SURFICIAL GEOLOGY OF THE ISABELLA QUADRANGLE, NORTHEASTERN MINNESOTA

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Plate I SURFICIAL-GEOLOGIC MAP OF THE ISABELLA QUADRANGLE

Plate II GEOMORPHIC SUMMARY MAP OF THE ISABELLA QUADRANGLE

ABSTRACT

A surficial-geologic map was constructed from field work, laboratory analysis, airphotos, and topographic maps. The study area is located in Lake County in northeastern Minnesota. Parts of the Isabella Quadrangle lie within the Toimi Drumlin Area, Border Lakes, Area, and the North Shore Highland. Bedrock in the surrounding areas is composed of Duluth Complex plutonic rocks, the North Shore Volcanic Group, Superior syncline clastics, and Vermilion District intrusive and metamorphic rocks.

Surficial materials were distinguished as to genesis and provenance. Two distinct provenance groups were identified: Brown-colored drift incorportating rock fragments from the Superior synclinė, North Shore Volcanic Group, and part of the Duluth Complex; Gray-colored drift incorporating rock fragments almost entirely from the Duluth Complex with minor Vermilion District input. Surficial materials were divided into genetic units as follows: Till, Ice-Marginal Gravels, Other Ice-Contact Deposits, Proglacial Outwash, Lag Acumulations, Loess, and Peat Deposits.

The most prominent landforms are the merging Highland and Vermilion Moraines composed primarily of brown and gray ice-marginal gravels. Additional minor brown-till end moraines are situated in front of the Highland Moraine, and are superposed on a gray-till ground moraine that represents the northeast corner of the Toimi Drumlin Area. These minor moraines are in turn partially buried by the Vermilion Moraine. The area behind the Vermilion Moraine is characterized by extensive outwash complexes, a long esker system, and a series of parallel ridges composed of gray till. Lakes have formed in outwash-plain depressions that resulted from wastage of stagnant-ice blocks.

The non-organic surficial materials in the area were deposited during the St. Croix (ca.>20,500 yr B.P.) and Automba (ca.>16,000 yr B.P.) phase of the late Wisconsin. Conterminous Rainy and Superior Lobes emanating from the Rainy Lake area and Superior Lowland deposited the materials composing the Toimi Drumlin Area during the St. Croix phase.

During the Automba phase the Superior Lobe advanced laterally out of the Superior Lowland in the southeast while the Rainy Lobe flowed southwestward into the study area. The ice masses met near the town of Isabella, producing interlobate terminal moraines. A sublobe of the Superior Lobe extended beyond the Highland Moraine, producing the minor brown-till end moraines. As this sublobe receded, part of the Rainy Lobe extended into the vacated area, forming a sharp bend in the

Vermilion Moraine. This extension is described as an ephemeral, thinned, frozen-base ice mass that sheared off sections of the substrate into thrust-block ridges. The extension stagnated and disintegrated rapidly as the Rainy Lobe receded, forming extensive ice-contact and outwash deposits.

Loess was winnowed from exposed brown-drift outwash plains and deposited as a thin, discontinuous blanket over the entire region. Extensive wetlands formed in poorly-drained depressions and other low-lying areas.

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INTRODUCTION

Location and General Information

The purpose of this study is to undertake a detailed survey and description of an area in order to ascertain the glacial history and genesis of Quaternary deposits.

The study area, located in the Superior National Forest of northeastern Minnesota, comprises the Isabella Quadrangle, shown on a 15-minute United States Geological Survey topographic map. The area is of particular interest because it marks the point of confluence of at least two major Late Wisconsin ice lobes. Not only does this circumstance produce great drift diversity, but it also provides an opportunity to define the time-stratigraphic relations of units deposited by the various ice masses.

The entire area is underlain by Precambrian bedrock of the Superior Upland division of the Canadian Shield (Sims and Morey, 1972). The depth to bedrock generally does not exceed 15 m. Although no outcrops were encountered in this area, bedrock exposures are plentiful 5 to 10 km to the north, beyond the region of extensive drift cover.

The landscape is dominated by bands of wooded hummocky topography interspersed with boggy lowlands and undulating plains. Prior to land settlement and initiation of logging, the original vegetation consisted of a mixed northern conifer-hardwood forest (Upham, 1894). The modern forest is primarily composed of replanted pines interspersed with second-growth conifers and hardwood trees and shrubs.

Physiography

The Isabella Quadrangle straddles the Laurentian Divide, a topographic feature diverting surface waters south to the Great Lakes and north to Hudson Bay. According to the physiographic area of Minnesota as delineated by Wright (1972a), the study area is almost wholly contained in the Toimi Drumlin Area (Figure 1). The central section of the quadrangle contains the Vermilion Moraine, which forms the edge of the Border Lakes Area. The southeastern corner of the study area extends into the North Shore Highland.

The topography of the Toimi Drumlin Area is controlled by comparatively thick glacial drift (Wright, 1972b). Drumlins and drumlinoid features cover much of the area. Their longitudinal axes are generally oriented in a southwesterly direction. The Border Lakes Area differs significantly in form and appearance. It is basically a rugged ice-scoured region with thin, discontinuous drift superimposed on bedrock-controlled topography. The North Shore Highland, located southeast of the Toimi Drumlin Area, is a northeast-trending ridge of Precambrian volcanic rocks (Phinney, 1972). The bedrock is obscured by the overlying Highland Moraine. Continuing to the southeast, a steep descent leads to the floor of Lake Superior, which marks the presence of a southwest-trending syncline composed of comparatively soft Precambrian clastic rocks. This feature is referred to as the Superior Lowland in subsequent discussions of glacial events.

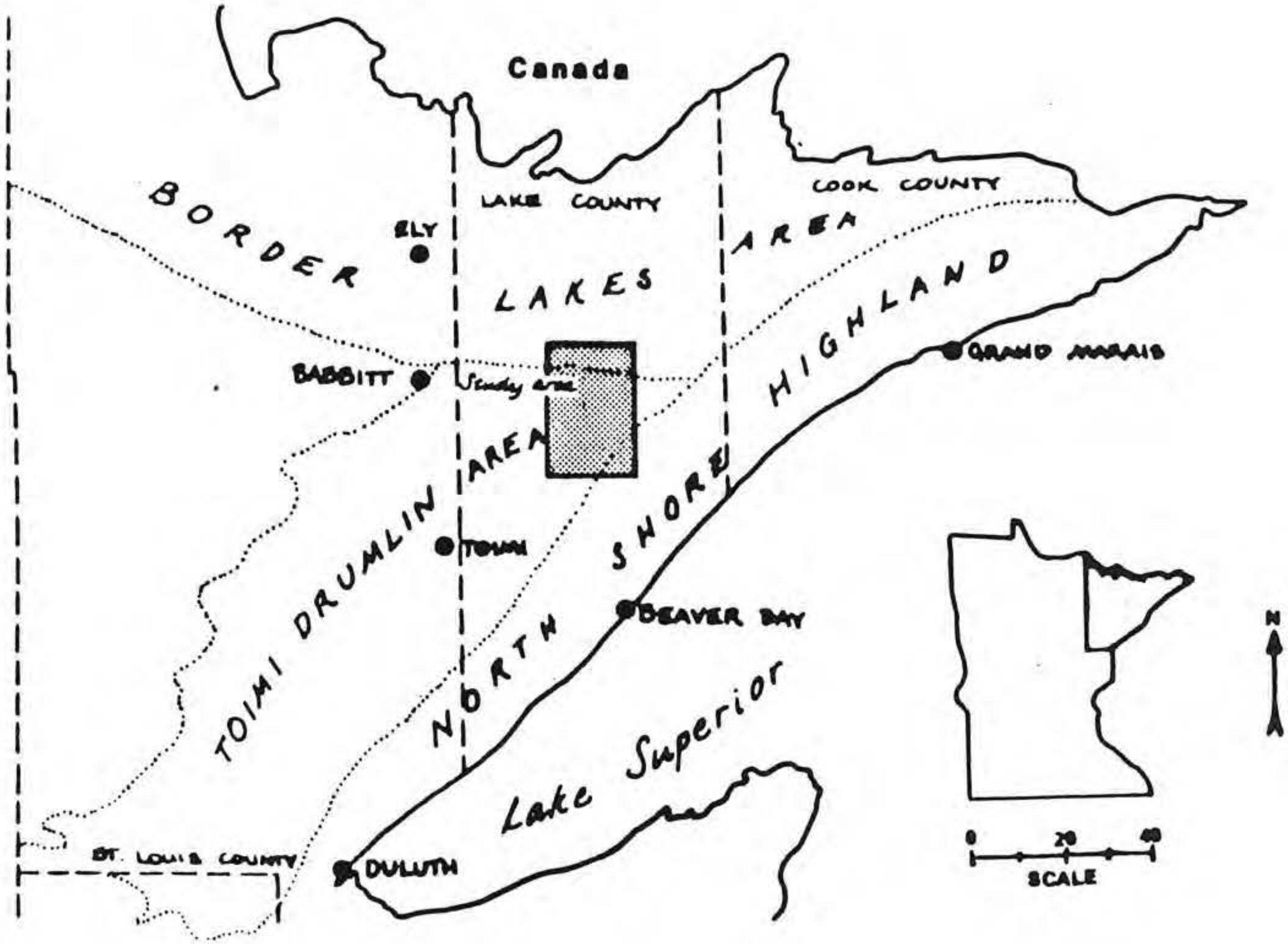


FIGURE 1. Physical Setting. Adapted from Wright (1972A)

Bedrock Geology

The bedrock geology of areas adjoining the Isabella Quadrangle must be described lithologically and areally to establish the provenance of glacial till. The lithology of pebbles and granules obtained from selected drift samples serves to indicate the flow paths of associated ice masses.

The northern half of the study area is underlain primarily by rocks of the Duluth Complex; the southern half is dominated by the North Shore Volcanic Group. The contact between these major lithologic terranes bisects the town of Isabella and trends approximately N. 55° E. (Figure 2).

The Duluth Complex is composed of upper Precambrian intrusions of mafic anorthosite, troctolite, diabase; intermediate granodiorites and diorites; and felsic granites collectively referred to as the Red Rock Series (Craddock, 1972; Davidson, 1972; Phinney, 1972). The North Shore Volcanic Group consists primarily of upper Precambrian basalt and felsite lava flows interbedded with clastic rocks. All units dip southeastward toward the axis of the Lake Superior syncline (Green, 1972).

The Lake Superior syncline is composed of late Precambrian Keweenawan red sandstones and shales, rocks that are softer than those of Duluth Complex and North Shore Volcanic Group (Sims and Morey, 1972).

The Vermilion District, lying to the north of the Duluth Complex, contains lower Precambrian felsic batholiths (Sims, 1972).

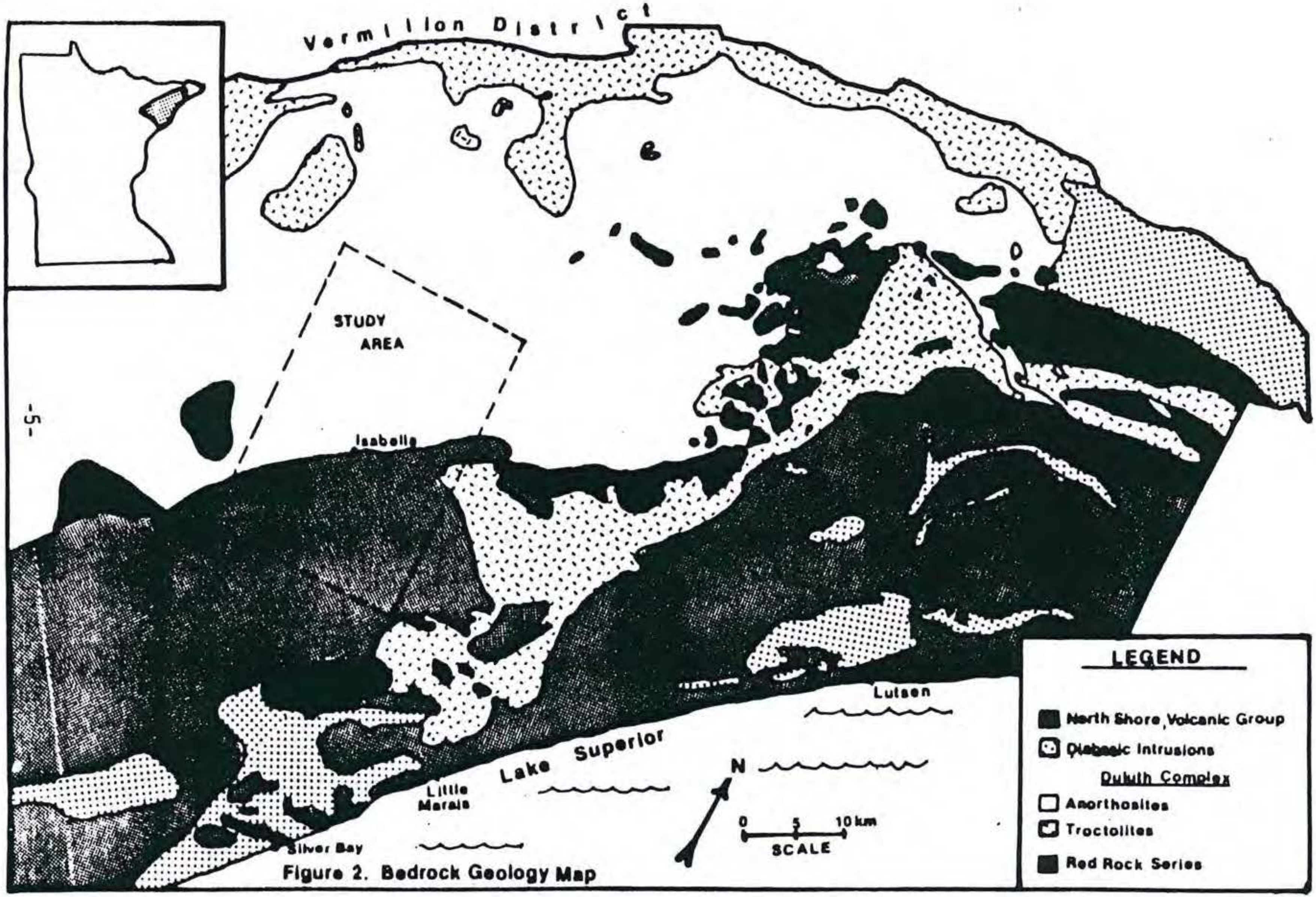


Figure 2. Bedrock Geology Map

History of Investigations

The first surficial-geologic study of the state was undertaken by Upham (1894), who classified landforms in northeastern Minnesota and established criteria for distinguishing different types of till. A series of twelve moraines was identified; the northernmost was called the Vermilion Moraine, and the ninth or Leaf Hills Moraine was closest to the North Shore of Lake Superior. These two features represent the moraines found in the Isabella Quadrangle.

Todd (1898) reviewed Upham's work and was the first to propose a noncontinuous ice sheet for northern Minnesota. He based this theory on the presence of intersecting moraines of contrasting materials. Todd delineated drift of two ice lobes, one advancing from the Red River Valley region, the other from the Lake Superior Lowland.

Elftman (1898) revised this hypothesis by suggesting that an ice lobe also traversed northeastern Minnesota from the Rainy Lake region along the Canadian border. This interpretation was primarily based on the presence of indicators from the Precambrian granites and metamorphic rocks that surround Rainy Lake. This ice lobe, termed the Rainy lobe, purportedly constructed many of Upham's series of recessional moraines. In addition, Elftman attributed the Leaf Hills Moraine to ice originating from the Superior Lowland and renamed it the Highland Moraine.

Winchell (1898) remapped and redefined the extent of the Vermilion Moraine in St. Louis County and noted that it intersected moraines composed of Superior Lobe till. He suggested that the formation of

Superior Lobe moraines post-dates the Rainy Lobe Vermilion Moraine. This observation represents a first attempt at establishing the regional chronology of glacial events.

Leverett and Sardeson (1917, 1932; Leverett, 1928) through careful mapping of landforms and cataloguing of materials, reconstructed the positions of the area's ice masses in more detail. Their results suggest two distinct source areas and two ice advances. The first lobe, originating in central Canada, advanced south-southeast across northeastern Minnesota. The ice mass, composed of both the Rainy and Superior Lobes, deposited recessional moraines as it retreated to the north. A second ice mass, originating in eastern Canada, advanced to the southwest through the Superior Lowland. Although the ice was flowing to the southwest, radial flow out of the Superior Lowland transported entrained debris to the northwest, constructing the Highland Moraine. Leverett and Sardeson located the intersection of the recessional moraines of the central Canadian lobe with the Highland Moraine at a point northeast of the Isabella town center.

Extensive research by Wright (Wright, 1955, 1969, 1971, 1972b, 1973; Wright et al., 1973; Wright and Watts, 1969; Florin and Wright, 1969) sought to establish a more accurate chronology of Wisconsin glaciation. Wright believes that the drift distribution of northern and central Minnesota evolved from a complex series of advances and retreats of several ice lobes emanating from different accumulation centers. Synchronous events are grouped into phases; each phase indicates a renewed period of glaciation. The St. Croix phase (ca. 20,500 yr B.P.) constitutes the first identifiable advances of the Rainy and Superior Lobes, which acted as a single continuous ice mass traversing northeastern Minnesota and terminating at the St. Croix Moraine in the central part of the state. The formation of the Toimi drumlins is attributed to the Rainy lobe during this phase.

Although advancing jointly, the Rainy and Superior Lobes produced different tills, as each lobe incorporated distinct lithological assemblages from the terranes they encountered. Following the retreat of ice at the close of the St. Croix phase, a readvance, the Automba phase, occurred. At this time, the Rainy and Superior Lobes advanced as discrete ice masses, separated by the North Shore Highland. The Rainy Lobe constructed the Vermilion Moraine across the northern end of the Toimi Drumlin Area, while radial flow of the Superior Lobe produced the Highland Moraine. The interlobate junction of these moraines was mapped at a point east of Isabella. Wright suggests that these moraines formed contemporaneously. Evidence for this hypothesis includes the coalescence of the two lobe's glaciofluvial deposits. Two subsequent advances of the Superior Lobe are proposed, but neither reached the Highland Moraine.

Winter _et al_. (1973), working in St. Louis County west of the Isabella Quadrangle, mapped and delineated tills deposited by ice advances that did not enter the present study area. A major portion of their work deals with the properties of till deposited by the Rainy Lobe. They defined this material as "bouldery till," after its most salient feature, and described its texture and lithology to establish provenance.

Stark (1977) investigated an area directly west and adjacent to the Isabella Quadrangle, comprising parts of the Greenwood Lake, Gabbro Lake, Kangas Bay, Babbitt, and Babbitt Northeast quadrangles. Stark's thorough mapping included references to local details that clarified the histories of the Rainy and Superior Lobes. He delineated a network of recessional moraines immediately south of the Vermilion Moraine, and he also mapped recessional moraines northwest of the Highland Moraine. He noted that the interlobate junctions of these moraines support a proposed contemporaneous existence of the Rainy and Superior Lobes in that area. He observed that Rainy Lobe recessional moraines appeared to be contorted around Superior Lobe moraines, implying that a sublobe of the Superior Lobe advanced into the area prior to the Rainy Lobe advance. In addition, Stark reported the presence of outwash derived from the Superior Lobe ice stratigraphically superposed on Rainy Lobe till, leading to a further speculation that the Superior ice remained active for a longer period of time.

Stark informally labelled the two surficial tills exposed in his area the "bouldery" and "red sandy" tills (after Winter et al., 1973). These designations correspond respectively to the deposits of the Rainy and Superior Lobes. The bouldery till contains approximately 30% cobbles and boulders in a matrix of silty sand. Predominantly gray, it contains stones derived from the Duluth Complex and undifferentiated granitic rocks. The red sandy till contains a lower concentration of cobbles and boulders in a matrix of silty gravelly sand. The Duluth Complex and the North Shore Volcanic Group are the dominant sources of the red sandy till.

SURFICIAL DEPOSITS

Introduction

Field work in the Isabella Ranger District was undertaken during the summer and early fall of 1978 under the auspices of the U.S. Forest Service and the Minnesota Geological Survey. Further field studies were conducted during the summer of 1979. Investigations entailed reconnaissance mapping of the surficial geology and detailed study at over 400 field localities within the two central townships (T.59N., R.8W.; T.60N., R.8W.). At each locality, a description of the surface and subsurface materials to a minimum depth of 1.2 meters was recorded (see Friedman, 1980).

At selected localities, samples were collected for laboratory analysis. The relative percentages of sand, silt, and clay were determined according to the procedure of Folk (1974) (see Appendix A). The color of air-dried samples was described according to the standard Munsell Color System. The lithology of granules (2-4mm diameter) separated from samples in the laboratory and pebbles (4-64mm diameter) collected from selected exposures was identified for provenance studies.

A glacial-geologic map was compiled from field observations with the aid of the United States Geological Survey Quadrangle topographic maps, 7½ minute orthophotoquads, U.S. Forest Service Township topographic maps, and stereoscopic aerial photographs. Mapping units were distinguished genetically and texturally and assigned to several classes as described in the following sections. Symbols in parentheses are those used on the glacial map symbols.

<u>Till</u>

Till is deposited directly from glacial ice and is therefore poorly sorted and unstratified. In this region, glaciers eroded crystalline bedrock, and the resulting till is sandy. The tills of the study area are texturally and lithologically distinct and can be divided into two descriptive classes: compact sandy and bouldery grayish till, and sandy brown till with fewer boulders. These two deposits correspond respectively to the "bouldery till" of Winter <u>et al</u>. (1973) and the "red sandy till" of Stark (1977). For clarity in this report, tills will be designated informally as either gray or brown. Color designations in this study are unrelated to the terminology used in earlier publications (particularly Leverett, 1928; and Leverett and Sardeson, 1917, 1932). Throughout the related literature, color terms were considered synonymous with particular ice-lobe advances. This practice was discontinued because local variations in bedrock geology can produce a wide range of hues within deposits of similar provenance. Color designations have been used here because they are the simplest descriptors of local deposits.

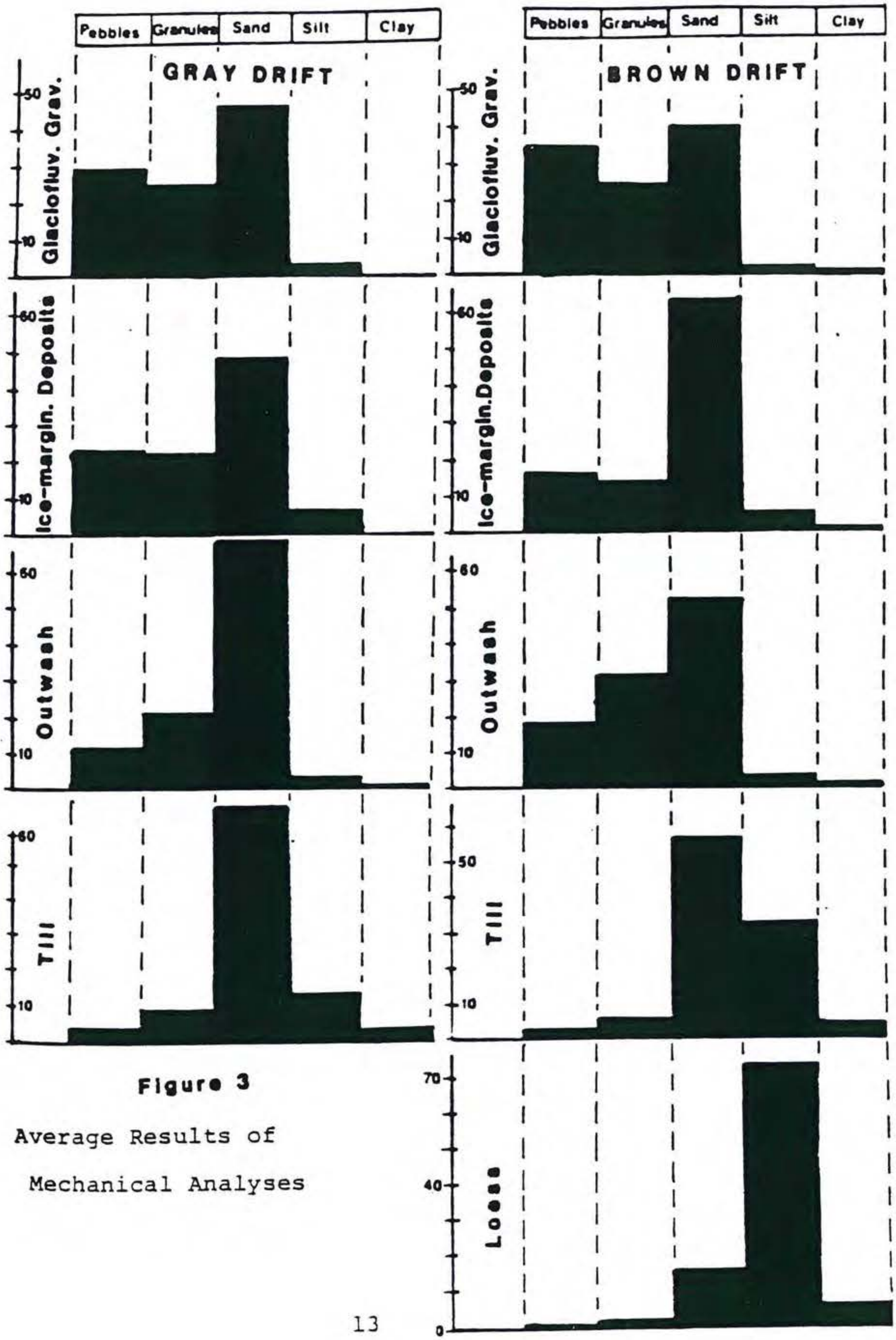


Figure 3

Average Results of Mechanical Analyses

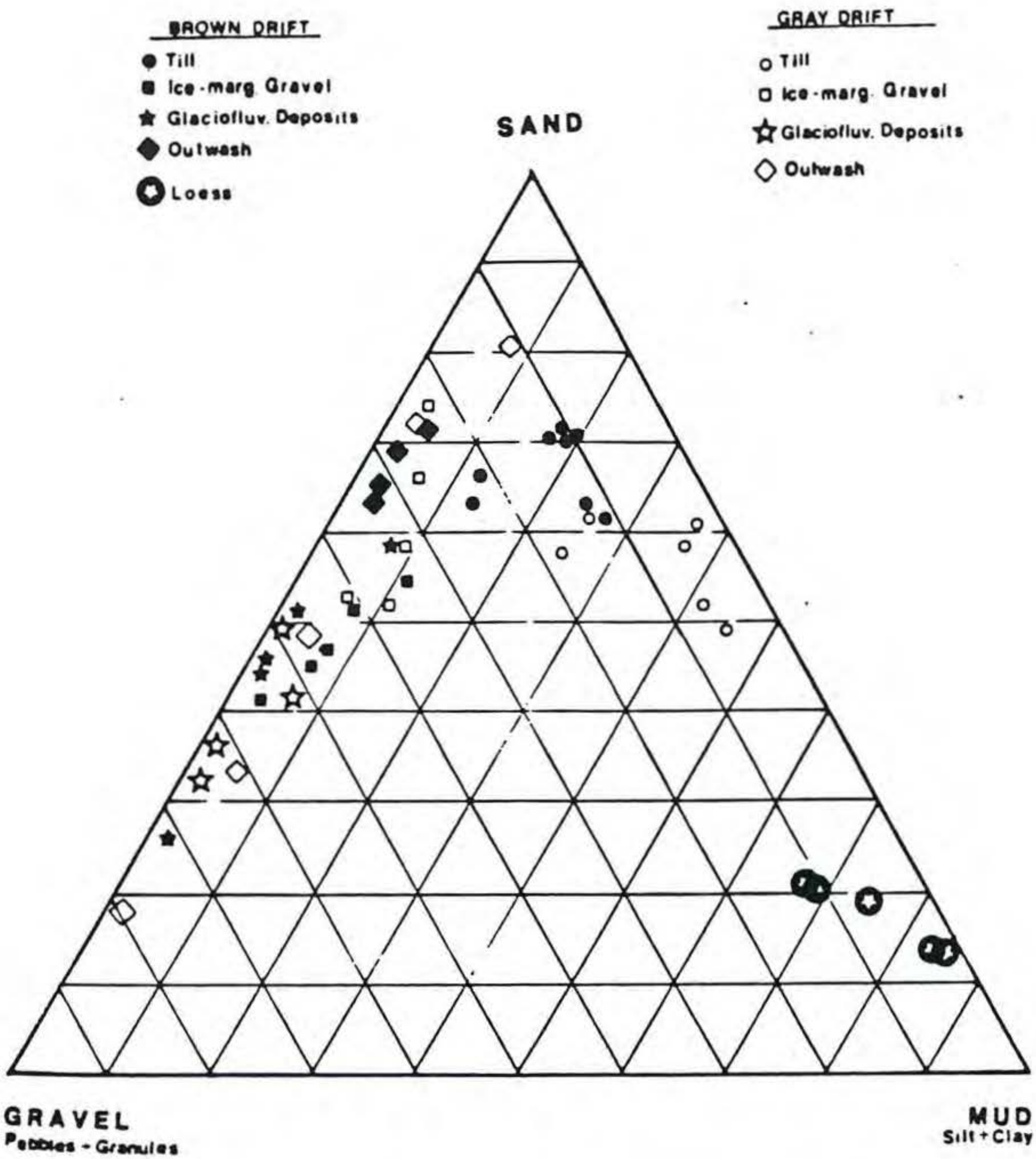


Figure 4 Comparison of Mechanical Analysis Results

Gray Till (Tg)

Textural analyses of gray-till samples yield a representative matrix composition of approximatly 80% sand, 15% silt, and 5% clay (Appendix A, Figures 3 and 4). Exposures contain greater concentrations of boulders and cobbles than the till-plain surface. By volume, gray till ranges from 15 to 25% cobbles and boulders. These coarse materials are angular or poorly rounded and exhibit little or no evidence of fluvial reworking. These characteristics suggest short distances of glacial transport.

The gray-till matrix is generally quite compact and difficult to excavate. Munsell dry colors range within the 2.5Y hue, indicative of the dark-colored rock types incorporated by the ice (Figure 5). Granule and pebble lithologies support this conclusion.

Gabbroic troctolites and anorthosites of the Duluth Complex and granites from Red Rock Series dominate the lithological assemblage. Minor fractions of Vermilion-District metavolcanic and mafic lavas are also present (Appendix B, Figures 5 and 6). The areal distribution of these rock-types confirms the northeastern provenance of the gray till.

Gray-till ground moraine is located in the southwestern and northeastern segments of the study area. The ground moraine in the northeast quarter includes a series of low, regularly spaced linear ridges trending northwest. These ridges are transverse to the

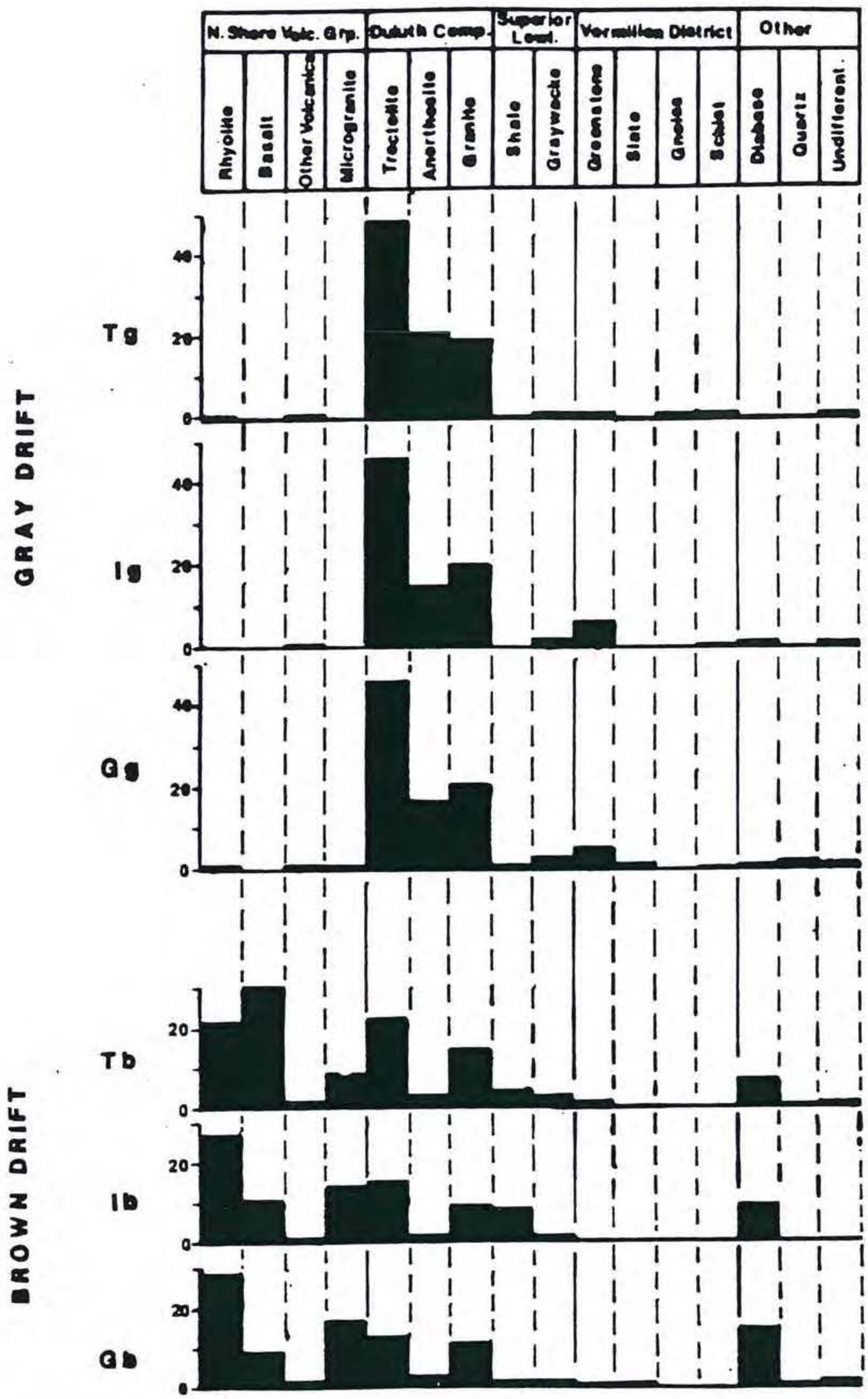


Figure 5 Average results of Rock-type Identification

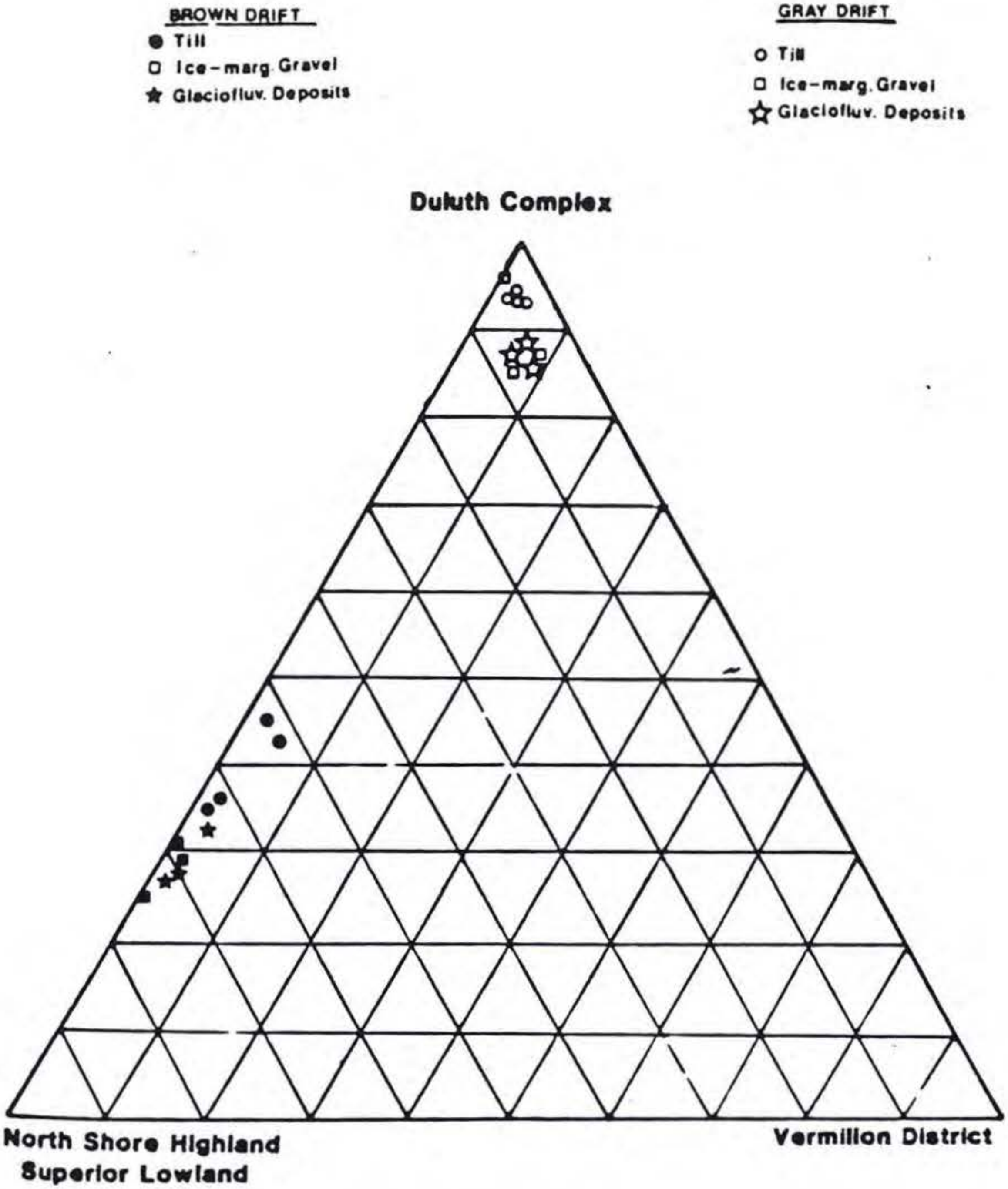


Figure 6 Provenance Comparisons

proposed ice-flow direction as inferred from esker and end-moraine orientations and provenance studies. The surface expression of these transverse features becomes less pronounced in the upglacier direction; the preferred orientation is no longer apparent at points greater than 12 km north of the Vermilion Moraine. Glaciological conditions promoting transverse ridge formation apparently existed only in the area immediately upglacier from the ice margin. The origin of these ridges is discussed in a later section.

In the southwest corner of the Isabella Quadrangle, the ground moraine is expressed as smooth to gently undulating topography with broad, rounded hills oriented parallel to the presumed ice-flow direction. This terrain represents the northern edge of the Toimi Drumlin Area. Immediately southwest of the Isabella Quadrangle, typical drumlinoid land forms are composed of compact bouldery gray till.

Gray till is also exposed in the Vermilion Moraine of the northwest corner of the study area. Till exposures elsewhere in this moraine are rare; they are more often mantled or supplanted by ice margin gravels.

Brown Till (Tb)

Brown till is far less bouldery than the gray till and contains larger proportions of silt and clay, with a concomitant reduction in the sand fraction (Figure 4, Appendix A). Textural analyses yield a representative matrix composition of 60% sand, 35% silt, and 5% clay (Figure 3). The matrix is predominantly brown in color (10YR hue), an indication of significant content of felsite and red sandstone.

Pebble and granule counts reveal the prominence of North Shore Volcanics with the additional contribution of Duluth Complex rock types. Rocks of the Lake Superior Syncline have only minor representation. Specifically, the major lithologies include gabbro, amygdaloidal and vesicular felsic and mafic lavas, granite and microgranite, and small amounts of fine-grained to sandy brown clastics. A southeastern Superior Lowland-North Shore Highland provenance is therefore suggested, supported by the orientation of the northeast trending marginal features in the Isabella Quadrangle, and by the presence of northwest-trending drumlins along the north shore of Lake Superior (Wright, 1972b). The most diagnostic indicator of a Superior Lowland-North Shore Highland origin for brown till is the inclusion of North Shore Volcanic Group red rhyolite. This rock is rarely found in significant quantities in the gray till of presumed north-northeast provenance.

Brown till ground moraine is located in the southeastern corner and west-central border of the study area. To the southeast, the ground moraine appears directly upglacier from the Highland Moraine and extends southeastward toward Lake Superior. The topography is generally flat to gently undulating and contains large areas of ponded drainage and boglands.

Brown till ground moraine is also located between two pro-Vermilion end moraines in the western part of the Isabella Quadrangle. This end moraine/ground moraine complex overlaps the northern edge of the Toimi Drumlin Area and is in turn truncated and overlain by the gray drift of the Vermilion Moraine. The most southerly end moraine curves eastward toward the center of the study area, where it is buried by Highland Moraine Outwash and ice-margin gravels. Both end moraines have well-defined distal slopes and gentle proximal slopes that grade into ground moraine. The topography of the ground moraine is quite subdued, with many low, rounded hills exhibiting no preferred elongation or orientation.

The proximal edge of the Highland Moraine is composed of brown-till, but the overall moraine complex is dominated by a broad band of superimposed hummocky ice-contact gravels.

Ice-Marginal Gravels

The Highland and Vermilion Moraine complexes are predominantly composed of loose, poorly sorted gravels. The gravels are lithologically similar to their associated tills, but texturally distinct.

Stark (1977) classifies these gravels as ablation till deposited directly from englacial and supraglacial positions during down-wasting of the ice mass. He distinguishes ablation till from the more poorly sorted and compact tills that were deposited from basal ice. The lack of fine particles, predominance of coarse gravel, rounding of grains, and overall topographic expression of this material clearly indicate deposition in the presence of significant quantities of water.

The ice-margin gravels of the Isabella Quadrangle appear similar morphologically and compositionally to descriptions of stagnant-ice disintegration features in southwestern Canada (Gravenor and Kupsch, 1959; Fulton, 1967). Fulton devised both descriptive and genetic classification schemes for the glacial features and materials of southern British Columbia. According to those schemes, the ice-margin gravels of the Isabella Quadrangle can be classified descriptively as hummocky morainal gravel, and genetically as the product of aqueous activity, where topographic form was controlled by ice. It was noted that such deposits could be confused with hummocky till, but the situation is clarified because the gravels always exhibit some degree of sorting and stratification and are less compact, coarser and more rugged topographically. Similar features are cited in texts under the descriptions of kame moraines (Flint, 1971; Sugden and John, 1976) and are also ascribed to formation by hydraulic processes in the presence of ice.

Gray Ice-Marginal Gravel (Ig)

Gray ice-marginal gravel is poorly sorted and poorly stratified, with a conspicuous absence of fine particles and notable presence of rounded cobbles and boulders. This deposit is highly variable, with an average matrix texture composed of approximately 25% pebbles, 20% granules, 50% sand, and no more than 5% silt. A clay fraction is virtually nonexistent (Figures 3 and 4, Appendix A).

Pebble and granule counts reveal a bedrock origin similar to gray till, with Duluth Complex and Red Rock Series rocks predominating (Figures 5 and 6, Appendix B).

The Vermilion Moraine is defined by a lobate arc from Sphagnum Lake in the northwest corner of the study area to Dumbell Lake on the eastern edge. This feature represents the area's most rugged terrain, a band of hummocky topography 1.5 km wide with many closed depressions and with knobs and ridges composed almost entirely of gray ice-marginal gravel. Deep roadcuts expose compact gray till 5 to 8 m below the gravel. The total relief of the Vermilion Moraine exceeds 20 m in places, suggesting that a till core may lie beneath a mantle of gravel. Erosion or nondeposition of ice-marginal gravel exposed a till core in the northwest corner of the study area. The Vermilion Moraine is buried by Highland Moraine deposits to the east of the vicinity of Delay and Dumbell Lakes. Outwash channels draining meltwater from the Highland Moraine incised the distal edge of the Vermilion Moraine.

Brown Ice-Marginal Gravel (Ib)

Brown ice-marginal gravel is finer than the gray and contains fewer cobbles and boulders. The average matrix texture consists of approximately 20% pebbles, 15% granules, 55% sand, and a maximum of 5% silt. Essentially no clay is present (Figures 3 and 4, Appendix A). The sand fraction exceeds 70% in some samples, presumably resulting from a high degree of hydraulic sorting. The occurrence of poorly stratified layers and graded beds in some areas further suggests the more active influence of water at the ice margin. Texture within the gravels ranges widely from isolated cobble layers to silt and clay lenses deposited in small localized depressions.

The lithology of the brown ice-marginal gravels coincides with the composition of brown-till samples. The North Shore Volcanic Group, Superior Lowland clastics, and to a lesser degree the Duluth Complex dominate the clast lithology, indicating bedrock sources to the south and southeast (Figure 6).

Brown ice-marginal gravel comprises the distal half of the Highland Moraine, forming a band of hummocky topography 3 km broad trending north-northwest in the southeastern corner of the Isabella Quadrangle. In comparison with the Vermilion Moraine, the Highland Moraine is broader and less prominent. The presence of many ridges, closed depressions, knobs, and kame-like hills attests to the considerable topographic control exerted by ice at this margin. These features become more subdued toward the proximal side of the Highland Moraine, where the brown gravels thin to a discontinuous cover over brown till. Although the gravel is clearly superposed over brown till, no exposure was sufficiently deep to reveal a till core within the Highland Moraine.

The distal edge of the Highland Moraine is obscured by other ice-contact deposits and by outwash deposits and wetlands. The brown ice-marginal gravels and outwash blanket the Vermilion Moraine in the vicinity of Delay and Dumbbell Lakes at the east-central border of the Isabella Quadrangle.

Other Ice-Contact Deposits

Isolated landforms such as eskers and kames are formed upglacier from the ice margin. Their form was controlled by ice contact. Hydraulic processes have a greater effect on sedimentary texture and structure than is the case with ice-marginal gravels, as indicated by the roundness of cobbles and boulders, presence of stratified and graded beds, and lack of fine particles.

Glaciofluvial Deposits Associated with Gray Drift (Gg)

Glaciofluvial deposits associated with gray drift are extremely coarse, partially sorted, and sub-stratified. Matrix is composed almost entirely of coarse sand and gravels (approximately 85% in .5-4mm group) (Figures 3 and 4, Appendix A). At least 20-30 volume percent of any glaciofluvial deposit is composed of large rounded cobbles and boulders of the Duluth Complex and Red Rock Series. Almost all glaciofluvial deposits associated with gray drift are situated in a long narrow zone from Section 29 Lake to Jack Pine Creek, a distance exceeding 10 km. An esker system extends discontinuously along the entire zone, rising an average of 15 m above the surrounding landscape. This system is flanked by outwash pitted with kame and kettle topography. West of Jack Pine Creek, the glaciofluvial gravels grade into an extensive pitted outwash plain abutting the proximal slope of the Vermilion Moraine. It should be noted that the esker system crosses and is oriented perpendicular to the series of ridges in the gray-till ground moraine.

Isolated occurrences of kames and other small ice-collapse features contain fewer boulders and large cobbles in a finer-grained matrix.

Glaciofluvial Deposits Associated with Brown Drift (Gb)

Glaciofluvial deposits associated with brown drift are similar in appearance to those associated with gray drift. Boulders and large cobbles occupy 25% of the material volume and are primarily derived from the Duluth Complex and North Shore Volcanic Group. The matrix is composed of coarse sand, and gravel, containing conspicuous felsic indicators from the North Shore Highland (Figure 6). However, provenance determinations based on rock types in glaciofluvial deposits are speculative, owing to the increased possibility of selected particle sorting by hydraulic processes.

All brown glaciofluvial deposits are situated on the distal side of the Highland Moraine, an indication of ice extension beyond the Highland Moraine prior to final wastage and retreat. Further evidence of ice extension beyond the line formed by the Highland Moraine is found in the brown till end/ground moraine complex in the western quarter of the study area.

Glaciofluvial deposits associated with brown drift generally occur as large kames or isolated esker remnants south of the town of Isabella. These deposits are expressed as high steep-sided features surrounded by outwash and boggy drainageways emanating from the Highland Moraine. These outwash deposits associated with brown drift bury and subdue the surface expression of the glaciofluvial features.

Proglacial Outwash

These deposits are typically sandy and well-sorted, containing stratified and graded beds. The valley trains were utilized to trace the path of meltwater drainage and resolve time-stratigraphic relations. Color and particle lithology may indicate ice-lobe source, but meltwater drainage could have issued from both ice lobes and coalesced to deposit one mixed unit. Therefore, origin is determined by stratigraphic relationships and orientation relative to other landforms.

Outwash Deposits Associated with Gray Drift (Og)

Outwash deposits associated with gray drift are quite variable but typically contain well-sorted and well-rounded sands and gravels (Figures 3 and 4, Appendix A). Stratification is evident in exposures along with other sedimentary structures such as graded beds, cross-beds, and channel features. The sand tends to be gray (2.5Y hue) indicating Duluth Complex/Granitic rock/Vermilion District lithologies similar to other materials of gray provenance (Figures 5 and 6). Mixing with other units obscures the origin of outwash sediments.

All gray outwash deposits are associated with depressions in the gray-till ground moraine. Pitted outwash plains are located on the flanks and at the downstream end of the esker system. The pits and occasional collapse structures indicate deposition in the presence of small blocks of stagnant ice. The remaining outwash deposits occupy valleys between the transverse ridges of the ground moraine. Drainage was to the west behind the Vermilion Moraine, forming an extensive system referred to as the Sawbill Outwash Plain (Univ. of Minn. Soil Science Dept. Map, 1977). This system extends west more than 30 km and occupies a shallow depression 5-10 km wide between the Vermilion Moraine and the Border Lakes Area. The northern boundaries of the Isabella Quadrangle and the Sawbill Outwash Plain roughly coincide.

Outwash Deposits Associated with Brown Drift (Ob)

Outwash deposits associated with brown drift are also highly variable, ranging from extremely well-sorted medium-grained sands to coarse gravels (Figures 3 and 4, Appendix A). Channel structures, cross-beds and graded beds are evident. Lithologic variability was probably introduced when ice-margin meltwater eroded previously deposited gray drift. While the diagnostic felsite indicators are always present, significant quantities of mafic intrusives, granites, and metamorphics were identified, indicating mixed gray/brown origin.

The most extensive brown outwash system lies on the distal side of the Highland Moraine, burying parts of the brown till recessional moraine/ground moraine complex, brown glaciofluvial deposits, and the Toimi Drumlin Area. While some meltwater channels drain southward off the Highland Moraine, most brown outwash deposits coalesce and funnel north and northeastward toward the town of Isabella. The town itself is constructed on a flat gravelly outwash plain that converges into a large, deep channel now occupied by the Little Isabella River. The channel eroded extensively into the distal margin of the Vermilion Moraine.

The major drainageway continues northwestward, emerging into another large brown outwash plain complex containing Flat Horn and Fishfry Lakes. Gravel pits in this complex present the best outwash exposures of the study area, exhibiting complex and detailed channel structures and outwash stratification. Topography remains quite smooth, with occasional small pits and gravelly mounds as evidence of minor stagnant-ice remnants. Most drainage continued northward from the Fishfry/Flat Horn Lakes outwash complex through the Vermilion Moraine to a confluence with gray and undifferentiated outwash deposits in the region of Grouse and Mitawan Lakes. Some drainage may have been diverted westward between the brown till recessional moraines, as indicated by the presence of boggy drainageways.

Another brown outwash sequence is associated with brown glaciofluvial deposits and brown ice-marginal gravels at the junction of the Highland/Vermilion Moraines. Outwash channels drain off the Highland Moraine and cut through the Vermilion Moraine, draining to the west and northwest toward the mixed undifferentiated outwash complexes near Grouse and Mitawan Lakes.

Most drainage paths can be traced through lakes within the Vermilion Moraine. One expansive outwash drainage system runs through Round Island, Delay, Redskin, Bine, and Eighteen Lakes along the proximal margin of the Vermilion Moraine. A large flat gravelly outwash plain was deposited around Eighteen Lake before meltwaters became constrained to a narrower drainageway now occupied by Hill Creek.

Lesser drainageways can be traced northwestward from Dumbbell, Tanner, and Divide Lakes, crossing the gray till ground moraine before merging with outwash deposits from the esker system. These meltwater paths were identified from outwash deposits and boggy drainageways within the gray-till ground moraine. Some of these drainageways were controlled by the transverse ridge topography of the ground moraine.

The overall topographic smoothness and extent of brown outwash features suggest high volumes of meltwater emanating from a glacier at the Highland Moraine margin and a lack of stagnant ice. Stratigraphic superposition and cross-cutting relationships with gray-drift landforms conclusively demonstrate that outwash associated with brown drift post-dates the wastage of ice from the Vermilion Moraine.

Lag Accumulations (Lb)

Lag accumulations result from increased meltwater velocity created by flow into narrow, restricted channels. A cobble/boulder residual is created as all fine- to medium-grained material is washed from the deposit. Lag material is very well-rounded and equally represents gray and brown provenance.

Two major lag accumulations were identified, both associated with outwash from the brown-drift Highland Moraine. An extensive lag boulder accumulation is exposed in the Little Isabella River drainageway along the distal margin of the Vermilion Moraine. The outwash plain deposits of the Isabella town center coarsen continuously as the

Little Isabella River drainageway is approached, indicating increasing flow velocities as the meltwater discharge became restricted to a narrow channel cross-section. Within the channel, a thin mantle of alluvium and organic soil covers well-rounded lag boulders ranging from 10 to 75 cm in diameter. The restricted drainageway opens up into the Fishfry/Flat Horn Lakes brown outwash complex. At present, the extremely underfit Little Isabella River occupies the lag channel, retracing the path of brown outwash from the Highland Moraine.

A smaller lag channel parallels the Little Isabella River drainageway on the proximal flank of the Vermilion Moraine and is traced by the drainage of modern-day Hill Creek. The Eighteen Lake outwash plain converges into this cobble and boulder deposit before emerging at the Grouse/Mitawan Lakes outwash complex. The smaller particle size (4 to 50 cm diameter) attests to the lower flow velocities related to lower meltwater discharges compared to those of the Little Isabella River drainageway.

Lag accumulations were also identified on a minor scale in boggy drainageways between ridges in the gray-till ground moraine. These deposits consist of well-rounded coarse gravel and cobbles of mixed gray/brown provenance. Most of the minor lag accumulations occur in the region between Trappers and Spear Lakes and the esker system. These small drainageways and associated outwash deposits represent minor drainage from the Highland Moraine flowing through the Vermilion Moraine.

Loess

A thin cap of brown silty loess mantles all non-organic deposits of the study area. Thicknesses range from .25 to .75 m with the thinnest cover at higher elevations. This material almost everywhere contains a significant percentage of stones, a factor that would seemingly preclude eolian transport. In fact, mechanical analysis reveal a matrix composed entirely of very fine sand and silt, extremely well-sorted, and containing none of the coarser sand common to till or proglacial outwash (Figures 3 and 4, Appendix A). In all cases, the quantity and lithology of stones within the loess cap are traceable to the underlying material. A mixing layer between the cap and underlying material is evident, with stone concentrations decreasing toward the surface. In some instances, large boulders are exposed on the surface of ground moraines, totally contained within the loess. It is suggested that all stony material has been elevated into the silt, perhaps during a periglacial period of pronounced frost action, as described by Tricart (1970). He notes that progressive uplift of stones due to freez-thaw cycle action is most pronounced in finer material where the soil frost-swelling capacity is increased. The high degree of sorting, the dominance of silt, and the distribution as a thin blanket over all topography suggest eolian deposition as loess.

The loess is clearly derived from glacial deposits of brown provenance. Hues of loess samples match those of brown till samples. Exposures in the brown-till ground moraine demonstrate that the contact between loess and the underlying brown till is visually indistinguishable.

Loess is characteristically associated with major meltwater river valleys (Flint, 1971), but none are evident in the immediate area. The very thin cover suggests a low-volume source, however, which could be attributed to newly exposed outwash plains. Meltwater drainage off ice behind the Highland Moraine converges into a very extensive series of outwash plains immediately west of the Isabella Quadrangle (Stark, 1977). No other source of silt is apparent in the region.

Although a discontinuous layer of loess mantles the entire region, no specific mention of this material occurs in the literature concerning northeastern Minnesota. Grigal (1969) notes that the uppermost soil horizons of samples taken in the Isabella Quadrangle bear no relation to the C horizon, but he makes no attempt at an explanation. It is highly unlikely that a silty cover would form from underlying coarse crystalline material.

Peat Deposits

A significant area of the Isabella Quadrangle is covered with peat deposits. These organic soils form when lack of adequate drainage retards the decomposition of vegetation.

The sandy tills, outwash, and ice-contact deposits are all extremely permeable, but poor drainage exist in till-plain depressions, meltwater drainageways, or areas of thin drift over relatively impermeable crystalline bedrock, provided the surface slope is insufficient to facilitate rapid runoff.

Two major bog networks are found in the area. One is associated with the distal side of the Highland Moraine along meltwater drainageways leading northward toward the Little Isabella River channel, and southwestward toward the present-day Cloquet River system, extending westward into depressions in the Toimi Drumlin Area till plain. Additional related peat deposits occur within the brown-till ground moraine on the proximal side of the Highland Moraine, outlining drainage paths leading northwestward toward the junction of the Highland Vermilion Moraines and southeastward into the Superior Lowland. The crest of this divide coincides with Forest Service Road No. 382, passing through Manitou Junction, in the southeast corner of the study area.

The second major bog network is associated with drainage through the gray-till ground moraine behind the Vermilion Moraine, in the linear troughs between the transverse ridges or in other till-plain depressions. These are areas of thinner drift cover and are therefore presumably closer to underlying bedrock.

Additional localized peat deposits are associated with the hummocky topography of ice-marginal gravel. These deposits occur in kettle depressions commonly shared with small ponds. The depressions intersect the local water table, and the lakes thereby formed underwent a succession to bogs as they became filled with sediment.

Peat deposits belong to the Histosol Order of soils, as defined by the U.S. Comprehensive Soil Classification System (Buol et al., 1973). The majority of drainageway and till plain bog deposits belong to the Fibric suborder, composed of relatively undecomposed organic material in which vegetation remains are still recognizable. Kettle bog peat tends to be more fully decomposed, rendering most vegetation remains unrecognizable and therefore representative of the Hemic suborder. In both cases, very little mineral material in the peat deposits is present. Drainageway and till-plain peats range from .5 to 1.5 m in thickness. Organic material is probably thicker in kettle bogs, although no measurements were made.

Drift Thickness

The absence of bedrock outcrops or deep drift exposures preclude detailed determination of drift thickness. However, the occurrence of extensive bedrock outcrops less than 10 km north of the study area, and the lack of drainage through extremely permeable materials in low lying areas, suggest a thin drift cover.

The International Nickel Company drilled 249 exploratory holes north of the Vermilion Moraine in the adjacent Gabbro Lake Quadrangle (Stark, 1977). Drift thickness in these holes averaged 3.5 m.

Thicker deposits coincide with the Highland and Vermilion Moraines. The deepest roadcuts in these features expose at least 12 m of ice-marginal gravel and till. Relief on these moraines relative to the surrounding landscape suggests drift thicknesses exceeding 18 m, assuming no bedrock control. Drift should generally be thicker on the distal sides of the moraines, owing to the extensive outwash deposits identified there.

Geomorphic Summary

The geomorphic features within the Isabella Quadrangle are summarized below and on Plate II. The most prominent features of the study area are the merging Highland and Vermilion Moraines. The junction occurs in the neighborhood of Delay and Dumbbell Lakes, where proglacial outwash and ice-contact deposits associated with the Highland Moraine lap onto and breach the Vermilion Moraine. These outwash deposits continue along the proximal margin of the Vermilion Moraine, funneling into a restricted drainageway, then re-emerging as extensive outwash complexes near Grouse and Mitawan Lakes. The prominence of both moraines is no longer apparent east of their juncture.

Additional ice-contact and proglacial outwash deposits are situated on the distal side of the Highland Moraine. These deposits coalesce into a large outwash plain at the town of Isabella. The outwash plain converges into a drainageway now occupied by the Little Isabella River. This drainageway opens onto another outwash complex containing Flat Horn and Fishfry Lakes. From here, outwash paths continue westward between two brown till recessional moraines and northward toward the Grouse/Mitawan outwash system.

The northeast-trending Toimi drumlins and associated gray-till ground moraine are truncated to the north by the brown-till end/ground moraine complex and to the east by the Highland Moraine. Outwash from the Highland Moraine extends into the Toimi Drumlin Area. This outwash has been traced to the southwest through valleys between the drumlins and into the proglacial lakes Upham and Aitken (Wright, 1972b) of the Automba phase.

The brown till end/ground moraine complex are in turn truncated to the north by the Vermilion Moraine and buried on the east by ice-contact and proglacial outwash material associated with the Highland Moraine.

Another brown-till ground moraine is situated on the proximal side of the Highland Moraine. Boggy drainageways in this ground moraine delineate a divide between meltwater flowing northwestward toward the junction of the Vermilion and Highland Moraines and southeastward into the Superior Lowland.

The gray-till ground moraine proximal to the Vermilion Moraine is overrun with outwash and ice-contact deposits. A conspicuous esker system trends northwest to southeast through the ground moraine, terminating in extensive pitted outwash plains that in turn merge with the Grouse/Mitawan Lakes outwash complex. Numerous northwest-trending outwash trains and boggy drainageways cross the ground moraine in valleys between a parallel series of ridges. These ridges are oriented parallel to the Vermilion Moraine and normal or oblique to the esker system. At the Vermilion Moraine, the ridges merge into a gently rolling till plain upland with no preferred orientations.

Outwash deposits north of the Vermilion Moraine drain westward across the Sawbill Outwash Plain, toward the Mesabi Range (Univ. of Minn. Soil Science Dept. Map, 1977).

SEQUENCE OF EVENTS

St. Croix Phase

The ground moraine of the Toimi Drumlin Area represents the oldest feature exposed in the study area. All other drift types identified are stratigraphically superposed on the Toimi Drumlin Area till. This gray till was deposited by ice flowing from a northeastern source, as determined by drumlin trends and rock-fragment identification. The Toimi ground moraine was therefore deposited by the Rainy Lobe flowing southwestward toward the St. Croix Moraine in central Minnesota.

The northern part of the St. Croix Moraine contains till of Rainy Lobe origin, but the southern part contains till derived from the Superior Lowland, indicating a contemporaneous advance of the Rainy and Superior Lobes at this time, although Superior Lobe drift of this age was not identified in the study area.

Radiocarbon Dates

Radiocarbon dates of basal sedimentary layers in lakes on deposits of the St. Croix phase lead to the conclusion that St. Croix phase ice attained its maximum extent at least 20,500 yr B.P. (Wright, 1972b). Dates from two lakes in the Toimi Drumlin Area of the St. Croix phase yield ages of approximately 15,000 years (Florin and Wright, 1969) but Birks (1980) suggests that Automba phase outwash was deposited after the lakes were originally formed. Lakes developed in the St. Croix Moriane have been dated at approximately 12,000 yr B.P., but Florin and Wright (1969) demonstrate that the time lag between exposure of a moraine and the onset of organic sedimentation into a newly formed lake could be thousands of years, assuming insulation of stagnant ice blocks by a mantle of glacial drift. The 20,500 yr B.P. St. Croix date was taken from a lake formed in a drumlin-field depression where the absence of a mantle of superglacial drift permitted permanent lake formation soon after ice retreat. That date therefore more closely defines the actual age of the St. Croix phase.

Glaciological Conditions

The occurrence of streamlined terrain in the Toimi ground moraine is useful in determining basal ice conditions of the St. Croix phase Rainy Lobe. The streamlined form of drumlins requires conditions permitting shaping by basal sliding of the overriding glacier (Moran *et al*., 1980). Therefore, the local thermal gradient must have been such that the pressure-melting point was reached at the bed. The glacier flow over a frozen bed cannot normally deform the bed because the shear strength of the frozen substrate materials exceed that of ice (Clayton and Moran, 1974). Thus the ice attained basal pressure-melting temperatures in areas where material was available for drumlin formation, as evidenced by the several drumlin fields proximal to the St. Croix Moraine.

At the close of the St. Croix phase, the Rainy Lobe receded to a position near the Minnesota/Canada border, and the Superior Lobe retreated at least to the outer limits of the Superior Lowland

(Wright, 1972b). Stagnant ice in the Toimi Drumlin Area is expressed today as kettle lakes or depressions. Much of the Toimi drumlin field has been covered by drift of later ice readvances.

Automba Phase

The remaining glacial materials in the study area were deposited by the Rainy and Superior Lobes during the Automba phase. Two brown-till end moraines and glaciofluvial deposits on the distal side of the Highland Moraine indicate Superior Lobe extension beyond the Highland Moraine. Similarly, two subsidiary Rainy Lobe moraines have been identified immediately south of the Vermilion Moraine in the adjacent Greenwood Lake Quadrangle (Stark, 1977). All of these minor moraines and the Vermilion Moraine hinge about a common point in the region of Gunsten Lake, 10 km due west from Cat and Grouse Lakes. This hinge point represents the interlobate junction between the Rainy and Superior Lobes prior to wastage of the Superior Lobe back to the Highland Moraine position. East of the hinge point, the confluence of Rainy and Superior lobes is not expressed as any identifiable land-form. The same situation was also noted by Wright (1972b) east of the junction of the Highland and Vermilion Moraines. He contrasted the lack of debris associated with the joining of two continental glacier ice lobes with the formation of medial moraines at the confluence of alpine valley glaciers.

Superior Sublobe

The lack of brown till exposures southwest of the two pro-Highland end moraines attests to the limited extent of ice advance beyond the Highland Moraine. While the northern limit of this extension cannot be determined, it is assumed that contemporaneous southerly flow of the Rainy Lobe would constrain any substantial northern expansion. The Superior Lobe extension is therefore pictured as a narrow sublobe bounded on the north by the Rainy Lobe (Figure 7).

The advance of the Automba phase Superior sublobe clearly predates the advance of the Rainy Lobe. Rainy Lobe recessional moraines bend northward abruptly where they meet Superior sublobe recessional moraines, an indication that the southward extent of Rainy Lobe ice was constrained by the presence of the Superior sublobe (Figure 11).

It is not clear why the Superor sublobe developed where it did or why the Superior Lobe advance preceded that of the Rainy lobe. The development of the sublobe could be attributed to a depression in the bedrock surface. While no direct evidence of a depression exists, geomorphic and stratigraphic relationships demonstrate that the Rainy Lobe advanced into the area vacated by the Superior sublobe after both ice masses began to disintegrate. Such preferential ice-flow behavior would seem to indicate a lowland or depression.

Several factors could have caused the Superior Lobe to advance earlier than the Rainy Lobe. The glacial response to climatic change may have been transmitted more rapidly from accumulation center to terminus for the Superior Lobe. A greater volume of ice behind the

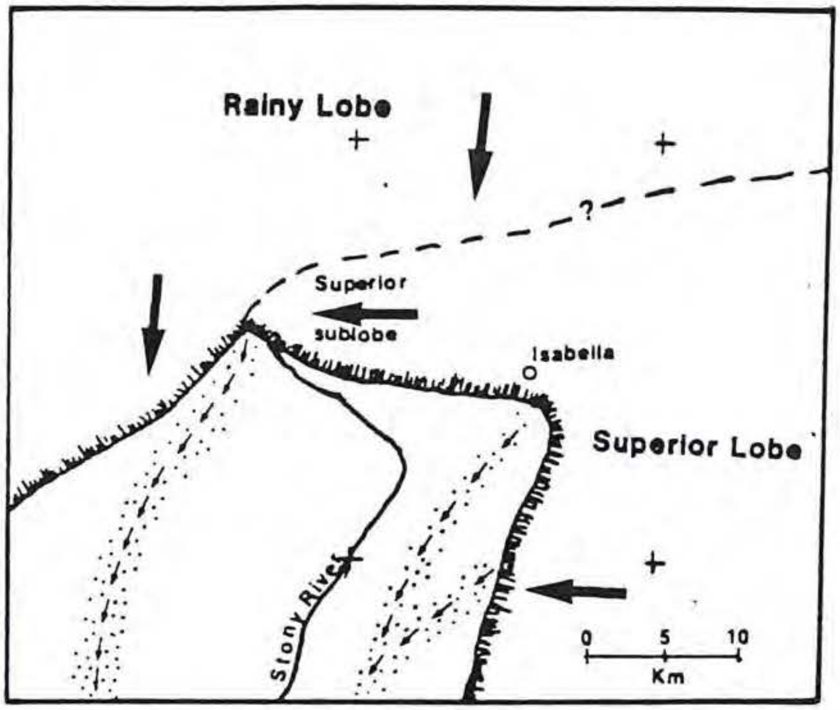


Figure 7 Maximum Extent of Automba Phase

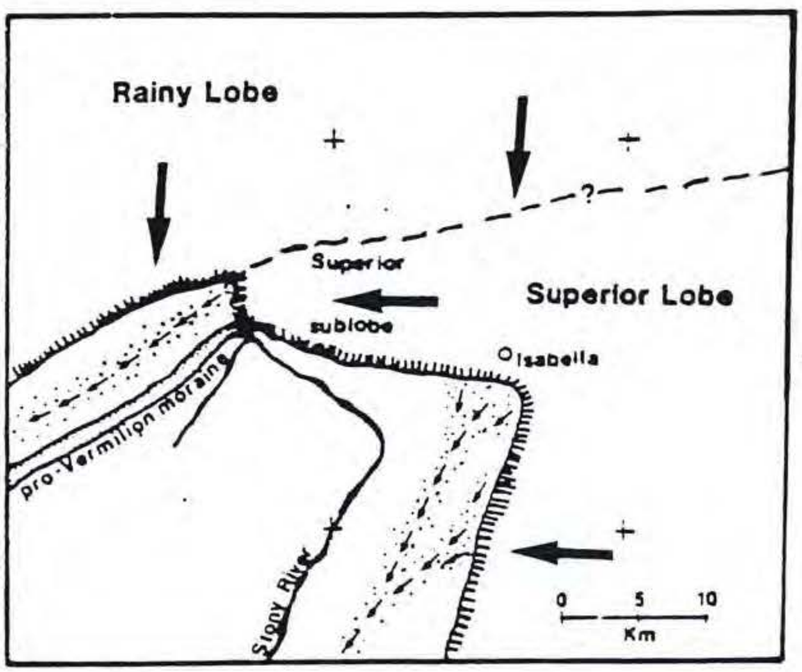
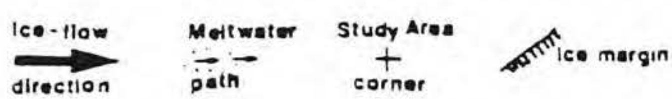


Figure 8 Rainy Lobe Retreat from First pro-Vermilion Moraine



Superior Lobe or a shorter distance from the accumulation center could contribute to the more rapid response.

Meltwater drainage paths were traced from the Rainy/Superior Lobes junction southwestward through the Toimi Drumlin Area and into the present-day Cloquet River system. Later, outwash trains from the Superior Lobe were deposited westward as the Rainy Lobe retreated (Stark, 1977).

Recession of Ice Lobes

The Rainy Lobe wasted back to its northernmost pro-Vermilion end moraine while the Superior sublobe remained active, as demonstrated by the occurrence of brown Superior Lobe drift superposed on the gray-till ground moraine between the southern and northern end moraines (Figure 8). The Rainy lobe continued wasting back to the Vermilion Moraine as the Superior sublobe receded to another pro-Highland end moraine. This moraine meets the three Rainy lobe moraines at the aforementoned hinge point, demonstrating that the Superior sublobe contracted in width but maintained its western extent (Figure 9). Outwash from the Superior Lobe was traced from the hinge point area westward between the northernmost pro-Vermilion end moraine and the Vermilion Moraine proper, demonstrating that the Rainy Lobe had receded northward as the Superior sublobe contracted. Meltwater from both ice masses was trapped and ponded in lowlands between the northernmost pro-Vermilion end moraine and the Rainy Lobe terminus, forming proglacial lakes 20 to 50 km west of the Superior sublobe (Winchell, 1901).

The marginal location of the Superior Lobe proper cannot be ascertained for this time period, but may have been parallel to, and 3 km west of the Highland Moraine's distal edge, where substantial ice-contact landforms exist.

Rainy Lobe Extension

The Superior sublobe disintegrated rapidly as the ice retreated to the Highland Moraine position, and the Rainy Lobe extended into the vacated area (Figure 10). The rapid disintegration is marked by scattered isolated ice-contact deposits to the distal side of the Highland Moraine, south of the extended Rainy Lobe drift. Rainy Lobe extension beyond the original Vermilion Moraine is indicated by an abrupt southward bend in the moraine immediately east of the hinge point, and an equally abrupt change in the character of ice-marginal material. The extended section of the Vermilion Moraine is composed of hummocky ice-marginal gravels (Ig), while the remainder is smoother and composed of till (Tg).

It is presumed that the change in ice-marginal drift characteristics is a result of rapid extension, thinning, and consequent stagnation of the Rainy Lobe at the pro-Vermilion Moraine position. The ice-marginal gravels exposed in the study area are very similar texturally and morphologically to stagnant-ice deposits identified in southwestern Canada (Gravenor and Kupsch, 1959). The lack of landforms attributable to the northern margin of the Superior sublobe indicates confluence with the Rainy Lobe and the absence of ice-

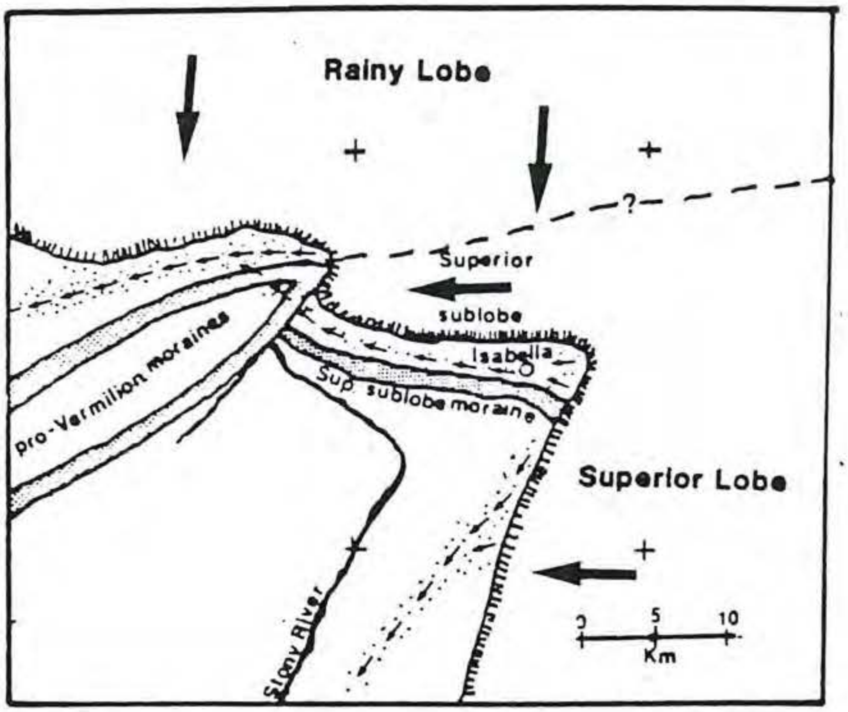


Figure 9 Recession of Rainy Lobe and Superior Sublobe.

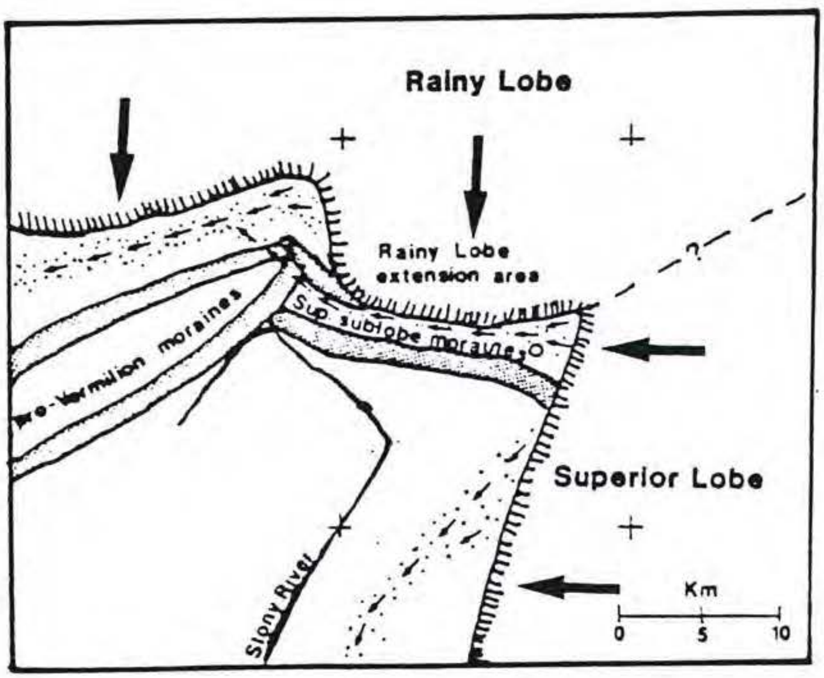
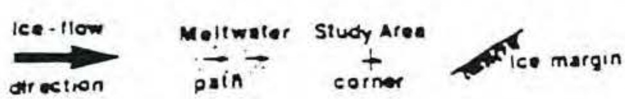


Figure 10 Retreat of Superior Sublobe and Extension of Rainy Lobe.



marginal features north of the extended Vermilion Moraine demonstrates the immediate and rapid advance of the Rainy Lobe as the Superior Lobe retreated. This extension commenced as the major portion of both ice lobes was either steady or receding, a circumstance favoring ice stagnation. The presence of significant ice-contact features within the extension area is a further indication of extensive disintegrating stagnant ice. Ice-contact features associated with the Rainy Lobe outside the extension area are noticeably absent.

Similar conditions existed at the margin of the Superior Lobe. Ice extended slightly beyond the Highland Moraine position, thinned and stagnated, forming ice-contact features.

Ice-marginal gravels of the Highland and Vermilion Moraines merge in the vicinity of Delay and Dumbbell Lakes. The similarity between morainal deposits and the absence of marginal landforms east of the junction indicates contemporaneous and conterminous existence of Rainy and Superior ice under similar environmental conditions.

Origin of Transverse Ridges

The topographic expression of the ground moraine in the Rainy Lobe extension area differs markedly from ground moraines of adjoininng areas. The extension area is characterized by a band 5 km wide of parallel till ridges proximal to the Vermilion Moraine and oriented normal to the Rainy Lobe flow path. Other Rainy Lobe ground moraines exhibit either no preferred orientations or contain streamlined landforms aligned parallel to ice flow. Transverse ridge features concentrated along ice margins have been identified in North Dakota, Alberta, and Saskatchewan by Moran _et al_. (1980, in press), and were referred to as composite thrust ridges. Descriptions of the composite thrust ridges compare very favorably with those in the study area. In both cases, parallel ridges are limited to a narrow band proximal to an ice margin, oriented normal to the ice flow path, and are situated on the upslope edge of major uplands (the North Shore Highland, in this case). Ridges in the study area are composed of a variety of materials ranging from till to bedrock.

Moran _et al_. contrasted the glaciological conditions of formation between streamlined and transverse landforms. The contrast is of particular interest because both types of glacier-bed landforms have been identified in the Isabella Quadrangle. As stated previously, streamlined landforms are attributed to shaping by basal sliding mechanisms in areas where the pressure melting point has been achieved on the glacier bed. Composite thrust ridges result from shearing of substrate material from the bed. A frozen glacier bed is required to transmit shear stress from ice to the substrate. Even then, the shear strength of most substrate materials exceeds that of ice. Moran _et al_. observed that thrusting occurred in areas where the potential for elevated substrate pore-water pressure was enhanced. The basal water pressure head was transmitted downglacier, then maintained at the margin wherever groundwater drainage was confined by a stratigraphic pinchout, by permafrost, or by ice. Elevated pore-water pressures serve to decrease the shear strength of bed materials to the point of failure. Failure occurred as thrust blocks that were transported and emplaced downglacier in a position of decreased pore-water pressure (i.e. increased shear resistance) or by refreezing to the bed. The strike of the shear plane is oriented perpendicular to the maximum principal stress direction (ice-flow path), producing transverse glacier-bed thrust block landforms.

The conditions outlined above could have occurred in the Rainy Lobe extension area. The thinned ice encouraged development of a frozen glacial toe, and a combination of adverse bed slope and thin drift cover over impermeable rock promoted the confinement of basal groundwater. The lack of primary sedimentary structures in till precludes direct observation of sheared or deformed beds. Detailed till-fabric analyses would have aided in discussion of the origin of the transverse ridges, but such a project is beyond the scope of this study.

Composite thrust blocks are only preserved near the margins because farther upglacier the blocks were exposed to thawed-bed basal sliding conditions, causing erosion, deformation, and sculpturing. The transition zone between thrust block and streamlined terrain has been identified in many areas by Moran et al. (1980, in press). If such a mechanism was in operation then further support is provided for conclusions derived from stratigraphic evidence. Although similar in composition, the Toimi Drumlin Area ground moraine is in no way temporally related to the ground moraine proximal to the Vermilion Moraine. The streamlined features of the Toimi Area would have formed upglacier (i.e. farther north) of the transverse ridge ground moraine if both areas were developed during the same phase. While it was not determined whether or not transverse ridges occur near the St. Croix Moraine southwest of the Toimi drumlins, streamlined features are evident on topographic maps upglacier from the Rainy Lobe extension area.

It should be noted that alternative hypotheses exist regarding the formation of transverse glacial features. Lundqvist (1969) studied similar features in Sweden, referred to as ribbed or Rogen moraine, and he proposed a mechanism involving no basal shearing. Instead the ridges formed in positions of major transverse crevasses during phases of glacial extension. The transverse features in this study area could have been deposited in a zone of extensive flow during the latest advance of the Rainy Lobe. However, Lundqvist noted that the transition from Rogen moraine to drumlinoid forms progressed in a downglacier direction, opposite from the configuration in the Isabella Quadrangle. Gravenor and Kupsch (1959) suggest that saturated basal till could be injected into subglacial cavities. Again, in the absence of till fabric data, definitive statements cannot be made to support such a mechanism. The ice-thrust mechanism as outlined by Moran et al. (1980, in press) most closely describes the features identified in this study area and is therefore considered the most attractive at this time. The mechanism can be utilized to envision glaciological conditions in the Rainy Lobe extension area. Comparatively thin ice advance against a frozen toe, shearing off sections of the substrate, then emplacing and smoothing the blocks into a series of smoothly rounded parallel ridges.

Retreat of Ice Lobes

Superior Lobe ice-contact features emanate from the northern end of the Highland Moraine and are superposed on Vermilion Moraine ice-marginal gravels. The ice-contact features are flanked with outwash traced to the west and northwest through Rainy Lobe drift. Outwash deposited by meltwater from Rainy Lobe is pitted with kettles resulting from stagnant ice. Superior Lobe outwash features are flat and smooth, even where Superior Lobe meltwater breached the extended part of the Vermilion Moraine. Therefore, although both lobes existed contemporaneously, the Superior Lobe persisted at the Highland Moraine while the Rainy Lobe wasted back from the Vermilion Moraine extension area (Figure 11). The Rainy Lobe extension is envisioned as an ephemeral advance prior to general wastage from the Vermilion Moraine proper.

The lack of marginal features east of the Highland/Vermilion Moraine junction indicates mutual retreat of both ice lobes after dissociation into discrete ice masses. Rainy Lobe meltwater drained westward behind the Vermilion Moraine constructing the Sawbill Outwash

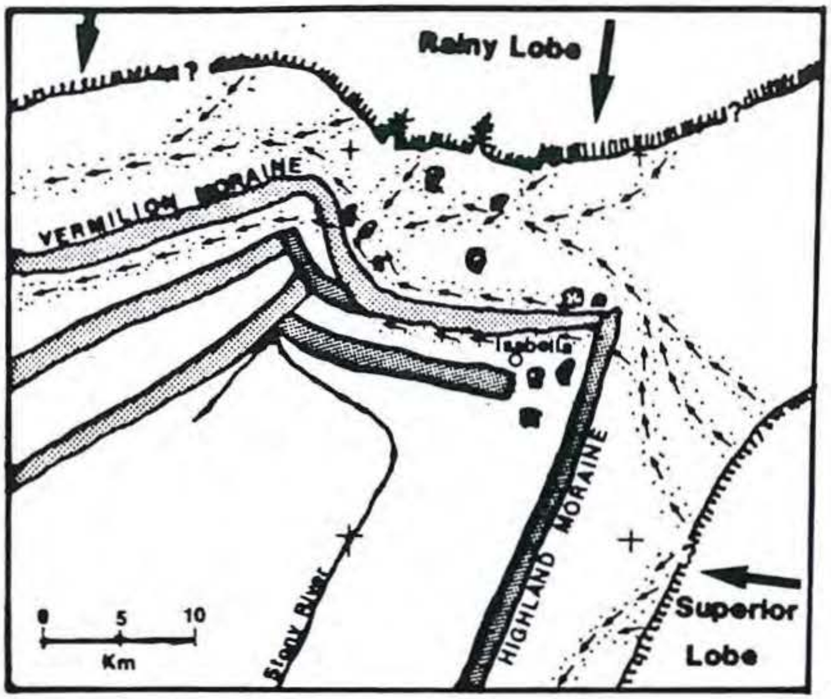

Rainy Lobe
VERMILION MORAINE
Isabella
HIGHLAND MORAINE
Stony River
Superior
Lobe
0 5 10
Km

Figure 11


Ice-flow direction
Meltwater paths
Study Area
Ice margin

Plain. Superior Lobe meltwater initially flowed westward toward the Giant's Range, but with further retreat the ice front crossed the North Shore Highland divide, diverting meltwater southwestward toward the present-day Cloquet River System.

As both lobes receded, silt was winnowed by the wind from outwash and flood-plain deposits to the west and southwest and deposted as a thin blanket over most of the study area. The loess blanket was situated in a periglacial zone where frost action elevated stones from the underlying drift into the silt.

Radiocarbon Dates

No direct radiocarbon dates are available from basal sediments in lakes in Automba phase deposits, owing to the lack of good stratigraphic records (Wright, personal communication, 1980). Birks (1980) recorded a date of approximately 16,000 years ago from Kylen Lake, immediately southwest of the Isabella Quadrangle in the Toimi Drumlin Area. He suggests that proglacial outwash from the Automba phase was deposited in the Kylen Lake basin approximately 1,000 years earlier. This would account for the anomalously late date for a lake situated in deposits of the St. Croix phase, dated elsewhere at greater than 20,500 yr B.P. (Wright, 1972b). A post-St. Croix phase date of approximately 15,000 yr B.P. was also recorded at Weber Lake situated in the Toimi Area, less than 12 km south of the Vermilion Moraine (Wright, 1972b). These lake dates establish a later limit of 16,000 yr B.P. for the Automba phase, the earlier limit being the

20,500 yr B.P. age of St. Croix phase sediments deposited in drumlin area depressions.

Post-Automba Phase Events

Later drift deposited in the Superior Lowland indicates at least two additional phases of the Superior Lobe, but neither advance flowed laterally out of the Superior Lowland into the study area (Wright, 1972b). Rainy Lobe deposits contemporaneous with the last Superior Lobe phases have not been identified.

Lakes developed in stagnant ice-block depressions at the junction of the Highland and Vermilion Moraines and in the outwash complexes on the proximal and distal edges of the Vermilion Moraine. Other depressions and areas of poor drainage have developed into extensive wetlands that trace the former courses of glacial meltwater. Most of the present-day drainage flows westward into the Stony, Cloquet, and St. Louis Rivers, while water on the proximal side of the Highland Moraine flows southeastward into the Manitou River, then into Lake Superior.

SUMMARY

Field mapping and laboratory analyses established a basis for cataloguing surficial deposits in the Isabella Quadrangle. The following drift units were used: Till, Ice-Marginal Gravel, Outwash, Glaciofluvial Deposits, Lag Accumulations, and Loess. In addition, peatlands were also identified and mapped. Surficial units are dervied from two distinctly different provenances, based on comparisons between rock types incorporated in the drift and the regional bedrock geology. 'Gray' drift is derived from crystalline and metamorphic rocks of the Border Lakes Region to the north and northeast, while 'brown' drift incorporated larger quantities of volcanics and clastics from the North Shore Highland and Superior Lowland to the southeast. These deposits were formed by two ice masses, termed the Rainy and Superior Lobes respectively.

Two phases of ice advance were identified on the basis of stratigraphic relationships. The St. Croix phase (ca. 20,500 yr B.P.) represents an advance of the Rainy Lobe from the northeast, forming the ground moraine in the southwest corner of the study area, part of the Toimi Drumlin Area. In the second, or Automba phase (ca. 16,000 yr B.P.) the Rainy and Superior Lobes deposited a series of end moraines over the ground moraine of the St. Croix phase.

The topography is dominated by the Vermilion and Highland Moraines, formed by the Rainy and Superior Lobes. These major features merge at Dumbbell and Delay Lakes immediately east of the town of Isabella. Subsidiary end moraines demonstrate that the ice lobes initially advanced farther than the margins indicated by the Highland and Vermilion Moraines. Although the Rainy and Superior Lobes coexisted, the geometry of contorted subsidiary end moraines indicates that at least a sublobe of the Superior Lobe advanced into the study area before the Rainy Lobe. As this sublobe receded, a portion of the Rainy Lobe became free to extend into the vacated area that covers the northern half of the Isabella Quadrangle. Numerous glacial landforms of interest are located in the Rainy Lobe extension area, including a long discontinuous esker system, a series of transverse till ridges proximal to the Vermilion Moraine, and an extensive complex of proglacial outwash deposits.

The transverse ridges may have formed as a result of shearing and block-thrusting of a frozen substrate, accompanied by decreased shear resistance in the presence of excess pore-water pressure. These conditions contrast with those involved in the formation of streamlined drumlinoid terrain. Streamlined terrain may have resulted from basal sliding over previously emplaced thrust blocks.

Disintegration of both ice lobes resulted in deposition of many ice-contact landforms as ice receded from the area. Outwash may have been deposited in depressions in the previously formed Toimi Drumlin Area, providing a basis for radiocarbon dating of the Automba phase, utilizing basal organic lake sediments. The Superior Lobe advanced again in later phases but never reached the study area.

Loess was winnowed from outwash plains to the west and southwest and deposited as a thin blanket over the entire region. Extensive wetlands formed in areas of poor drainage. Lakes formed at the junction of the Highland and Vermilion Moraines and in the proglacial outwash complexes as stagnant ice blocks melted out of the surrounding drift. Present-day surface-water drainage tends to parallel the hypothesized drainageways of glacial meltwater.

CONCLUSIONS

The atypical ice-contact composition of the Highland and Vermilion Moraines prompted a departure from conventional nomenclature for surficial deposits. The separation of ice-contact materials into ice-marginal gravels and glaciofluvial deposits may be cause for confusion because they are similar texturally. The distinction is justified however, because the units are exposed in wholly dissimilar landforms and represent different glaciological locations. Others also have made similar distinctions in areas of extensive ice disintegration features (Gravenor and Kupsch, 1959; Fulton, 1967).

The overall sequence of events conforms with the general chronology of Wright (1972b). Descriptions of local complexities of the interactions between the Rainy and Superior Lobes support observations made directly to the west by Stark (1977). The southernmost of the two pro-Vermilion end moraines is actually a prominent regional feature referred to as the Big Rice Moraine (Univ. of Minn. Soil Science Dept., 1977) and extends from the hinge point area at least 40 km to the west. Small-scale mapping and reconnaissance has exposed further complexities of ice lobe advances and retreats in this area.

Suggestions for Further Work

A number of aspects of this study would be improved by additional work. Analyses of till fabric within streamlined ground moraine, end moraines, and transverse ridges could provide more substantive information on which to base hypotheses of glaciological conditions. The lack of well-log information prevented determinations of drift thickness and deeper stratigraphic relationships. Augering several sites might provide additional support for premises made in this paper regarding relative superposition of units, occurrence of bedrock depressions, causes of poor subsurface drainage, and composition of the cores of the Highland and Vermilion Moraines.

Additional field work east of the junction of the Highland and Vermilion Moraines might identify features associated with the dissociation of the Rainy and Superior Lobes at the close of the Automba phase.

Lastly, direct radiocarbon dating of lakes in landforms of the Automba phase would aid in refining the chronology for the entire region. Perhaps lakes immediately northeast of the transverse ridge area would provide a sufficiently continuous sedimentary record for this purpose.

REFERENCES CITED

Buol, S.W., F.D. Hole and R.J. McCracken, 1973. Soil Genesis and Classification. Iowa State Univ. Press, Ames, Iowa. 360pp.

Birks, H.J.B., 1980. Late Wisconsin Vegetational and Climatic History at Kylen Lake, Northeastern Minnesota. Limnological Res. Center, Univ. of Minnesota. Unpublished manuscript. 37pp.

Craddock, C., 1972. Late Precambrian, regional geologic setting, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 281-291.

Clayton, L., and S.R. Moran, 1977. A glacial process-form model, in Glacial Geomorphology (D.R. Coates, ed.) Binghampton, State Univ. of N.Y., p. 89-119.

Davidson, D.M., Jr., 1972. Eastern part of Duluth Complex, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 354-259.

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

Embleton, C. and C.A.M. King, 1975. Glacial and Periglacial Geomorphology: Edward Arnold, Ltd., London, 608pp.

Flint, R.F., 1971. Glacial and Quarternary Geology: John Wiley and Sons, Inc., p. 147-192.

Florin, M.B. and H.E. Wright, Jr., 1969. Diatom evidence for the Persistence of stagnant glacial ice in Minnesota. Geol. Society of America Bull., vol. 80, p. 695-704.

Folk, R.L., 1974. Petrology of Sedimentary Rocks: Hemphill Publishing Co., Austin, Texas, 182pp.

Friedman, A.L., 1980. Glacial Geology, part 1 of the Isabella District, Superior National Forest, Minnesota. Minn. Geol. Survey Report Item 310. 26pp.

Fulton, R.J., 1967. Deglaciation studies in Kamloops region, an area of moderate relief, British Columbia. Geol. Survey, Canada Bull. No. 154, 36pp.

Grigal, D.F., 1968. The relationship between plant communities and soils in northeastern Minnesota. Unpublished Ph.D. Dissertation, Univ. of Minn., 288pp.

Gravenor, C.P. and W.O. Kupsch, 1959. Ice disintegration features in western Canada: Jour. Geol., Vol. 67, p. 48-64.

Green, J.C., 1972. North Shore Volcanic Group, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds): Minn. Geol. Survey, p. 293-332.

Leverett, F., 1928. Moraines and shorelines of Lake Superior basin: U.S. Geol. Survey Prof. Paper 154A, p. 1-38.

Leverett, F. and F.W. Sardeson, 1917. Surface formations and agricultural conditions of northeast Minnesota: Minn. Geol. Survey, Bull. no. 13, 67pp.

Leverett, F. and F.W. Sardeson, 1932. Quaternary geology of Minnesota and parts of adjacent states: U.S. Geol. Survey Prof. Paper 161, p. 39-55.

Lundqvist, J., 1969. Problems of the so-called Rogen Moraine. Sv. Geol. Unders. Vol. 648, p. 1-32.

Moran, S.R., L. Clayton, R. LeB. Hooke, M.M. Fenton and L.D. Andriashek, 1980. Glacier-bed landforms of the prairie region of North America. Manuscript in press, Journ. of Glaciology. 34pp.

Phinney, W.C., 1972. Duluth Complex, history and nomenclature, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 333-334.

Sims, P.K., 1972. Vermilion District and adjacent areas, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 49-62.

Sims, P.K. and G.B. Morey, 1972. Resume of Geology of Minnesota, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 3-15.

Stark, J.R., 1977. Surficial geology and ground-water geology of the Babbitt-Kawishiwi area, northeastern Minnesota with planning implications. Unpublished Masters thesis, Univ. of Wisc., Madison. 98pp.

Sugden, D.E. and B.S. John, 1976. Glaciers and Landscape. Edward Arnold, Ltd., London. 376pp.

Todd, J.E., 1898. Revision of the moraines of Minnesota: Am. Jour. Sci. (ser. 4), v. 6, p. 469-477.

Tricart, J., 1970. Geomorphology of Cold Environments. Macmillan and Co., Ltd., London, p. 59-85.

Univ. of Minnesota, Dept. of Soil Science, 1977. Soil Landscapes and Geomorphic Regions-Two Harbor Sheet.

Upham, W., 1894. Preliminary report of the field work during 1893 in northeastern Minnesota, chiefly relating to the glacial drift: Geol. and Hist. Survey of Minnesota, 22 Ann. Rpt., p. 18-66.

Winchell, N.H. 1898. The geology of the north part of St. Louis County, in The Geology of Minnesota: Geol. and Nat. Hist. Survey of Minn., v. 4, p. 222-265.

Winchell, N.H, 1901. Glacial Lakes of Minnesota. Geol. Soc. Am. Bull., vol. 12, p. 124-126.

Winter, T.C., R.D. Cotter and H.L. Young, 1973. Petrography and stratigraphy of glacial drift, Mesabi-Vermilion Iron Range area, northeastern Minnesota: U.S.Geol. Survey Bull. 1331-C, p. C1-C41.

Wright, H.E., Jr., 1955. Valders drift in Minnesota: Jour. Geol., v. 63, p. 403-411.

Wright, H.E., Jr., 1969. Glacial fluctuation and forest succession in the Lake Superior region: Internat. Assoc. Great Lakes Res., 12th Conf. Proc., p. 397-405.

Wright, H.E., Jr., 1971. Retreat of the Laurentide ice sheet from 14,000 to 9,000 years age: Quaternary Research, v. 1, p. 316-330.

Wright, H.E., Jr., 1972a. Physiography of Minnesota, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 561-567.

Wright, H.E., Jr., 1972b. Quaternary history of Minnesota, in Geology of Minnesota (P.K. Sims and G.B. Morey, eds.): Minn. Geol. Survey, p. 515-547.

Wright, H.E., Jr., 1973. Tunnel valleys, glacial surges, and subglacial hydrology of the Superior Lobe, Minnesota: Geol. Soc. America, Memoir 136, p. 251-276.

Wright, H.E., Jr., C.L. Matsch and E.J. Cushing, 1973. Superior and Des Moines Lobes: Geol. Soc. America. Memoir 136, p. 153-185.

Wright, H.E., Jr. and W.A. Watts, 1969. Glacial and vegetational history of northeastern Minnesota: Minn. Geol. Survey, Spec. Paper no. 11, p. 1-35.

APPENDICES AND PLATES

APPENDIX A

MECHANICAL ANALYSIS DATA

PROCEDURE

1. Sample was dried for 24 hours at 120°C and the dry Munsell color recorded.

2. Sample was split to about 50 grams and weighed.

3. Weighed sample was sieved through -2ϕ, -1ϕ, 0ϕ, and 4ϕ screens with a Ro-Tap for 15 minutes. Some samples required wet sieving through the 4ϕ screen.

4. Amounts caught on each screen were removed and weighed to calculate percentage of the original sample.

5. Remaining pan fraction was dispersed in a 1 liter cylinder.

6. 20 sec. after thorough mixing, 20 ml of suspension was withdrawn, added to 20 ml of water, dried, and weighed.

7. After 1 hr., 51 min., 20 ml of suspension was withdrawn from a depth of 20 cm and added to 20 ml of water, then dried and weighed. This represents the $> 8\phi$ fraction.

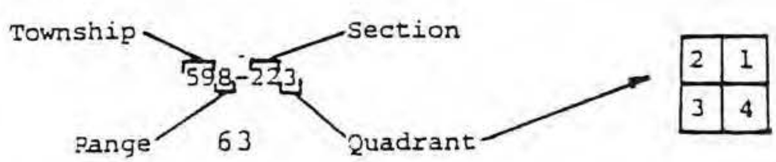
8. It was assumed that the difference between the weights in steps 6 and 7 was the amount of the silt fraction. Silt and clay percentages were recalculated on the basis of the pan fraction percentage of the original sample.

9. Approximately 100 pebbles and granules were split from the sieved material and examined under a binocular microscope to identify lithology. Alternatively, approximately 100 stones were randomly selected directly from an exposure. Usually, fragments needed to be broken to examine unweathered surfaces.

APPENDIX A. MECHANICAL ANALYSIS DATA

Sample No. and Location*	Pebbles	Matrix Material Weight Percents Granules	Sand	Silt	Clay
Gray Till (Tg)					
598-193	9.7	16.0	62.2	10.3	1.8
599-142	8.5	14.7	66.0	9.8	1.0
607-062	3.4	6.4	70.9	12.0	7.3
607-312	3.0	10.3	69.9	10.7	6.1
608-111	2.3	8.0	70.1	18.8	0.8
608-293	1.2	9.5	61.7	24.9	2.7
619-244	5.5	7.8	63.8	16.3	6.6
619-282	4.5	5.8	70.4	13.5	5.8
Mean =	4.7±3.0	9.8±3.7	66.9±3.9	14.5±5.2	4.1±2.7
Brown Till (Tb)					
597-203	0.8	4.7	49.1	41.1	4.3
598-083	2.2	3.9	52.0	38.2	3.7
598-254	0.3	1.7	60.1	31.0	6.9
598-364	0.9	3.0	58.2	39.5	9.4
599-094	3.7	8.9	62.7	23.3	1.4
609-342	5.1	11.4	58.1	22.5	2.9
Mean =	2.2±1.9	5.6±3.7	56.7+5.1	32.6±8.3	4.8±2.9
Gray Ice-Marginal Gravels (Ig)					
598-031	24.4	23.2	46.1	5.5	0.8
608-292	31.7	16.3	45.1	6.9	0.0
608-324	16.9	24.2	51.3	7.4	0.2
609-261	16.9	17.1	57.8	8.0	0.2
609-101	25.8	30.3	40.9	3.0	0.0
Mean =	23.1±6.3	22.2±5.8	48.2±6.5	6.2±2.0	0.3±0.3
Brown Ice-Marginal Gravels (Ib)					
598-223	15.9	11.1	67.2	5.2	0.6
598-272	9.8	12.5	74.3	3.4	0.0
598-322	21.5	19.3	52.7	4.4	1.1
599-132	17.4	15.6	59.6	6.0	1.4
Mean =	16.1±4.9	14.5±3.6	63.2±9.3	4.7±1.1	0.7±0.6

*Location of Samples:



Sample No. and Location	Pebbles	Matrix Material Weight Percents Granules	Sand	Silt	Clay
Gray Glaciofluvial Deposits (Gg)					
608-024	43.8	28.6	27.4	0.2	0.0
608-051	29.4	19.1	51.2	0.3	0.0
608-102	30.1	22.6	46.8	0.5	0.0
617-292	13.0	20.7	58.8	7.5	0.0
618-364	25.5	29.0	44.3	1.2	0.0
Mean =	28.4±11.0	24.0±4.6	45.7±11.6	1.9±3.1	0.0
Brown Glaciofluvial Deposits (Gb)					
598-091	29.2	20.1	49.6	1.1	0.0
598-121	32.6	29.5	37.2	0.7	0.0
598-132	38.1	27.7	31.0	2.2	1.0
598-162	30.2	24.0	41.5	3.9	0.4
Mean =	32.5±4.0	25.3±4.2	39.8±7.8	2.0±1.4	0.4±0.5
Gray Outwash Deposits (Og)					
608-021	9.8	24.9	64.0	1.3	0.0
608-102	11.4	20.1	66.5	2.0	0.0
608-182	11.3	16.7	69.8	1.7	0.5
609-124	12.7	13.5	70.1	3.4	0.3
Mean =	11.3±1.2	18.8±4.9	67.6±2.9	2.1±0.9	0.2±0.2
Brown Outwash Deposits (Ob)					
597-072	6.1	19.4	72.4	2.1	0.0
598-032	2.2	10.4	81.1	5.5	0.8
598-092	38.4	41.5	18.7	1.4	0.0
608-343	12.8	51.9	33.8	1.5	0.0
609-274	12.6	35.0	48.8	3.3	0.3
Mean =	14.4±14.1	31.6±16.7	51.1±26.0	2.7±1.7	0.2±0.3
Loess					
597-074	4.6	6.1	20.3	63.5	5.4
598-094	1.0	0.0	15.4	77.7	5.9
598-363	0.4	0.1	14.9	77.1	7.5
608-102	2.3	5.4	19.1	67.2	6.0
608-342	.6	.1	20.	6 .	5.5
Mean =	1.7±1.9	2.3±3.1	16.5±3.3	73.2±9.7	6.2±0.8

Dry Munsell Colors of Samples

Gray Drift		Brown Drift	
Sample No.	Munsell Color	Sample No.	Munsell Color
TILL			
598-193	5Y6/3	597-203	10YR4/3
599-142	5Y6/3	598-083	10YR3/2
607-062	5Y6/3	598-254	10YR3/2
607-312	5Y6/3	598-364	10YR4/3
608-111	5Y6/4	599-094	10YR3/3
608-293	5Y6/3	609-342	10YR4/3
619-244	5Y6/3		
619-282	5Y6/3		
ICE-MARGINAL GRAVEL			
598-031	2.5Y3/3	598-223	2.5Y4/2
608-292	2.5Y4/3	598-272	10YR5/3
608-324	2.5Y3/3	598-322	10YR6/4
609-261	2.5Y4/3	599-132	10YR5/3
609-101	2.5Y3/3		
GLACIOFLUVIAL DEPOSITS			
608-024	2.5Y4/2	598-091	10YR6/3
608-051	2.5Y4/3	598-121	10YR4/2
608-102	2.5Y4/2	598-132	10YR4/2
617-292	2.5Y3/3	598-162	10YR5/3
618-364	2.5Y3/3		
OUTWASH DEPOSITS			
608-021	2.5Y6/4	597-072	5Y6/4
608-102	5Y6/3	598-032	2.5Y4/2
608-182	2.5Y4/2	598-092	10YR4/3
609-124	5Y6/3	608-343	5Y6/3
		609-274	10YR5/3
LOESS			
		597-074	10YR3/3
		598-094	10YR3/2
		598-363	10YR3/2
		608-102	10YR3/3
		608-342	10YR3/2

APPENDIX B. ROCK-TYPE IDENTIFICATION DATA

Sample No. and Location *	North Shore Volcanic Group: Rhyolite	Basalt	Other Volc.	Micrographite	Duluth Complex: Troctolite	Anorthosite	Granite	Superior Lowland: Shale	Graywacke	Vermilion District: Greenstone	Slate	Gneiss	Schist	Other: Diabase	Quartz	Undifferent.	Total
Gray Till																	
598-193	-	-	1	1	.73	32	20	1	2	1	-	2	3	2	-	1	139
599-142	1	-	1	1	54	30	28	-	1	2	-	3	1	1	2	-	125
607-244	1	-	2	-	51	17	24	-	1	1	1	-	2	-	-	3	103
619-244	1	-	2	-	63	29	25	-	1	2	-	1	2	1	1	1	130
Mean %	0.7	0	1.2	0.5	48.2	21.6	19.4	0.3	1.1	1.2	0.3	1.2	1.6	0.8	0.7	1.2	
S.D. %	0.4	0	0.5	0.5	7.9	5.4	2.6	0.4	0.4	0.5	0.4	1.0	0.6	0.6	0.8	1.0	
Brown Till																	
597-203	31	19	4	9	36	4	22	7	2	1	-	-	-	18	-	2	155
598-083	22	11	2	12	28	2	16	4	5	3	-	-	-	7	2	1	115
598-364	23	32	2	10	24	3	17	5	2	2	-	-	1	8	1	1	131
609-342	37	23	-	15	28	5	13	5	3	1	-	-	1	5	1	1	138
Mean %	21.0	15.8	1.5	8.5	21.5	2.6	12.6	3.9	2.2	1.3	0	0	0.4	7.0	0.7	1.0	
S.D. %	5.3	6.4	1.2	1.9	3.7	1.0	2.7	1.0	1.0	0.7	0	0	0.4	4.3	0.6	0.4	
Gray Ice-Marginal Gravel																	
598-223	1	1	1	-	42	13	31	2	3	4	1	-	2	1	-	1	103
598-322	-	1	1	-	53	19	26	1	1	-	-	-	-	7	-	2	111
599-132	-	-	2	1	69	24	22	1	2	11	-	-	-	3	1	1	137
Mean %	0.3	0.6	1.1	0.3	46.8	16.0	22.5	1.1	1.7	4.3	0.3	0	0.6	3.2	0.3	1.1	
S.D. %	0.5	0.5	0.5	0.5	11.6	4.7	3.8	0.5	0.9	4.8	0.5	0	1.0	2.7	0.5	0.5	
Brown Ice-Marginal Gravel																	
598-223	41	10	-	18	13	3	16	13	3	-	-	-	-	9	1	-	120
598-272	30	11	-	16	18	2	10	9	1	-	-	-	-	12	-	2	111
599-132	33	18	1	21	23	2	9	10	1	1	1	-	-	17	-	1	138
Mean %	27.3	10.3	0.2	14.5	14.2	1.8	9.2	8.5	1.3	0.2	0.2	0	0	10.0	0.2	0.8	
S.D. %	4.5	3.5	0.5	2.0	4.0	0.5	3.0	1.7	0.9	0.5	0.5	0	0	3.2	0.5	0.8	
Gray Glaciofluvial Gravel																	
608-024	1	-	2	-	44	19	19	1	2	4	-	-	1	2	3	1	99
617-292	-	-	-	1	56	17	26	-	5	7	2	-	1	-	1	2	118
618-364	-	-	1	-	57	22	27	1	4	6	1	-	1	1	-	2	123
Mean %	0.3	0	0.9	0.3	46.1	17.0	21.1	0.6	1.9	5.0	0.9	0	0.9	0.9	1.1	1.5	
S.D. %	0.5	0	0.9	0.5	6.3	2.2	3.9	0.5	1.7	1.3	0.9	0	0.0	0.9	1.3	0.5	
Brown Glaciofluvial Gravel																	
598-121	23	14	2	20	11	2	19	2	3	2	-	-	-	19	1	2	120
598-132	29	9	2	18	12	2	11	1	2	1	-	-	-	13	1	2	102
598-162	44	7	1	17	18	4	7	1	1	-	1	-	-	10	2	1	114
Mean %	28.6	1.5	1.5	16.5	12.3	2.4	11.0	1.2	1.8	0.9	0.3	0	0	12.6	1.5	1.5	
S.D. %	9.7	3.2	0.5	1.4	3.4	1.1	5.5	0.5	0.9	0.9	0.5	0	0	4.1	0.5	0.5