pebble counts, BC= boulder counts, Out= outwash. Sample numbers correspond to locations on Plate 1 (back folder).

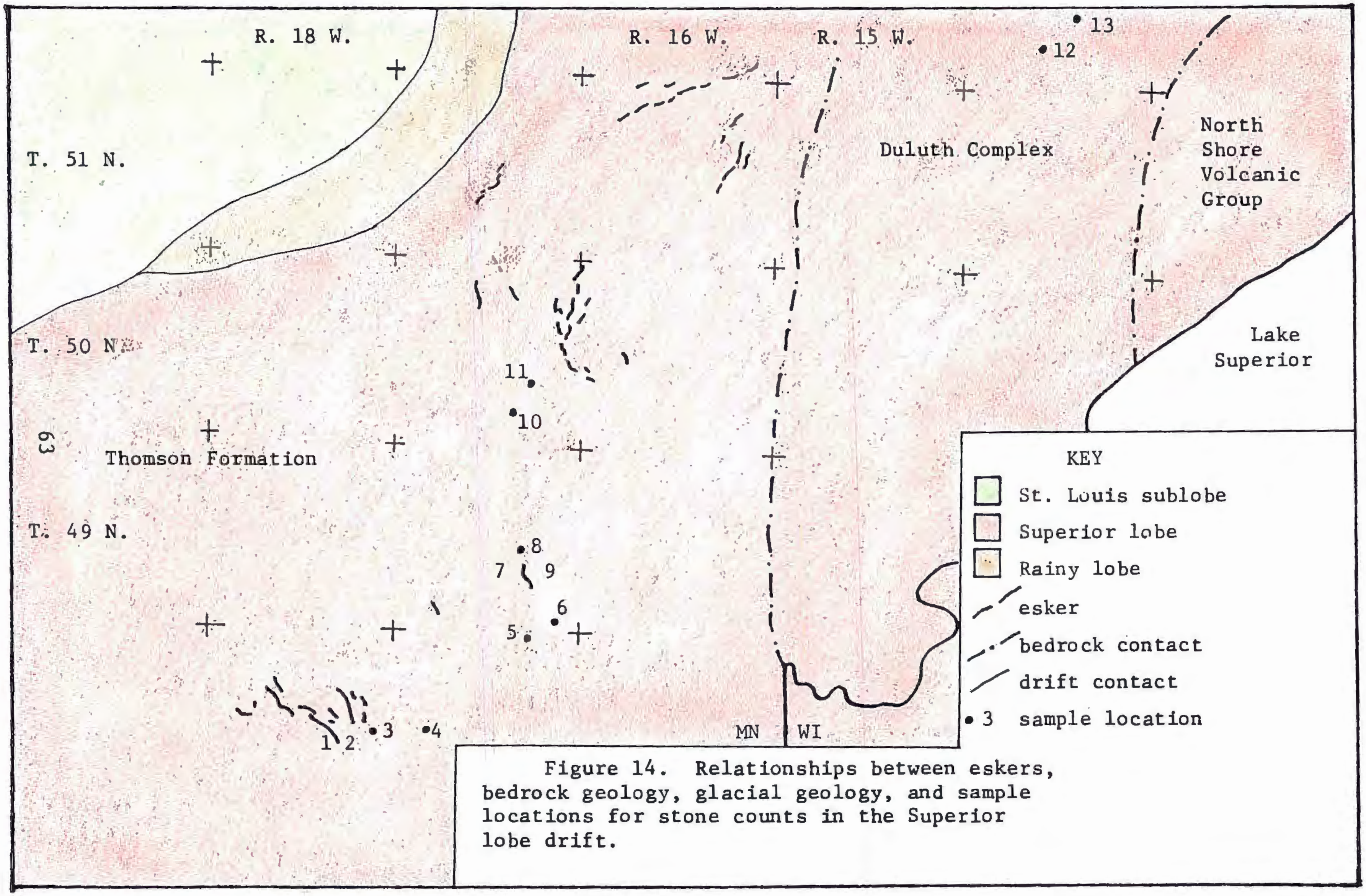


Figure 14. Relationships between eskers, bedrock geology, glacial geology, and sample locations for stone counts in the Superior lobe drift.

These counts include the Cloquet esker, and other eskers deposited during the Split Rock Phase, various till and outwash counts, and counts done on the Four Mile Lake esker in the northeastern corner of the study area.

The major lithologies incorporated into the Superior lobe drift include basalt, sandstone, and gabbro, along with a number of minor lithologies (such as agate, and diabase). Sandstone is more common in the pebble counts than in the boulder counts and appears in nearly equal proportions in both the till and the glaciofluvial material. Boulders of sandstone are easily broken down into smaller pieces and, as a result, are not often seen in the boulder fraction.

Slate and greywacke of the Thomson Formation underlie the Split Rock phase eskers. This lithology appears in the boulders and pebbles of the eskers with a range from 24 to 31% for the boulders, and 4 to 12% for the pebbles. A wider range is seen in the outwash-- from 2 to 14% for both pebbles and boulders. From these results, it seems boulders in the eskers give the best indication about the underlying bedrock. Boulder counts in the till in this area show 24% slate, very similar to the percentage seen in the esker. This relationship is nearly duplicated by the percentages of the dominant esker lithologies of gabbro and basalt, which could indicate the esker material is derived either from englacial material, or subglacial erosion of the underlying till.

The counts done on the Four Mile Lake esker (counts 14, 15, and 16) located on the Lake-Cook County border (T. 60 N., R. 5 W.) are especially interesting. The esker was deposited near the junction between the Rainy lobe and the Superior lobe. It is difficult to tell which lobe of ice deposited the esker, although Sharp (1953) concluded it was left by the Rainy lobe. The topography which this esker crosses varies from an elevation of 1750 feet on the west end to 1670 feet at the east end of the esker in Four Mile Lake, and the meltwater that deposited it flowed from east to west, up the topographic gradient under hydrostatic pressure.

The esker was chosen for investigation because it lies across a well-established contact between two distinctive rock types of the Duluth Complex. The western segment of the esker is underlain by pink-colored granophyre, whereas dark-colored gabbro comprises the bedrock on the eastern end. The sketch in Figure 15 shows these relationships.

From east to west, in the inferred direction of meltwater flow, the percentage of granophyre increases from 33 to 51 to 64, while the percentage of basalt decreases from 44 to 17 to 2. The gabbro increases from east to west, ranging from 15 to 27 to 32.

The results of the boulder counts appear somewhat anomalous with respect to the bedrock lithologies. If the meltwater stream that deposited the esker flowed from east to west, then the granophyre should not even be seen in the esker. However, granophrye constitutes over 50% of the boulder counts at two locations (64% and 51% at locations 16 and 15 respectively).

The best explanation for these anomalous results would require a brief review of the glacial history of the area. The Superior lobe incorporated gabbro- and granophyre-rich Rainy lobe deposits into its load as it

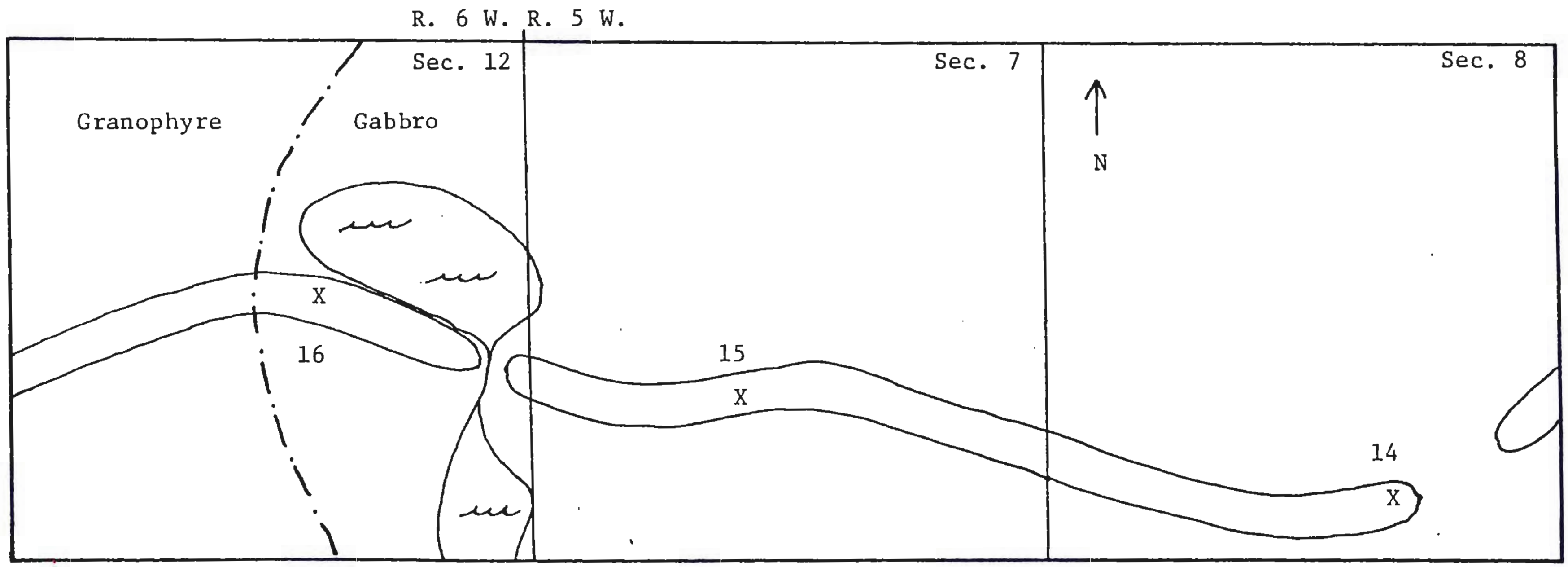


Figure 15. Four Mile Lake esker, bedrock lithology, and locations of stone count sites. T. 60 N. Each square is one section, or one square mile.

advanced up and out of the Lake Superior basin. Blending of the two tills, and subsequent melting of the Superior lobe has left an esker with lithologies that are representative from each lobe (gabbro and granophyre from the Rainy lobe, and relatively unaltered basalts from the Superior lobe). This blending of the tills would be concentrated in the lower portions of the advancing ice sheet and contribute to the basal ice debris. Since the material in the esker is most likely derived from the basal ice debris, as shown by stone counts done further south, than the underlying bedrock probably made little, if any, contribution to the esker.

St. Louis Sublobe Deposits: There were 12 stone counts done in the drift deposited by the St. Louis sublobe including 6 pebble counts (3 esker, 2 till, and 1 outwash count), and 6 boulder counts (2 esker, 3 till, and 1 outwash count). See Figure 16.

Deposits of the St. Louis sublobe are characterized by a reddish-brown, fine-textured drift that contains sparse clasts of Paleozoic limestone and Cretaceous Pierre Shale from the Winnipeg lowland, but none of these were seen in any of the counts. It is unlikely that either of the lithologies would survive much transport in a meltwater stream as they are fairly soft and break down easily. Pieces of limestone and shale were seen during the course of the field work, but none were encountered during the stone counts. Granite boulders, with a percentage range from 38 to 50 in the till, and 41 to 57 in the esker appear to be

LITHOLOGY	17 PC esker	18 BC esker	19 PC till	20 PC till	21 BC out.	22 BC till	23 PC out.	24 PC esker	25 BC esker	26 PC esker	27 BC till	28 BC till
granophyre	2	-	2	2	8	9	11	5	2	-	-	10
basalt	15	15	15	15	33	3	38	24	1	19	8	10
gabbro	10	6	12	12	44	28	24	7	3	9	30	22
sandstone	1	-	15	15	-	-	2	6	-	6	-	-
granite	23	41	29	29	5	43	5	27	57	27	50	38
gneiss	5	14	5	5	-	6	6	10	9	12	6	8
black slate	8	8	2	2	-	-	3	-	19	3	-	2
greywacke	21	12	18	18	8	7	12	11	-	14	4	4
iron formation	-	-	-	-	-	-	-	-	-	-	-	2
quartzite	2	-	-	-	-	-	-	-	-	-	-	-
conglomerate	-	-	-	-	-	-	-	-	-	-	2	2
metavolcanics	9	4	-	-	-	11	2	2	1	2	-	-
diabase	-	-	-	-	-	-	-	2	-	-	-	-
agate	-	-	-	-	-	-	-	1	-	-	-	3
rhyolite	-	-	-	-	-	-	-	-	-	-	-	-
unknown	4	-	2	2	2	-	-	4	8	8	-	-

Table 5. Results of the stone counts from the St. Louis sublobe drift. PC= pebble counts, BC= boulder counts, Out= outwash. Sample numbers correspond to locations on Plate 1 (back folder).

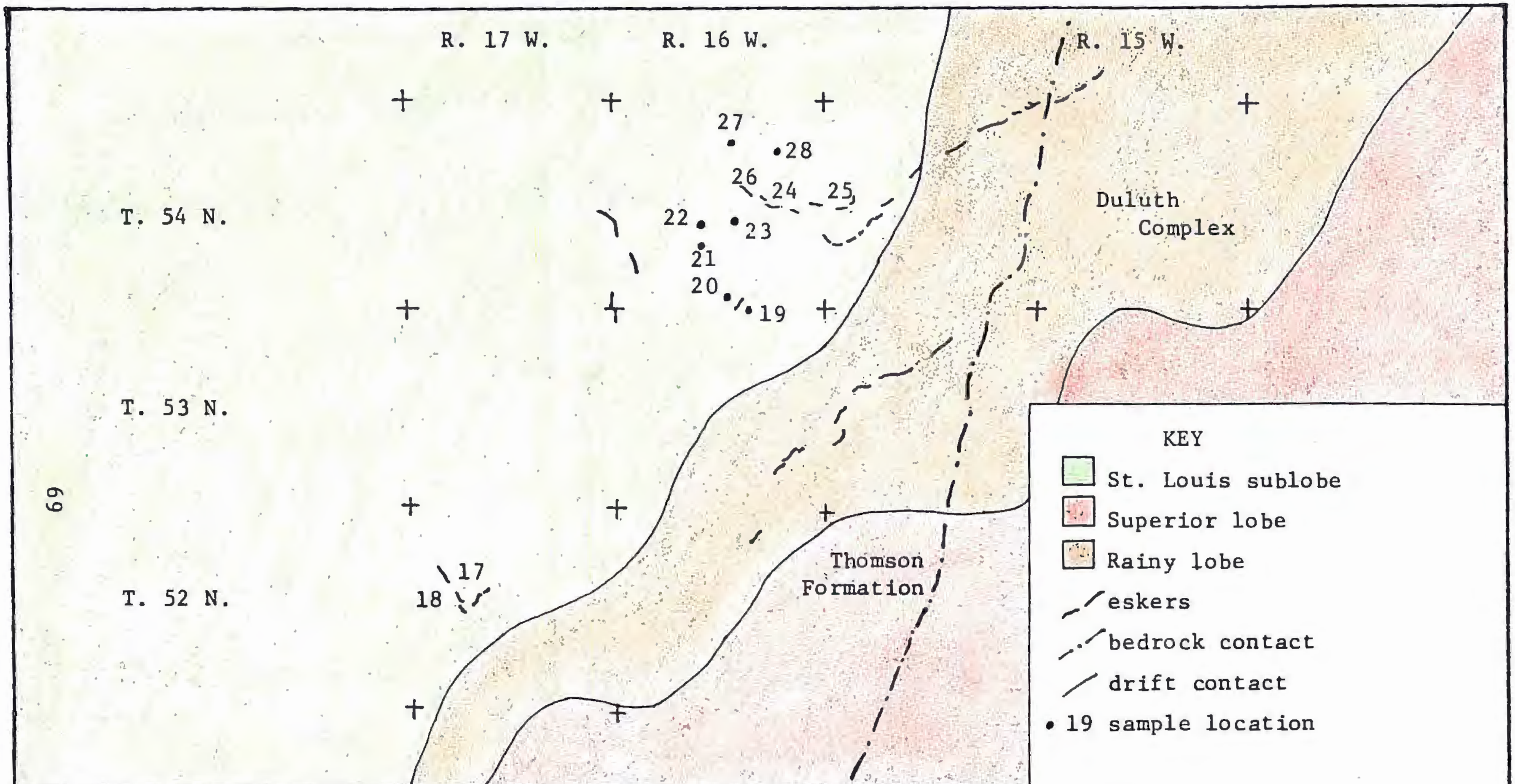


Figure 16. Relationships between eskers, bedrock geology, glacial geology, and sample locations for stone counts in the St. Louis sublobe drift.

good indicators of up-ice bedrock lithology. Granite pebbles show the same results, although the percentages are lower (23 to 27 in the eskers, and 29 in the till).

The high percentages of gabbro and basalt in the boulders and pebbles of the esker, outwash, and till counts (3 to 44 for gabbro, and 1 to 38 for basalt) could indicate a blending of the tills as the St. Louis sublobe overrode the gabbro-rich Rainy lobe deposits in the area. Metasediments (greywacke and black slates) are also fairly common in the counts, ranging from 4 to 21% in the boulder and pebble size.

The granite component was probably derived, originally, from the southwestern end of the Giants Range batholith, while the metasediments could be from the Thomson (Virginia) Formation.

The lack of a high percentage of slate and greywacke from the underlying bedrock, combined with the relatively high percentage of basalt and gabbro, indicates the origin of the esker material was either englacial material (most likely the basal ice debris), or was eroded by the meltwater stream from the underlying, possibly blended, till. Meltwater erosion of subglacial bedrock does not seem to be a source for the esker material.

Summary

The stone counts appear to be a fairly quick and easy way to examine the eskers and obtain information about the bedrock. Results show the boulders, in almost every case, gave a better indication than do the pebble counts about the up-ice lithology, as the pebble population was often diluted (percentages of a given lithology were not as high in the pebble fraction as in the boulder fraction). In one case, (St. Louis sublobe counts) the underlying bedrock of slate and greywacke was not as well represented in either boulder or pebble counts as the more long-distance transported granite clasts were. A possible explanation for this case is that the St. Louis sublobe may not have been in an eroding mode and may not have even touched bedrock due to the underlying blanket of Rainy lobe drift. In another case, (counts 49, 50, 34, and 35) the pebble fraction gave a better indication of the underlying bedrock.

One consistent fact shown by the stone counts is that the percentage of a given lithology in the esker, usually in the boulder fraction and often in the pebble fraction, has a similar percentage in the till. This, combined with evidence from the St. Louis sublobe counts, where the underlying bedrock is poorly represented in the boulder and pebble fractions, indicates the material in the esker was derived from either the englacial load, or by meltwater erosion of the underlying till. A meltwater-bedrock erosion source is not indicated in any of the results, and therefore the esker material is probably derived from the englacial load, and more specifically, derived from the basal ice debris. The best evidence for this is from the similar lithologies between the clasts in the eskers and in the neighboring tills. It is further supported at locations where one lobe of ice overrode deposits from a previous lobe such as the Four Mile Lake esker, and eskers from the St. Louis sublobe. The clast lithologies in eskers at these locations reflect drift input from at least 2 different lobes of ice.

HEAVY MINERAL STUDIES

General statement

Heavy minerals from glacial drift have been studied by many workers to see if questions about provenance and drift prospecting could be answered.

Trefethen and Trefethen (1944) separated heavy minerals from the Kennebec Valley esker, near Augusta, Maine. Their study gave no positive information about the length of transport because the same general mineral assemblage persisted throughout the entire length of the esker. An increase of local material was noted 3 to 8 miles down esker from the point where the esker crosses bedrock contacts of contrasting lithology. They concluded 5% or less of the pebbles counted had been carried more than 50 miles. They observed that fragments of the Hallowell granite appear at a point where the esker, which lies wholly on schist, passes nearest the outcrop of the granite, a distance of about 2 km.

A comparison of the heavy mineral assemblages in the Lower Peninsula of Michigan by Dworkin and others (1985) allowed them to differentiate three different Late Wisconsinan tills. The assemblages could also be associated with different source areas on the Canadian Shield.

Lee (1965, 1968) studied the nearly continuous, 250 mile long Munro esker, named after the township of Munro, Ontario, because it passed through the Kirkland Lake gold camp. The esker crosses extensions of known gold-bearing structures, the shear zone of the Upper Canada Mine, and the Larder Lake fault. This geologic control gave known sources for the gold abundance peaks in the esker.

The 1.3 cubic feet of sample they collected was field-checked for the concentration of dunite, gold, and pyrope. Distances could then be measured between the peak abundances of distinctive minerals and rock fragments. This led to the concept of the transport distance "k" defined by Lee (1965, p. 7) as "The displacement distance between the bedrock source and the position of peak abundance for any component is defined as the transport distance "k" " (Figure 17).

Lee determined the transport distance "k" from two different sources was 8 ± 2 miles for dunite and 2 ± 2 miles for gold grains. Pyrope peaks were used in a later study. He concluded (1965, p. 1) from his results that "the data are geologically reasonable and encouraging."

In a later study by Lee (1968) on the same esker, the previously mentioned pyrope grains were used to discover a kimberlite dike. Distribution curves of gold particles and pyrope grains showed a common peak distribution, and since both were subjected to the same displacement vector, then both were thought to have the same general source area. Detailed study of the most promising rocks in the Upper Canada Mine led to the discovery of a Late Jurassic dike cross-cutting the Precambrian rocks and the eventual classification of the dike rock as a kimberlite. This is important to prospectors because kimberlites occur not only in groups but also because there is a known association of some kimberlite bodies with diamonds.

During the summer of 1984, 97 bulk sand and gravel samples were

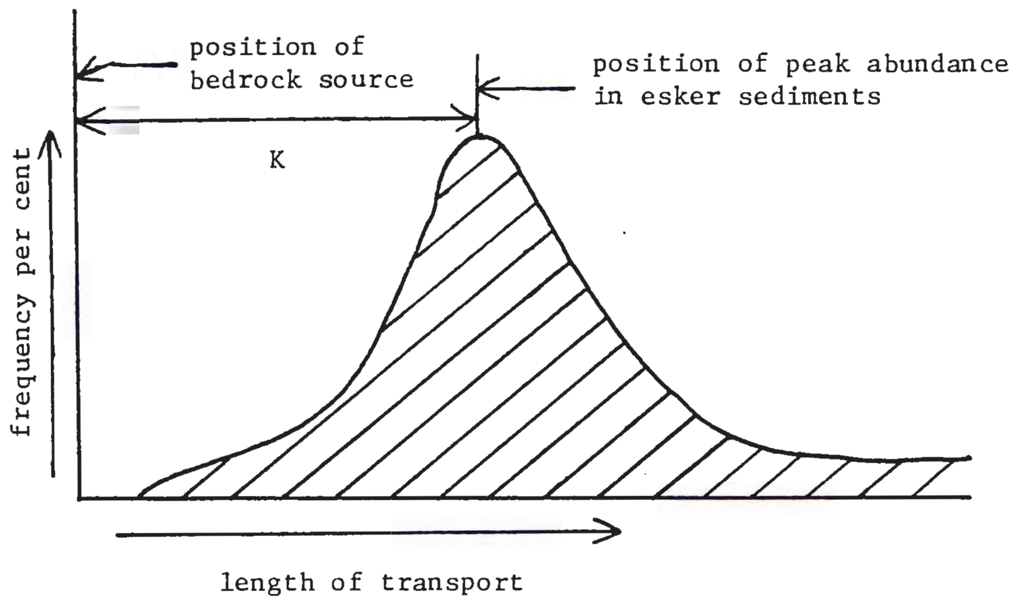


Figure 17. Hypothetical frequency distribution illustrating the concept of the transport distance "K", after Lee (1965).

collected from 59 different sites in northeastern Minnesota that included 53 eskers, 4 drumlins, and 2 outwash plains. Approximately 5 pounds of the finest-grained material available were also collected at each site to be assayed in addition to the bulk sample. The samples were stored, concentrated, and split for analyses that included both assaying for base metals, precious metals, and other indicator elements, and X-ray diffraction studies. A portion of the X-ray diffraction split was used for the optical studies discussed in the next section. A flow chart summarizing the sample processing steps is shown in Figure 18.

Ore minerals and various associated alteration minerals were targeted as potential indicators of up-ice mineralized bedrock, including pyrope, magnesian ilmenite, chrome diopside, diamond, scheelite, pyrite, pyrrhotite, chalcopyrite, sphalerite, arsenopyrite, barite, molybdenite, apatite, tourmaline, galena, fuchsite, chromite, magnetite, copper, gold, silver, platinum group minerals (platinum, palladium, rhodium, iridium, ruthenium, osmium), pyrochlore, and idocrase. The sample numbers, locations, and weights are given in Appendix I, while the locations and selected geochemical anomalies are displayed on the base map in the back folder (plate 1).

Jigging Procedures

The first step in concentrating the bulk sample was to shovel the 600-800 pound sample onto the jig, which was covered by a grill having a

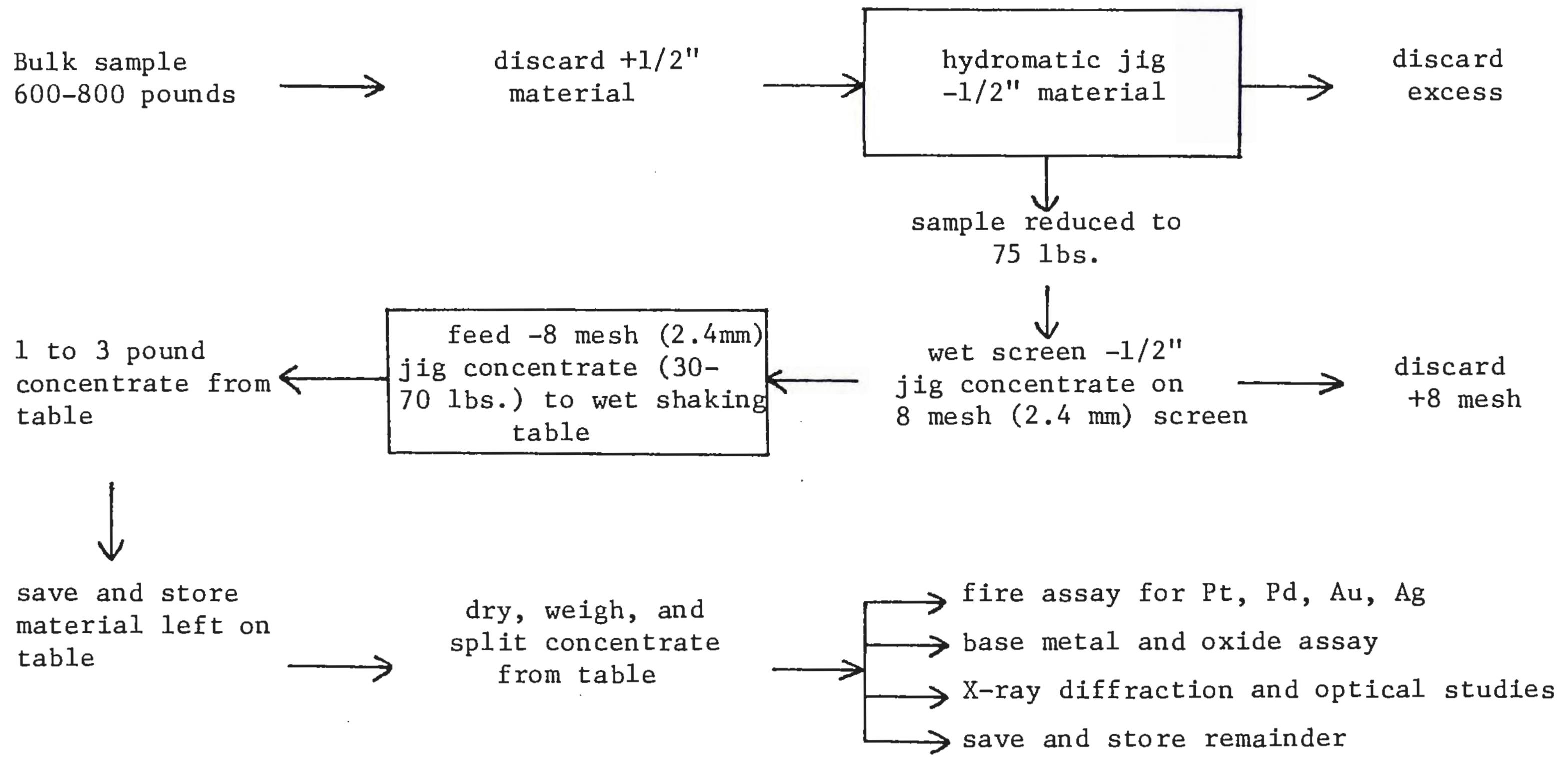


Figure 18. Flow chart summarizing bulk sample processing steps, after Martin (1985).

1/2 inch spacing between its parallel bars. The +1/2 inch material was discarded, while the finer fraction (-1/2 inch) was jigged and concentrated by shaking and washing with water (Figure 19).

This initial processing step reduced the bulk sample to around 75 pounds, which was then further concentrated by washing through an 8 mesh (2.4 mm) screen. The material greater than 8 mesh (2.4 mm) was discarded. The -8 mesh (2.4 mm) concentrated sample, which weighed between 30 and 70 pounds, was run across a wet shaking table where it was further concentrated to a 1-3 pound sample of the heaviest fraction.

The final concentrate was dried, weighed, and split for analysis. Fire assay was used to determine platinum, palladium, gold, and silver contents in a 30 g split, while base metals and oxides were assayed from another split. Approximately 100 g was used for X-ray diffraction studies, and the remainder was stored.

Test samples were processed on the jig and shaker table using a known amount of galena and magnetite in three different samples to quantify its efficiency. Galena grains, -65 mesh (0.23 mm) and +150 mesh (0.1 mm), were added to two separate samples and processed in the usual manner through the jig and shaker table and the results were analyzed. Calculated results (Martin, D.P., 1985, pers. comm.) showed that 76.6% and 79.2% of the galena grains were recovered. The magnetite used was medium- to fine-grained and processed through one sample. Additional calculated results showed only 9.5% of the magnetite was recovered. The majority of the magnetite was found in the jig tails rather than on the wet shaking

Figure 19. Photograph of hydromatic jig during processing of bulk samples. Orange barrels were used to store bulk samples.

table. The large difference between the recovered amounts of galena and magnetite seems to indicate that specific gravity plays a more important role than does grain size in the final concentrate. The specific gravity of galena is 7.5 and magnetite is 5.18. This is important as many of the target minerals have specific gravities that are less than that of magnetite.

X-ray Diffraction

Procedures

The 100 g split used for the X-ray diffraction studies was processed in the following way: The samples were split again into a smaller sample that was easier to use (about 10 g). The magnetite present in the final split was removed with a hand-held magnet, and weights were recorded.

A small amount (1-2 g) of this magnetite-free sample was powdered with a silica mortar and pestle, and this powder was scanned by the X-ray diffractometer. The powder was placed on a 2 inch square glass slide, mixed with a few drops of water to produce a slurry, spread as evenly as possible over the glass slide, and allowed to dry. When the sample was dried, it would remain adhered to the slide during analysis. The sample was run at 2 degrees per minute from 5 to 60 degrees. This range allowed the major peaks of most of the anticipated minerals to be seen if they were present. The resulting charts were then examined using a search manual (Joint Committee on Powder Diffraction Standards, 1974), and mineralogies were recorded.

Results

Appendix II shows the minerals that were determined to be present in each sample that was X-rayed. The most frequently identified minerals included quartz, clinopyroxene, orthopyroxene, hematite, ilmenite, and plagioclase. The question mark (?) that follows some of the mineral names implies that identification was uncertain.

Fifteen samples were concentrated with tetrabromoethane for optical studies and are discussed in the next section. Six of these were X-rayed to compare results before and after heavy mineral concentration. The X-rays before separation showed peaks for quartz in each sample, and plagioclase in most of them. The X-rays run after separation gave slightly better results, although no more than two or three minerals could be identified. Table 6 lists the results.

The results from the X-ray diffraction studies were disappointing, in that it was impossible to identify most of the minerals present. The few minerals that were identified had enough individual peaks so that a combination of two or three of them would effectively mask the other mineral peaks. Identification of other minerals was further complicated by the presence of solid solution minerals such as the feldspars and pyroxenes that had a range of peaks. Specific minerals were identified if possible, including diopside, hornblende, and hypersthene; otherwise they are listed more generally as pyroxene, amphibole, or plagioclase.

It is difficult to see any type of a trend or pattern that could be

SAMPLE NUMBER	MINERALS PRESENT BEFORE CONCENTRATION	MINERALS PRESENT AFTER CONCENTRATION
RIL-3	quartz diopside ilmenite	amphibole diopside ilmenite
JR-1	quartz ilmenite plagioclase	diopside ilmenite hornblende
BLRNE-1	quartz plagioclase	diopside amphibole
BLRNE-3	quartz hematite pyroxene	hypersthene amphibole augite
TDF-1	quartz pyroxene	diopside ilmenite amphibole
MC-1	quartz ilmenite (?) plagioclase	diopside ilmenite

Table 6. Minerals identified from selected samples by X-ray diffraction before and after concentration with tetrabromoethane.

used to assist a prospecting program based on these results. Furthermore, conclusions about provenance for esker material cannot be drawn with any certainty.

Optical Studies

Procedures

A total of 15 samples were further examined by optical methods. These included 6 from the Rainy lobe drift (4 eskers and 2 drumlins), 5 from the Superior lobe drift (3 eskers, 1 drumlin, and 1 outwash sample), 2 from eskers deposited by the St. Louis sublobe, and 2 bedrock samples. The 13 drift samples used for the optical studies were part of the final 100 g split of jig-concentrated material that was left over from the X-ray diffraction studies. The locations for the samples are shown in Figure 20.

The fifteen samples of heavy minerals were separated with tetrabromoethane following standard laboratory procedures, using the 0.5 mm fraction. The light fraction was discarded and a portion of the heavy fraction was mounted on a glass slide with Canada balsam. Another portion of the heavy mineral fraction was powdered and X-rayed for comparison purposes.

The heavy mineral mounts were examined under the petrographic microscope and three hundred grains were point-counted in each mount. No

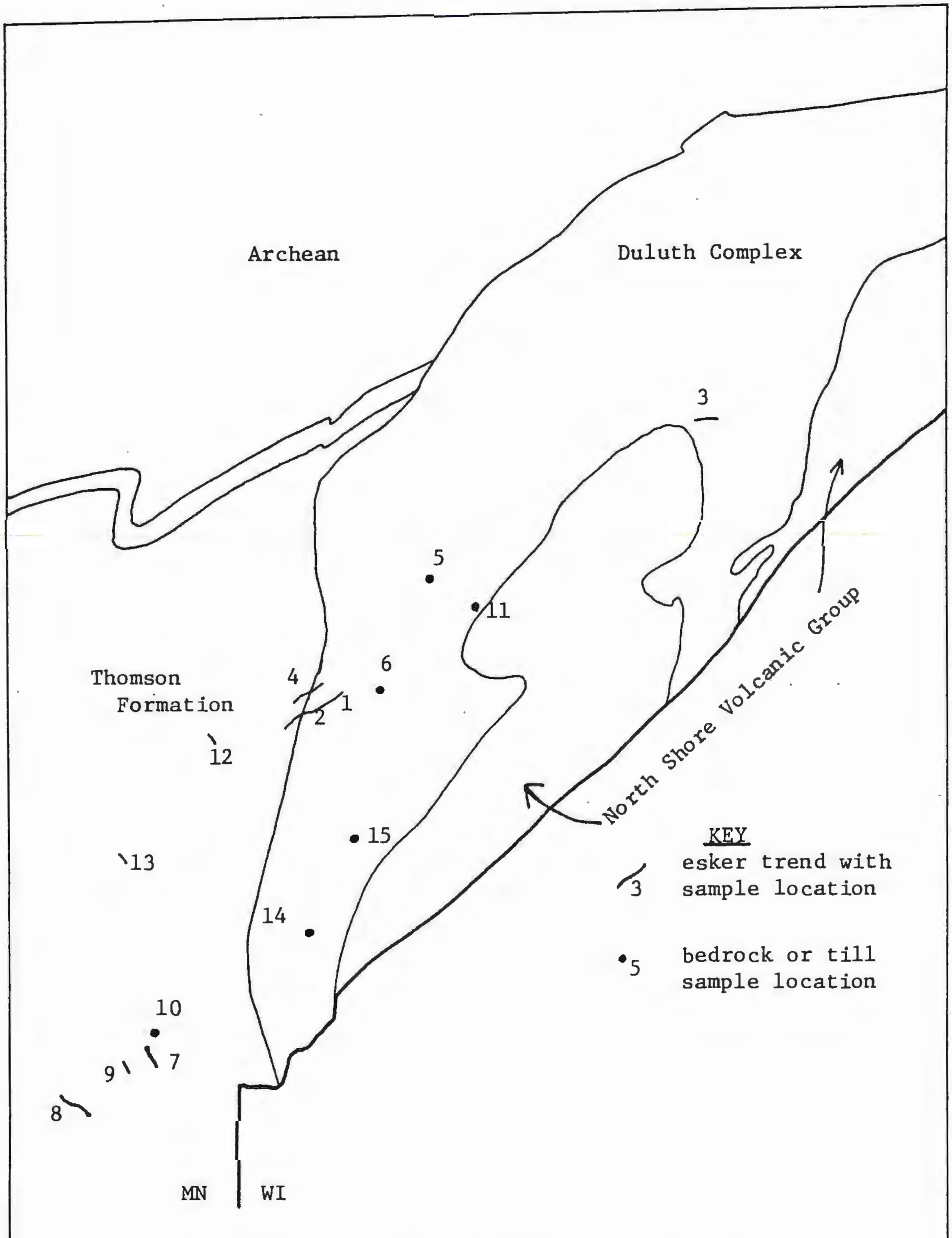


Figure 20. Generalized geologic map showing sample locations for heavy mineral studies by optical methods. Also shown are selected esker trends.

heavy minerals were found in two bedrock samples from the Thomson Formation. Heinrich's text (1985) was used to aid in the identification of unknown minerals.

Mineral Descriptions

Several different minerals were identified with the petrographic microscope and a brief description of each follows. They are listed in alphabetical order.

Amphibole (anthophyllite). This is usually colorless, but some grains show brown to gray pleochroism. It is commonly prismatic, and shows parallel extinction and high relief. The grains are subangular to subrounded.

Apatite. The few apatite grains seen are fairly well rounded, clear, and have few inclusions, although some grains from the St. Louis sublobe sample have numerous inclusions (sample numbers 12 and 13).

Clinopyroxene. The most common grains in the mounts are the brown to dark brown clinopyroxene. Most grains are altered to various stages, commonly with opaque minerals present along cleavage planes. They are typically prismatic, and are most likely augite.

Epidote. These grains are subangular to subrounded, with high relief and characteristic birefringence. Most grains contain a few dark inclusions and would not go totally extinct.

Garnet. Most of these grains are clear or light pink with few to several inclusions. They range from subangular to round. Two of the grains seen in sample number 10 are prismatic in shape, and could have been broken along some crystallographic weakness or fracture plane. The light pink color of the grains could be indicative of the spessartite variety (Heinrich, 1965, p. 60).

Hornblende. The color of the hornblende ranges from light green to dark green. Grains are prismatic, pleochroic, show inclined extinction, and are subrounded.

Hypersthene. The prismatic hypersthene grains show the characteristic pink to green pleochroism, high relief, parallel extinction, and appear to be slightly altered. Parallel extinction was also seen.

Olivine. High relief, fractured grains, and characteristic conoscopic figures are displayed by the olivine grains. Most are subrounded.

Orthopyroxene. Most of the orthopyroxene grains that are not hypersthene are probably enstatite. They are prismatic, subrounded, show parallel extinction, and have moderate alteration.

Rutile. Only a few grains of rutile are present and these are characterized by a dark red color, high relief, and prismatic shape. They are subangular to subrounded.

Sphene. The grains of sphene are mostly subangular, yellow to brown in color, and contain numerous inclusions. Some alteration was seen on most of the grains and most also fail to show complete extinction. A few of the grains are clear to honey yellow, and show little alteration.

Tremolite. Clear, prismatic or fibrous grains that are subangular to subrounded and show inclined extinction were identified as tremolite.

Zircon. The zircons are well rounded, prismatic, clear, with high relief and parallel extinction.

Results

The optical studies allowed a much better indication of minerals present in the samples than did the X-ray process. It was much quicker and easier to identify minerals under the microscope than it was to identify them with the X-ray charts, and the degree of confidence was higher with the microscope. The results of the heavy mineral point-counts are displayed in Table 7.

The most dominant minerals in each of the samples from the bedrock and the Rainy lobe and Superior lobe eskers include clinopyroxene (augite), orthopyroxene (enstatite), and sphene. Minor amphiboles, epidote, garnet, rutile, hornblende, and olivine were also seen. The most common minerals found in the esker deposited by the St. Louis sublobe include clinopyroxene, orthopyroxene, sphene, garnet, and hornblende along with lesser amounts of hypersthene, epidote, and rutile.

The opaque minerals, primarily magnetite, ilmenite, and hematite, were not included in the results.

SAMPLE NUMBER	cpx	sphene	enstatite	hornblende	hypersthene	garnet	anthophyl.	tremolite	epidote	rutile	apatite	olivine	zircon	unknown	collected from/ lobe
1.	41	28	11	4	–	1	2	5	2	–	1	1	–	4	esker/ Rainy
2.	52	28	6	10	–	–	–	1	–	–	–	–	–	3	esker/ Rainy
3.	57	26	7	5	2	–	–	–	–	–	–	–	–	–	esker/ Rainy
4.	25	30	8	4	2	5	3	6	7	2	2	–	–	6	esker/ Rainy
5.	39	27	10	11	–	2	–	2	–	–	–	–	–	9	drumlin/ Rainy
6.	42	23	5	6	4	6	–	–	6	4	–	–	1	3	drumlin/ Rainy
7.	44	32	4	10	2	3	–	2	–	–	1	–	–	2	esker/ Superior
8.	45	30	6	8	2	–	–	3	–	2	–	–	1	3	esker/ Superior
9.	35	26	2	7	4	8	–	–	4	–	5	4	1	4	esker/ Superior
10.	47	32	–	8	8	3	–	–	–	–	–	–	–	2	drumlin/ Superior
11.	36	35	14	3	2	2	–	–	–	2	1	–	–	5	outwash/ Superior
12.	20	19	10	19	6	15	–	–	3	2	1	–	–	5	esker/ St. Louis sub.
13.	22	18	2	5	3	42	2	–	–	3	–	–	–	3	esker/ St. Louis sub.
14.	83	4	10	–	–	–	–	–	–	–	–	–	–	3	bedrock
15.	58	24	14	–	–	–	–	–	–	–	–	–	–	4	bedrock

Table 7. Results of point counts for 15 samples, in per cent. 300 grains counted per sample.

Geochemistry

A split of the final 1 to 3 pound concentrate was assayed for precious metals, base metals, and oxides by Bondar-Clegg in Vancouver, British Columbia. The chemical analyses will not be discussed in detail but some interesting points will be mentioned.

Selected anomalies and their sample locations are displayed on Plate 1. Several interesting anomalies were seen in splits from both the heavy mineral concentrate (HMC) from the bulk sample, as well as the fine grained (fine sand, 0.250 mm to silt sized, 0.016 mm) material collected from each sample site (S/C).

Visible gold was seen in one sample, RIL-3, during preparation for analysis by Bondar-Clegg. They noted that "gold was found in the +150 mesh (0.1 mm) fraction after screening, and calculated into the total." (Martin, D.P., 1985, pers. comm.).

Provenance for this gold is difficult to determine but it was found in a Superior lobe esker whose material may have been partly derived from the underlying Rainy lobe drift. The Rainy lobe may have picked up the gold as it advanced across the Vermilion district, or further to the northeast in Ontario.

Summary

The results of the X-ray diffraction studies were somewhat disappointing for the amount of time invested in preparation, running the samples, and interpretation. It should also be noted that there may be some sampling problems since only 0.0003% of the total bulk sample was analyzed by X-ray diffraction. If a certain mineral is going to show as peaks on the X-ray charts then a minimum of 5% of the sample must be that mineral (Green, J.C., 1984, pers. comm.). If 5% of the 100 g split used in the X-ray diffraction studies were gold, then the same proportion would be in the 1 to 3 pound final concentrate (if the splitting process were done correctly). This would correspond to an anomalously high value of gold present in the sample. It seems likely that many of the target minerals would not be present in such high concentrations, and therefore, would not be detected during X-ray analysis.

It would be difficult to use any of the minerals identified by X-ray diffraction as either provenance or economic indicators. They are all fairly ubiquitous minerals that can commonly be found in the underlying bedrock.

Optical examination of the heavy mineral mounts appears to be a more favorable technique as the minerals can be identified more easily and confidently.

Garnets found in the Rainy lobe deposits infer a metamorphic source area for some of the sediments, but they comprise a very small percentage and most likely traveled a considerable distance (tens of miles). The majority of the heavy minerals, such as the pyroxenes, feldspar, and sphene, are derived from basic igneous rocks such as the Duluth Complex, while the minor minerals, like garnets and amphiboles, could have been derived from a more felsic source. The Giants Range batholith and other intrusions further north, as well as the Archean greenstone belts, could be potential sources. The fairly close agreement between the heavy minerals in the esker and in the till could infer that the till was the source from which the meltwater stream derived its sediment load.

The suite of minerals from the St. Louis sublobe eskers shows a mixed source. The garnet was most likely derived from a metamorphic source area such as the greenstone belts of northwestern Minnesota. The pyroxenes and sphene may have been derived from the various intrusive rocks such as the southeastern end of the Giants Range, and other more mafic intrusions further northwest, or possibly from reworking of an earlier glacial drift which had overridden gabbroic rocks, such as the Rainy lobe.

It is important to note that the high percentage of garnet in sample 13, and to a lesser degree in sample 12, is much higher than the garnet percentages from either the Rainy lobe drift or the Superior lobe drift.

The heavy minerals from the Superior lobe (samples 7 through 11) include a high number of mafic minerals that include clinopyroxene, sphene, and enstatite, as well as a smaller number of minor minerals such as garnet, epidote, rutile, and olivine.

There is little difference between the heavy mineral population in the Superior lobe and in the Rainy lobe, and two factors could explain this: (1) both lobes of ice overrode large areas of mafic bedrock that contributed many of the minerals seen in the glacial deposits load, and

(2) blending of the two tills as the Superior lobe overrode deposits left by the Rainy lobe. The similarity between heavy minerals in the Superior lobe eskers and the till could imply, as seen in the Rainy lobe drift, that the esker material was derived from either the englacial load, or by meltwater erosion of the underlying drift.

While the Superior lobe and Rainy lobe drifts have similar populations of heavy minerals, they can be differentiated from the St. Louis sublobe drift, primarily due to the high percentage of garnet found in the latter.

VI. CONCLUSIONS

GENERAL STATEMENT

A relatively quick, easy technique that uses the glacial drift as a prospecting tool to help gather information about the underlying bedrock would be beneficial to companies involved in mineral exploration in heavily glaciated areas. This project originated to assess the value of heavy minerals in eskers as one such drift prospecting technique.

It was expanded to develop a better understanding about the way eskers form, and about the source of rock and mineral fragments in the eskers in northeastern Minnesota. Some of these questions have been answered through field studies and laboratory work.

Two main types of eskers have been recognized that can be differentiated by their morphology, sedimentology, and origin. The shorter, continuous eskers were formed when an ice sheet was stagnant, or nearly stagnant, and meltwater flowed through a tunnel and deposited sediment in the tunnel as well as onto an adjacent outwash plain. Beaded eskers may have formed in actively retreating ice and give an annual average retreat rate of 365 meters per year. The underlying topographic irregularities apparently exerted some control on the path of the esker as did the irregularities of the overlying ice.

Stone counts, more specifically boulder counts, appear to be most helpful in determining provenance of esker material. Boulder counts have indicated, in almost every case, that the esker sediment is most likely derived from basal ice debris. Pebble populations indicate the same source as the boulders, but with smaller percentages, due perhaps, to the more frequent contribution of up-ice lithologies in the smaller fraction. There is little evidence to indicate that bedrock contributed directly to the compositions of the eskers.

The results of the heavy mineral studies by X-ray diffraction were somewhat disappointing, and no more than broad conclusions can be made. Mineral identification was much quicker and more reliable with the petrographic microscope than with the X-ray diffraction charts. Results seem to show the bulk of the identifiable minerals are locally derived. No economic indicator minerals were found with either method.

Petrographic studies of heavy mineral mounts appear to be useful in differentiating glaciofluvial material deposited by different lobes of ice. The Rainy lobe and Superior lobe left deposits with similar heavy mineral populations reflecting mafic source rocks, or possibly a blending of the tills as the Superior lobe overrode the underlying Rainy lobe drift. The St. Louis sublobe deposits can be differentiated from the Rainy lobe and Superior lobe deposits by having a much higher garnet population.

The similar heavy mineral populations between the eskers and the till in the various drift sheets indicates the source of the esker material is either from the basal ice debris or from subglacial meltwater erosion of the underlying drift, rather than from subglacial bedrock erosion by the meltwater streams. This is in good agreement with the results from the stone counts.

PROBLEMS

A better understanding of the numerous problems encountered could help with future drift prospecting programs.

The results of the test samples spiked with known amounts of galena and magnetite indicated some problems in recovering the total heavy mineral fraction during bulk sample processing. This could be related to grain properties such as size, shape, and specific gravity. Processing more test samples might help define the optimum conditions under which the maximum amount of certain minerals could be recovered.

The amount of material used in optical studies and X-ray diffraction was such a small fraction of the bulk sample that it may not give an accurate representation of the minerals present.

X-ray diffraction of bulk samples was not the most efficient, or reliable, way to determine mineralogy for a number of reasons. A good deal of time was spent trying to find the best way to process the sample from powdering, to mounting, to interpretation of the charts. Perhaps the largest problem was in the interpretation of the charts. Only a few minerals could be identified and the peaks associated with these few minerals effectively masked those of any other minerals that may have been present.

Another problem with X-ray diffraction is that a given mineral must comprise at least 5% of the X-rayed sample before it will show up on the chart. It seems highly unlikely that most of the economic indicator minerals would be present in such a high percentage.

The lack of good bedrock control over the Duluth Complex made provenance determinations even more difficult.

SUGGESTIONS FOR FURTHER DRIFT PROSPECTING

Several suggestions can be made that might help with future studies using eskers as a prospecting tool.

A good understanding of the glacial history in the area is important. Using the oldest drift would be the most helpful since this would be the least reworked and least diluted by subsequent glacial advances.

It is also important to have the best possible control of the underlying bedrock geology. This would help in understanding the transport distances of the material involved.

Heavy minerals have been used successfully as a prospecting tool in other places such as the Kirkland Lake area in Ontario, as shown by Lee (1965, 1968), and helped in differentiating deposits deposits from various lobes of ice in Michigan (Dworkin, and others, 1985). They could be further studied in northeastern Minnesota, but X-ray diffraction does not seem to be a useful tool for bulk mineral identification.

Glaciofluvial deposits such as eskers and outwash are better sampling locations than glacial till due to the hydraulic concentration and sorting of the sediment during ablation. It appears that the provenance, as shown by stone counts and optical studies of heavy mineral mounts from both continuous and beaded eskers, is probably from local sources such as the englacial load or underlying till, rather than from meltwater erosion of the underlying bedrock.

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APPENDIX I

Sample numbers, locations, and weights of bulk samples and concentrated samples.

Sample No.	7.5 Min. quadrangle	Location Sec-Tw-Rg	1/4 of 1/4	Bulk Wt.(kg)	Conc. Wt. (g)
SIR-1	Sawbill Landing	30-61-7	NE-SE	348	1280
SIR-2	Sawbill Landing	30-61-7	NE-SE	312	1570
JPC-1	Mitawan Lake	31-61-8	NE-NE	306	1480
JPC-2	Mitawan Lake	31-61-8	NE-SW	363	1500
JPC-3	Mitawan Lake	31-61-8	SE-SW	371	1590
SIR-3	Sawbill Landing	36-61-8	SE-SE	369	1060
IC-1	Mitawan Lake	27-61-9	NE-SE	335	820
SPGL-1	Mitawan Lake	27-61-9	NW-NW	400	1340
ISR-1	Slate Lake East	29-61-9	SW-SW	345	630
IC-2	Mitawan Lake	35-61-9	SE-SW	356	750
4ML-1	Toohey	8-60-5	SE-SW	272	1750
HCR-1	Wilson Lake	5-60-6	SE-NE	340	1420
WIL CR-1	Wilson Lake	24-60-6	SW-SW	358	1290
HL-1	Wilson Lake	29-60-6	SE-NW	316	1150
WR-1	Silver Island Lake	33-60-7	SE-SW	407	490
TLR-1	Sawbill Landing	34-60-8	NE-SW	349	1580
TLR-2	Sawbill Landing	34-60-8	NE-SW	305	680
SIR-4	Sawbill Landing	10-60-8	NW-NW	368	1370
JPC-4	Mitawan Lake	7-60-8	SE-NE	339	1400
WCC-1	Mitawan Lake	7-60-8	SE-NE	368	1330
ARC-1	Sawbill Landing	5-60-8	SW-SW	311	1630
GL-1	Mitawan Lake	15-60-9	NW-SE	338	1700
GL-2	Mitawan Lake	15-60-9	SE-SW	295	1500
SHAM-1	Slate Lake East	4-60-10	NW-SE	310	1200
DL-1	Sawbill Landing	2-59-8	NE-NW	272	1035
DL-2	Isabella	1-59-8	SE-SW	347	1390
RIL-1	Isabella	12-59-8	NW-NE	297	960
RIL-2	Isabella	12-59-8	NW-NE	314	345
RIL-3	Isabella	12-59-8	NW-NE	337	1210
RIL-4	Isabella	12-59-8	SW-SW	321	1610
MCD-1	Greenwood Lk. East	11-59-10	SE-SE	292	1230
GRR-1	Greenwood Lk. East	29-59-10	NW-NE	386	940
SL-1	Greenwood Lk. West	18-59-10	SW-NE	273	700
EMCO-1	Greenwood Lk. West	33-59-11	SE-NE	362	600
GWC-1	Mt. Weber	26-58-11	NE-SE	371	1440
MC-1	Kane Lake	33-57-11	SW-SW	-	1300
TDF-1	Skibo	32-57-12	NE-NE	321	1700
LSC-1	Harris Lake	36-57-14	SE-SW	365	1650
ML-1	Brimson	18-56-11	NE-NE	366	1600
DMIR-1	King Lake	13-55-12	SE-SW	384	513
ROL-1	Brimson	16-55-12	NE-NW	317	547

Sample No.	7.5 Min. quadrangle	Location Sec-Tw-Rg	1/4 of 1/4	Bulk Wt (kg)	Conc. Wt (g)
SBR-1	Harris Lake	5-55-13	NW-SW	341	510
WOL-2	Fairbanks	15-55-13	NW-NE	371	1560
WOL-1	Fairbanks	16-55-13	NW-NE	255	1758
BLRNE-1	Boulder Lk. Res. NE	32-55-13	NW-NE	-	1170
BL-1	Pequaywan Lake	36-55-13	NE-NW	321	486
BL-2	Pequaywan Lake	36-55-13	NE-NW	381	1820
MARTR-1	Boulder Lk. RES. NE	35-55-14	SW-NW	260	1020
JR-2	Comstock Lake	36-55-15	SE-SE	392	1080
STEW-1	King Lake	6-54-11	NE-SW	374	517
MTE-2	Boulder Lk. Res. NE	6-54-13	NE-NW	324	688
BLRNE-3	Boulder Lk. Res. NE	2-54-14	SW-SW	323	1270
BLRNE-6	Boulder Lk. Res. NE	16-54-14	SE-SW	288	970
BLRNE-7	Boulder Lk. Res. NE	16-54-14	SE-SW	358	896
JR-1	Comstock Lake	1-54-15	NE-NE	325	1370
PL-1	Whiteface	14-54-16	SW-SW	360	960
PL-2	Whiteface	14-54-16	SW-SW	317	790
ATE-1	McCarthy Creek	12-53-12	NE-SW	-	1860
TL-1	Thomson Lake	11-53-14	SE-NE	327	675
IL-2	Boulder Lake Res.	23-53-15	SW-SW	-	1380
BL-1	Boulder Lake Res.	23-53-15	NW-SE	343	1330
ISLE-3	Thomson Lake	4-52-14	SE-NE	352	1610
VR-1	Boulder Lake Res.	5-52-14	SE-NW	314	960
IL-1	Boulder Lake Res.	5-52-14	SW-SW	-	1285
FL-1	Twig	29-52-15	NW-SW	335	1500
BR-1	Twig	30-52-15	SE-SW	368	417
BR-2	Twig	30-52-15	SE-SW	388	1440
BERG-1	Twig	14-52-16	NE-NW	384	1133
MPL-1	Twig	25-52-16	SW-SW	342	1262
DWP-1	Twig	35-52-16	NW-SE	324	1225
ET-1	Twig	36-52-16	SE-NW	341	1500
ARTL-1	Alborn	7-52-17	SW-SE	329	1080
NERC-1	Twig	11-51-16	SW-SE	340	650
NERC-2	Twig	11-51-16	SW-SE	313	925
CS-1	Twig	23-51-16	NW-NW	260	1495
SUNL-1	Independence	9-51-17	NE-NE	340	1000
PRL-2	Gowan	27-51-20	SE-SW	251	1130
PRL-3	Gowan	27-51-20	SE-SW	252	1820
LGL-1	Saginaw	1-50-17	SW-NE	322	1750
MUDL-1	Gowan	21-50-20	SE-NE	296	1720
PRL-1	Prairie Lake	21-50-20	SW-SW	322	1000
AUD-1	Cloquet	12-49-17	SE-SE	332	1590
CLQ-1	Cloquet	26-49-17	NW-NE	251	-
CLQ-2	Cloquet	26-49-17	NW-NE	310	-
CLQ-3	Cloquet	26-49-17	NW-NE	353	-
CLQ-4	Cloquet	26-49-17	NW-NE	323	646
CE-1	Cloquet	26-49-17	NW-NE	282	903

Sample No.	7.5 Min. quadrangle	Location Sec-Tw-Rg	1/4 of 1/4	Bulk Wt(kg)	Conc. Wt (g)
CE-2	Cloquet	26-49-17	NW-NE	306	1490
CE-3	Cloquet	26-49-17	NW-NE	299	1080
CE-4	Cloquet	26-49-17	NW-NE	397	570
IVER-1	Iverson	32-49-17	NE-NW	262	700
BOBLAKE-2	Atkinson	23-48-18	SE-SW	403	1760
SEC14-1	Iverson	14-48-18	SE-SE	311	1870
BOBLAKE-1	Sawyer	16-48-18	SW-NW	390	1170
WBMR-1	Barnum (15')	22-47-19	NW-NW	420	1470
KETR-1	Cromwell (15')	20-47-20	NW-SW	419	703
BGP-1	Bruno (15')	11-46-19	NE-NE	384	648
WLWR	Denham	20-44-20	NW-NW	288	783

APPENDIX II

Mineralogies determined by X-ray diffraction from samples collected in the glacial drift, and weight per cent of magnetic minerals removed from the small split that was X-rayed from each sample. Minerals are listed in no particular order.

KEY:

q- quartz	il- ilmenite	di- diopside
pl- plagioclase	ol- olivine	ksp- K-Feldspar
hem- hematite	hyp- hypersthene	r- rutile
pyx- pyroxene	sph- sphene	am- amphibole

Sample Numbers	Minerals identified	Per cent magnetics
SIR-1	q, il	21
SIR-2	q, il	24
JPC-1	hyp, pl	15
JPC-2	il, pyx	26
JPC-3	q, pl	19
SIR-3	pl, q, il, pyx	24
IC-1	il, ksp, pyx, r (?)	42
SPGL-1	q, pl, il	34
ISR-1	q, pl, hem	18
IC-2	q, pl, ol	16
4ML-1	q, pl, il	54
HCR-1	q, pl, pyx, am	22
WIL CR-1	q, pl	36
HL-1	q, pl	33
WR-1	q, il, pl	59
TLR-1	q, hem, pl, pyx, am, ksp	46
TLR-2	q, pl	39
SIR-4	q, pl, hem	38
JPC-4	q, il, pyx, pl	46
WCC-1	q, pl, il, pyx	37
ARC-1	pl	30
GL-1	q, pl	17
GL-2	q, pl	38
SHAM-1	pyx, pl	36
DL-1	pyx, il, q	54
DL-2	q, hem, pyx, il	48
RIL-1	q, il	38
RIL-2	q, pl, pyx	58
RIL-3	q, pyx, pl	38
RIL-4	q, pl, il	41
MCD-1	q, il, pl (?)	39

Sample numbers	Minerals identified	Per cent magnetics
GRR-1	q, pl, pyx (?)	6
SL-1	q, pl,	32
EMCO-1	hem	54
GWC-1	q, pl	39
MC-1	q, pl, il (?)	38
TDF-1	q, pyx	34
LSC-1	q, pl	34
ML-1	hyp, di, q	11
DMIR-1	q, pl, hem, il, pyx	57
ROL-1	hem, il, pl (?)	61
SBR-1	q, pl, hem	31
WOL-2	hem, pl, q	49
WOL-1	q, pl, il, pyx (?)	34
BLRNE-1	q, pl	23
BL-1	q, pl, pyx	34
BL-2	il, pyx	63
MARTR-1	q, pl, pyx	54
JR-2	q, pl	48
STEW-1	q, pl, hem, ksp	49
MTE-2	q, pyx, pl	19
BLRNE-3	q, hem, pyx	34
BLRNE-6	q, pl, hem (?)	-
BLRNE-7	q, pl, ksp, il	31
JR-1	il, q, pl	54
PL-1	q, pl, pyx	9
PL-2	q, pl	13
ATE-1	q, pl, py, ksp	30
TL-1	q, pyx, ksp, pl	18
IL-2	q, pl, hyp	27
BL-1	q, ksp	40
ISLE-3	q, pl, hem	32
VR-1	q, pyx, pl, hem, il	40
IL-1	q, pl, pyx	27
FL-1	q, hem, pyx	52
BR-1	q, hem,pl, pyx	35
BR-2	q, pl, pyx	15
BERG-1	q, pl, ksp, hem	7
MPL-1	q, pl, pyx	21
DWP-1	q, pl, pyx	30
ET-1	q, pl	22
ARTL-1	q, pl, hem, il	47
NERC-1	q, pl, hem	36
NERC-2	q, am (?), pyx, sph (?)	14
CS-1	q, pl	29
SUNL-1	q, pl	26

Sample numbers	Minerals identified	Per cent magnetics
PRL-2	il, ol (?)	45
PRL-3	q, hem, pl, pyx	43
LGL-1	q, pl	24
MUDL-1	q, pl, pyx (?)	28
PRL-1	q, pyx	18
AUD-1	q, pyx	20
CLQ-1	test samples	-
CLQ-2	"	-
CLQ-3	"	-
CLQ-4	"	-
CE-1	q, pl, pyx	13
CE-2	q, pl	10
CE-3	q, pl	14
CE-4	q, pl	15
IVER-1	q, hem	21
BOBLAKE-2	q, pl	9
SEC14-1	q, hem	36
BOBLAKE-1	q, pl	10
WBMR-1	q, pl	16
KETR-1	q, pl	8
BGP-1	q, hem, pl	16
WLWR	q, hem, pyx, pl (?)	25