THE STRATIGRAPHY AND LITHOLOGY OF THE GLACIOGENIC SEDIMENTS OF THE TWO HARBORS AREA, NORTHEASTERN MINNESOTA

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by

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ABSTRACT

Five texturally distinct sedimentary units are differentiated in the Quaternary deposits of the Two Harbors and Whyte quadrangles in Lake County, northeastern Minnesota. Their specific properties are attributed to differing (1) bedrock sources, (2) conditions of glacier flow, and (3) methods and environments of deposition. These glacially derived sediments, including a clay-rich diamicton, record the advance, stagnation, and retreat of the Rainy and Superior Lobes, two appendages of the Laurentide Ice Sheet, sometime after 30,000 years B.P.

The dominant surficial deposit of the northwestern half of the Whyte quadrangle is a gray to brown, sandy to stony till, the Sullivan Lake Formation. The average sand:silt:clay ratio is 76:21:03. The clasts and surface boulders are predominantly granophyre, granite, greenstone, basalt, and gabbro-diabase. The source of sediment for this formation is the underlying Duluth Complex and other Precambrian igneous and metamorphic sources cropping out to the north and northeast. The Sullivan Lake Formation was deposited by an actively moving, wet-based glacier. For the most part, it was deposited in the basal zone as a lodgement till. This till is attributed to the Rainy Lobe advance from the northeast about 20,500 ± 400 years B.P. (Wright, et al., 1973).

Geomorphic features attributed to this ice advance are the northeast- southwest trending Toimi drumlins, small eskers, and a tunnel valley, partially occupied by Sullivan Lake.

The glaciogenic sediments that comprise the southeastern half of the Whyte quadrangle and the northern part of the Two Harbors quadrangle (the Cromwell Formation) are markedly different from the Sullivan Lake

Formation. They are a distinct reddish brown in color and rich in rock fragments eroded from the late Precambrian North Shore Volcanic Group (basalt and rhyolite) and "red" sandstone of Keweenawan age from the Lake Superior basin to the east. The Cromwell Formation resulted from the advance, stagnation, and retreat of the Superior Lobe approximately 20,000 to 16,000 years B.P. (Wright, et al., 1973), as it moved westward and southwestward out of the Lake Superior basin.

Supraglacially derived debris of the Cromwell Formation is mainly contained within the Highland Moraine. It is texturally quite variable with an average sand:silt:clay ratio of 66:30:04. Topographically, the debris forms a hummocky kettle and kame terrane. A variety of depositional processes were active in the terminal zone of the glacier. These include melt-out, as well as the secondary processes of sediment gravity flow, slump, and sheet and rillwater flow.

Subglacially derived debris, exposed southeast of the Highland Moraine, is differentiated from the supraglacial debris by a finer texture and a fluted topographic expression. It has an average sand:silt:clay ratio of 57:32:11. The presence of the Highland flutes suggests deposition by lodgement processes from an actively flowing, wet-based glacier.

A clay-rich (loam) facies of the Cromwell Formation occurs in an isolated area southward from the flutes. It has an average sand:silt:clay ratio of 40:39:21. Overriding of proglacial lake deposits and incorporation of fine-textured sediment into the basal zone could explain this textural change.

Sediment supplied from stagnant ice sources and meltwater from the retreating Superior Lobe formed large deposits of outwash in the form of fans, braided stream deposits, deltaic deposits, and resedimented deposits of till. They occur randomly on the till surface, and along a northeast- southwest trending zone at about 350 to 366 m (1150 to 1200 feet). The stratified sand and gravel deposits along this zone are interpreted as deltas and other shoreline features of Glacial Lake Duluth and its immediate predecessors.

The Wrenshall Formation, a clay-rich diamicton in the southeastern half of the Two Harbors quadrangle, forms another texturally distinct unit. The clay is reddish brown with an average sand:silt:clay ratio of 14:16:70. It is typically massive, jointed, and locally laminated. It ranges from clast-rich to clast-poor and commonly occurs in association with sand and silt sequences. Distinguishing between a subglacially deposited clayey till and a lacustrine clay in the Lake Superior region is problematical. This clay- rich unit is differentiated from the upland glacial deposits by its fine texture, sedimentary structures, the presence of ice-rafted material, and its restricted occurrence below the 350 to 366 m (1150 to 1200 feet) high level strandlines. This suggests deposition from suspension in Glacial Lake Duluth, formed during the final retreat of the Superior Lobe after 10,800 years B.P. (Wright, _et al_., 1973).

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INTRODUCTION

A broad spectrum of glacially-derived sediments resulting from a complexity of depositional environments is distributed throughout the Two Harbors area in Lake County, northeastern Minnesota. These deposits, all Quaternary in age, are distinct records of the Late Wisconsin glaciation. Most of the glacial sediments resulted from the advance and ultimate stagnation of two appendages of the Laurentide Ice Sheet, the Rainy and Superior Lobes, during the St. Croix and Automba phases of glaciation, sometime after 30,000 years B.P.

This study describes in detail the sedimentologic characteristics and stratigraphic relationships of the glacial debris, particularly the red clay unit, a prominant surficial deposit of the North Shore of Lake Superior. An investigation of the red clay along Wisconsin's south shore of Lake Superior west of the Bayfield Peninsula has recently been completed by Johnson and Need (1980). At present, the depositional environment of the red clay of the south shore, whether glacial or lacustrine, is controversial. This study presents a correlation of the red clay units of the western Lake Superior region, clarifies its mode of origin, and enhances the understanding of the late- and post-glacial history of the Lake Superior region.

LOCATION

The study area includes the Two Harbors and Whyte 15 minute quadrangles, located 35 km northeast of Duluth in Lake County, Minnesota. This region includes a 28 km segment of the North Shore of

Lake Superior and extends for 45 km northward from Two Harbors through the Superior National Forest (Figure 1).

OBJECTIVES

The main objectives of the project were: (1) to map the surficial distribution of the deposits; (2) to determine the stratigraphic relationships of the glacial sediments; (3) to describe the lithologic characteristics of the deposits; (4) to reconstruct the depositional environment of the sediments, especially the clay-rich unit in the southern part of the Two Harbors area; and (5) to develop an up-to-date interpretation of the glacial history of northeastern Minnesota.

METHODS OF INVESTIGATION

Field methods

Field work was conducted during the summer and fall of 1981, with field checks during the spring of 1982. United States Geological Survey topographic quadrangles (1:62,500 series) served as base maps. Numerous samples were collected along the lakeshore and stream valleys, along road cuts, railroad cuts, and in every gravel pit within the Two Harbors area. Oriented samples were also taken along the lakeshore with the aid of a tulip bulb planter as a modified coring device.

Methods of analysis include field observations of color, texture, lithology, fabric orientation, stratigraphy, and distribution. Paleocurrent direction indicators were measured where possible.

Field density tests were performed at six localities within the study area. The test is a standard procedure used by the State of

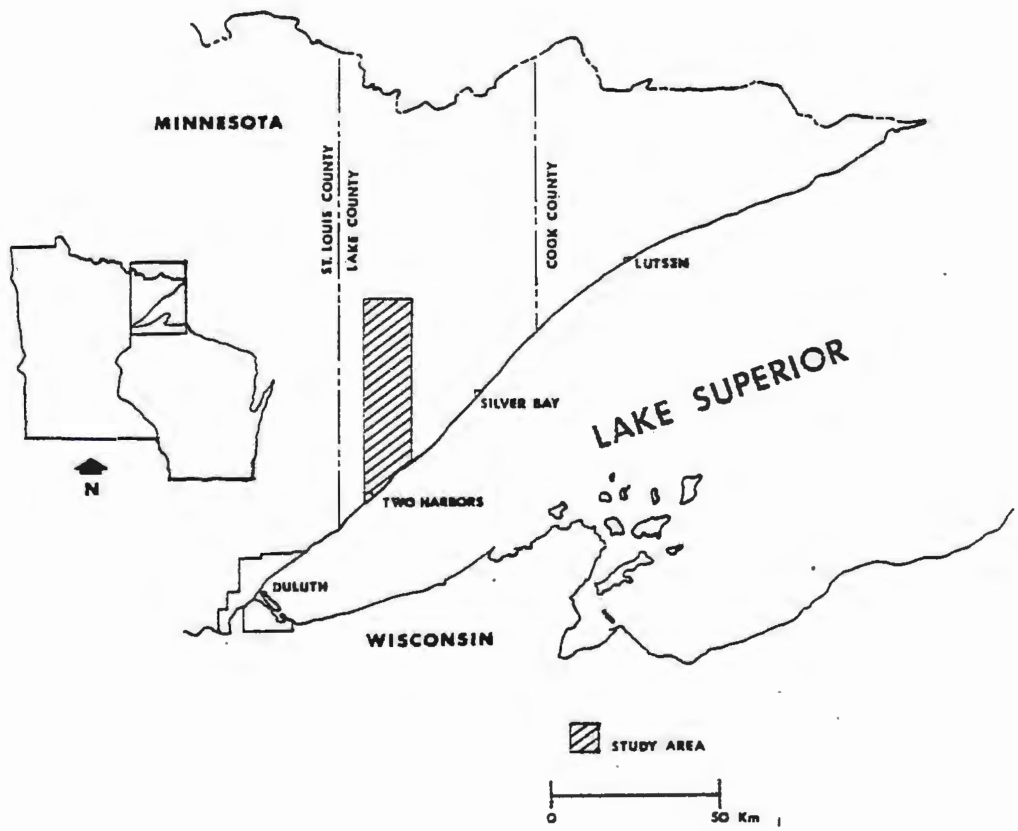


Figure 1. Location map of the study area.

Minnesota Department of Highways. It involves the removal of a quantity of in place material from an embankment or natural ground, determination of the dry weight of the removed material, and the in place volume of the removed material. Dry weight was measured in the field using a 26 gram "Speedy" moisture tester. The in place volume was determined by replacing the removed material with a measured quantity of standard sand of known density. Ottawa silica sand, C-190, 20-30 graded was used. It has a density of 1.56 g/cc. The data yielded very low densities that ranged from 0.83 to 1.12 g/cc in six measurements. These results appear much too low and are discounted. Laboratory methods and results were much more reliable and believable for bulk density testing of the glacial material.

Laboratory methods

Complete sieve and pipette analyses, as described by Folk (1980), were performed on 58 samples in order to determine grain size distribution.

Lithology of the 1-2 mm coarse sand fraction was determined by identifying 150-250 grains per sample using a binocular microscope.

X-ray diffraction analysis for mineral identification of the less than 4 μm fraction of the clay unit was performed with a Picker diffractometer using Ni-filtered CuK_{α} radiation.

Oriented samples of the clay were cut with a band saw into 3 to 5 mm- thick vertical and horizontal slabs for microfabric analysis. Radiographs were made from the slabs using a Torrex 150 self-contained x-ray unit and Industrix M film. Settings for the x-ray intensity ranged from 100 KV, 3 MA to 150 KV, 5 MA (which is the highest setting), and exposure time ranged from 30 seconds to 4 minutes.

Though x-ray radiography has proven useful in the study of structures in homogeneous sediments, this technique was not effective in enhancing the visible, yet poorly defined structures on the slabs of clay. Horizontal slabs of clay were assumed to be bedding planes, and it was hoped that x-rays could record possible microfoliation and coarse fabric orientation. Vertical slabs represented a cross- section of the clay, where x-rays could highlight fine laminations or other subtle sedimentary structures.

The x-rays in the Torrex unit were not powerful enough to record internal images of the clay. Other workers have obtained positive results on different x-ray units, using samples approximately 3 mm-thick, and exposing them for 2 seconds at 35 KV, 30 MA (Hamblin, 1962), and at 90 KV, 15 MA (Calvert and Veevers, 1962). Johnson, Carlson, and Evans (1980) x-rayed 1 cm-thick slabs of sediment from Lake Superior with a Dynamax 40 tube at 50 KV, 200 MA, to reveal the fine sedimentary structures of contourites.

The structures visible on the vertical slabs of clay were clearly recorded with a 35 mm camera, using a telephoto lens and Ektachrome, ASA 64 film.

Oriented thin sections were prepared from several of the sliced samples. The clay was impregnated with epoxy cement and cut using standard thin section techniques.

Bulk densities of the clay units were also measured in the lab. Samples of laminated clay, massive pebble-free clay, and pebble-rich compact clay were collected in the field as relatively undisturbed chunks (~25 cm cubes) and cores (10 cm length, 5 cm diameter). The clay was preserved in plastic wrap and aluminum foil until laboratory work could be carried out. The samples were prepared by slicing and hammering off approximately 4 cm pieces of clay, weighing from 4 to 30 grams. The volume of the samples was determined by the difference between their weight in water and their weight in air. Since the clay pieces tended to flake and disperse when immersed in water, an impervious coating was essential. Though other workers have used paraffin and plastic bags, thin coats of petroleum jelly and epoxy were experimented with, the latter proving quite successful and introducing only a small increase in weight.

Nineteen samples were weighed dry, weighed epoxied, and weighed in water, on a pan that hung suspended from a triple-beam balance. Corrections were made for both the weight of the epoxy and the weight of the suspended pan.

Although laboratory results proved conclusive, several uncertainties in bulk density testing must be kept in mind: (1) laboratory methods are not standardized. Easterbrook (1964) used liquid displacement techniques, saturating the sample in water; Moss (1977) did not publish her techniques; (2) Errors in volume are introduced because the samples are no longer "in place"; (3) Epoxying nct only adds a thin film to the sample, but also slightly penetrates the clay, infilling some of the pore spaces (thus decreasing the volume of air); (4) Air bubbles are sometimes present on the surface of the clay while it is submersed in water (perhaps mercury could be a substitute for deionized water); and (5) The accuracy of measurement and human error must be accounted for. Samples were weighed to the nearest 0.01 gram, and the calculated precision of density measurements ranged from ± 0.006 to 0.003 grams. To conclude, the bulk density data precision is estimated to be ± 0.01 grams.

PHYSIOGRAPHY

Northeastern Minnesota is dominated by three striking physiographic regions: the North Shore Highland, which extends from Duluth to the Canadian border, the Toimi drumlin area, northwest of the highland, and the Glacial Lake Duluth area, located near the head of the Lake Superior basin southeast of the Highland (Wright, 1972).

The North Shore Highland, which rises between 275-460 m (900 to 1500 feet) above Lake Superior, is underlain mostly by the southeastward-dipping North Shore Volcanics of basaltic lava flows and mafic intrusions. Streams 16 to 24 km long flow from the Highland to Lake Superior.

The lakeward edge of the North Shore Highland is a drainage divide between the coastal streams and the streams of the St. Louis River System. The divide coincides roughly with the northwestern limit of the lava flows, but the boundary is actually the toe of the Highland moraine (Wright, 1972).

The Toimi drumlin area is dominated by southwestward trending drumlins and a trellis stream pattern. The drumlins are 2 to 7 km long, 1/2 km broad, and 9 to 15 m high. This region is drained to the southwest by the Whiteface and Cloquet Rivers, which join with the St. Louis River, which then flows southeastward to the head of Lake Superior.

Located at the head of the Lake Superior basin, the Glacial Lake Duluth area represents a former lake bed. This lake bed is deeply dissected by the St. Louis River and its tributary, the Nemadji River. Deltaic deposits and wave cut cliffs mark the ancient strandlines at approximately 335 m (1100 feet) above sea level, or 152 m (~498 feet) above the present level of Lake Superior. Deposits of lacustrine red clay are distributed throughout and confined to this basin.

BEDROCK GEOLOGY

The bedrock geology of Minnesota has played a major role in the patterns of ice movement during the Wisconsin glaciation. Differential resistance of various rock types determined the location of preglacial bedrock lowlands that channeled the ice lobes as they protruded from the Laurentide Ice Sheet.

The most conspicuous area of erodible rocks in northeastern Minnesota is the Lake Superior Lowland, which is essentially a syncline containing a core of Late Precambrian Keweenawan red sandstone. It is bounded on the northwest by resistant lava flows of the North Shore Volcanic Group and the intrusive bodies of the Duluth Complex, and on the south side by sandstones and volcanics of the Bayfield and Keweenaw Peninsulas (Figure 2).

These rocks represent a southern extension of the Canadian Shield. They formed in late Precambrian time, during the Keweenawan period of continental rifting and igneous activity. Lava flows, ranging in composition from olivine basalt to rhyolite, erupted through a rift along what is now the central axis of Lake Superior. Anorthositic, gabbroic, and granitic intrusions were then emplaced along an unconformity between the older Precambrian rocks and the lava flows (Green, 1972). Radiometric dating of zircons from rhyolitic flows of the North Shore Volcanic Group, and from granitic to intermediate fractions of the Duluth Complex, indicates that the intrusive rocks and flows are nearly contemporaneous and belong to the main pulse of Keweenawan rifting and igneous activity which peaked 1,110 ± 10 m.y. ago (Van Schmus, _et al._, 1982). The area subsequently subsided and a

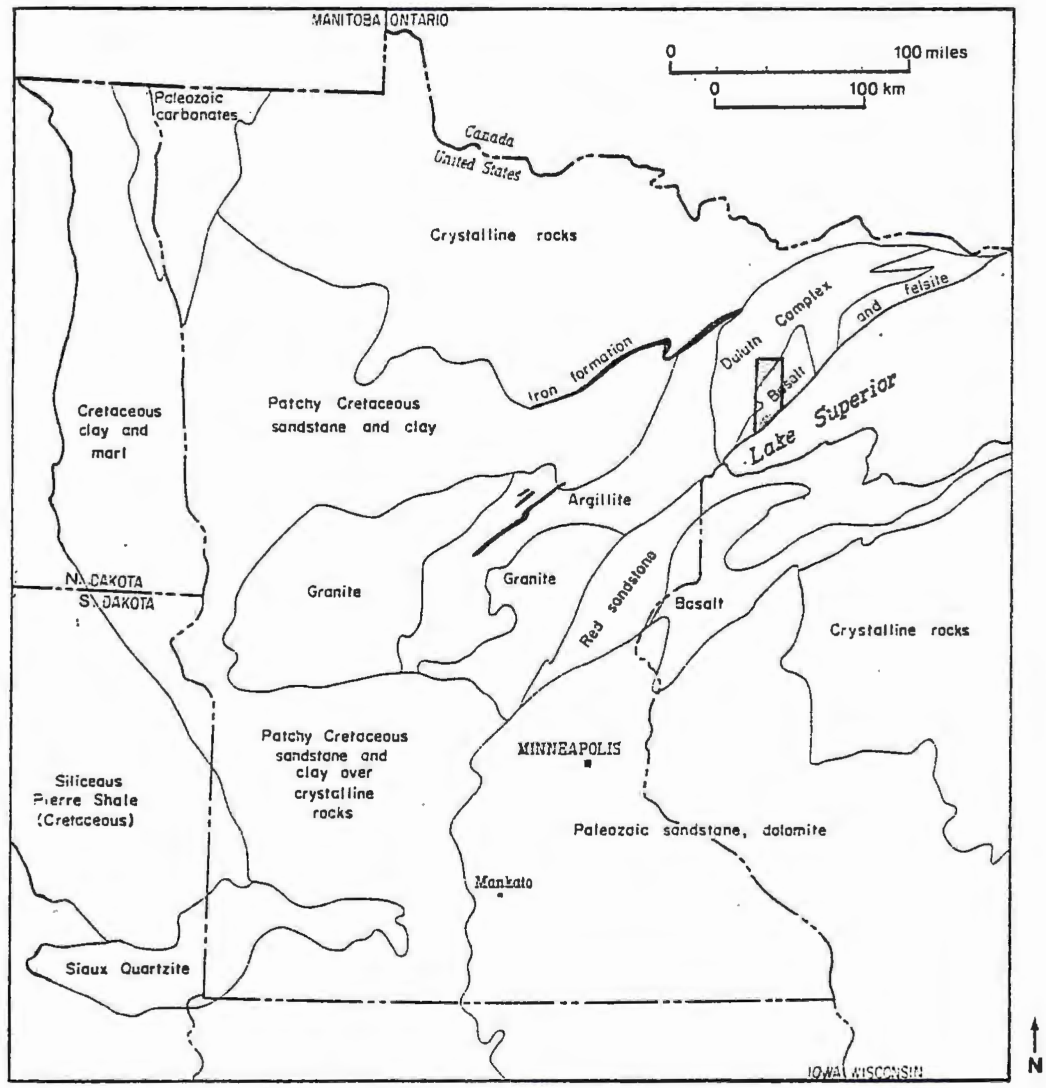


Figure 2. Bedrock geology of Minnesota (from Wright, 1972). Shaded area represents study area.

thick sequence of clastic sediments, mainly quartz sandstone and lithic sandstone, were deposited on the flows.

Exposures of bedrock within the Two Harbors area occur primarily as cliffs and bluffs along the lake shore and crop out along the banks of Stewart River, Silver Creek, Encampment River, and Crow Creek (Green, et al., 1977).

PREVIOUS WORK

The study of glacial features of the Lake Superior region can be traced back to the 1840's during the pioneer days of Louis Agassiz, when he first applied the concept of continental glaciation to North America. In the summer of 1948 Agassiz lead an expedition to the northern shore of Lake Superior for the purpose of studying the natural history of the area. Results of the expedition were presented in several papers dealing with glacial geology, ichthyology, and botany.

N. H. Winchell, the first Minnesota State geologist, along with the assistance of Warren Upham, systematically mapped the glacial geology of Minnesota from 1872-1895. This involved a county by county descriptive survey of local topographic features and glacial landforms. Winchell and Upham recognized the existence of two ice lobes: the Lake Superior Lobe, now called the Superior Lobe, which advanced from the northeast; and the Minnesota Lobe, now the Des Moines Lobe, which came from the northwest. Though these lobes were thought to be contemporaneous, their interaction was never fully worked out.

In 1893, Warren Upham prepared a comprehensive outline of the glacial and lake features of northeastern Minnesota for the annual report of the State Geological Survey. In 1901 N. H. Winchell published a special paper in the Bulletin of the Geological Society of America on the glacial lakes of Minnesota, in which he described the relation of the lakes to the retreating ice borders.

Around the turn of the century, studies by Lawson (1893) and Taylor (1894, 1895, 1897) enhanced the glacial history of the Lake Superior area.

Frank Leverett of the U.S.G.S. was actively involved in field studies of the glacial geology of Minnesota from 1906-1912. In 1929 Leverett published a professional paper entitled "Moraines and shorelines of the Lake Superior basin." He recognized the Patrician Ice Lobe (now the St. Croix Phase of the Superior Lobe) which moved southward along the axis of the Lake Superior basin, and the Superior Ice Lobe (the Automba Phase of the Superior Lobe) which extended 19 to 24 km beyond the limits of the present Lake Superior. Leverett also noted the presence of small lakes on the border of the retreating Superior Lobe, which eventually became confluent with one another, forming what is now recognized as Glacial Lake Duluth. He stated that the abandoned shorelines are evident in the Duluth area at an elevation of 355 m (1165 feet) above sea level and may be correlated with a shoreline at 335 m (1100 feet) on the south side of the basin in western Douglas County.

In 1932 Leverett published a generalized map of the surficial material of the state of Minnesota. He placed emphasis upon the morphology of the glacial features rather than the lithology and stratigraphy of the deposits.

In two reports, Sharp (1953a, 1953b) traced the Rainy and Superior Lobe advances in northeastern Minnesota, elaborated on their interlobate junction, and described the glacially derived sediments of the area.

Sharp was in basic disagreement with Leverett (1929) on two accounts: (1) the exact localities of the Lake Duluth shoreline and (2) the degree of tilting by relative uplift of the Lake Duluth and post-Lake Duluth shorelines.

Leverett (1929) used the upper limits of "wave-washed" slopes as an indicator of highest shorelines. Yet, in Cook County, as well as other areas of the north shore, bare rock slopes are numerous far above the level of the Glacial Great Lakes. This criterion was therefore inappropriate. Also, Leverett cited no localities and gave no elevations for the "well represented" post-Lake Duluth stages of the Algonquin and Nipissing level shores in Cook County.

Sharp (1953b) calculated the lakes Duluth, Algonquin, and Nipissing shores to be less steeply tilted than supposed by Leverett. He thus disagreed with Leverett's postulate of a strong differential tilt between the uppermost and lowermost Lake Duluth shores.

H. E. Wright (1965, 1969, 1972, 1973) traced four major advances of the Superior Lobe in northeastern Minnesota (Figure 3). Radiocarbon ages from basal organic sediments date the St. Croix phase at 20,500 ± 400 years B.P., the Split Rock phase at 15,250 ± 220 years B.P. (16,000 years), and the Nickerson phase at 12,000 years B.P. (Wright, et al., 1973). The radiocarbon age for the Automba phase is not known. It is deduced to be younger than the St. Croix phase and older than the Split Rock phase, based on cross-cutting geomorphic trends. Wright attributed the last two advances to ice surging, based on nonsynchronized advances with adjacent ice lobes and a nonmatching pattern of climatic reversals with ice lobe fluctuations. He explained surging as the result of a buildup of basal meltwater that was trapped behind the frozen toe of the Superior Lobe. Wright's work contributed greatly to understanding the glacial chronology and stratigraphic evidence left by the Superior Lobe as it advanced and retreated during the Late Wisconsin stage.

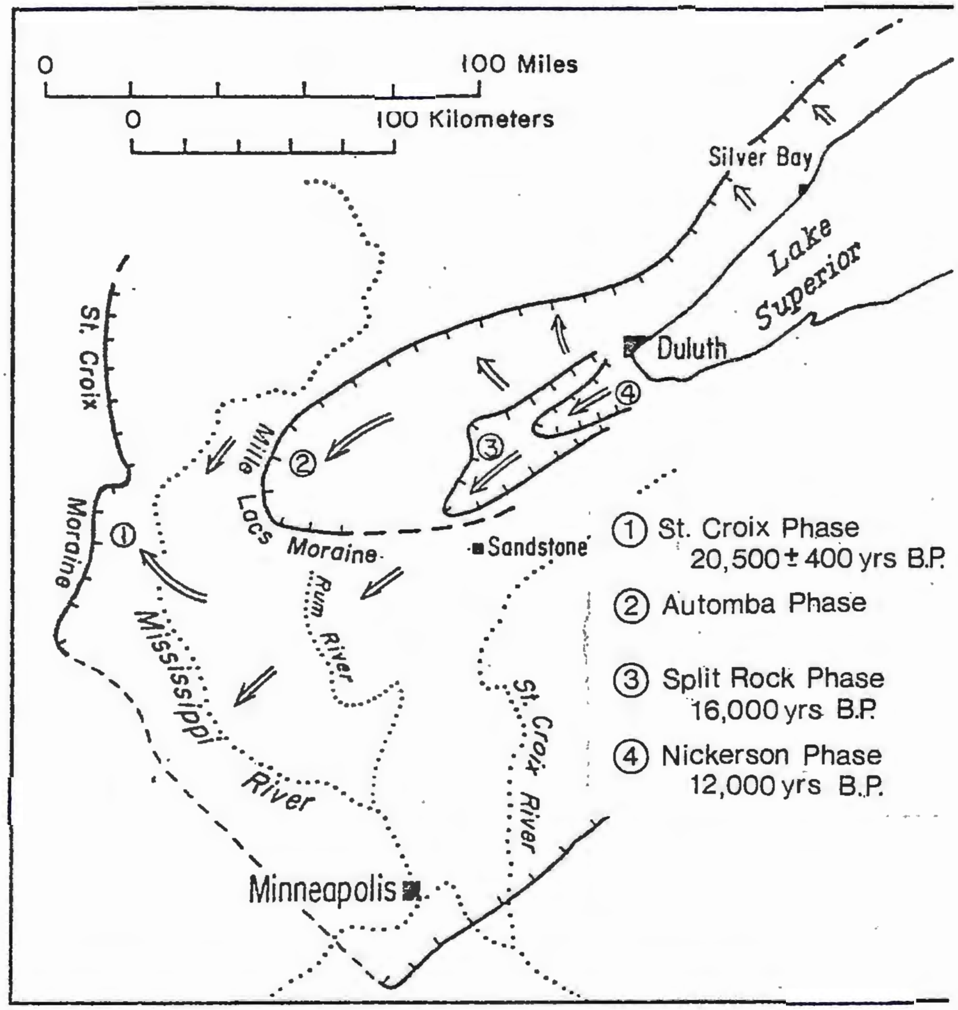


Figure 3. Advances of the Superior Lobe, during the Late Wisconsin glaciation, northeastern Minnesota (from Wright, 1973).

Farrand (1960, 1969) investigated the former shorelines of the western and northern parts of the Superior basin. He traced the history of Lake Superior and its varying drainage outlets from the time the ice front first withdrew into the basin to the present. Farrand, like Leverett, concluded that several small lakes were dammed in front of the wasting Superior Lobe to the east and west of the Bayfield Peninsula (Wisconsin) which eventually coalesced to form Glacial Lake Duluth. This lake discharged into the Mississippi River System through two outlets: Solon Springs, Wisconsin, between the headwaters of the Brule and St. Croix Rivers; and through Moose Lake, and the Kettle River, southwest of Duluth.

Saarnisto (1974) established a relative chronology of the deglaciation history of the Lake Superior region from Late Wisconsin to early Holocene time (12,000 - 8,000 years B.P.) (Figure 4). His work was based on the recognition of recessional moraines across northern Ontario and Michigan which, along with other glacial features, indicated ice marginal positions. The moraines, formed between 11,000 and 10,100 years, were deposited during successive halts in the retreat of the Laurentide Ice Sheet. The ice mass readvanced locally during the Valders and Cochrane ice advances, dated at 11,800 and 8,000 years ago.

The relation of these ice marginal positions to pollen stratigraphy was also discussed by Saarnisto. Pollen analysis failed to show a climatic reversal in the continuous trend toward a warmer climate. Cold climate is last documented in northeastern Minnesota by the presence of tundra until about 10,400 to 10,200 years B.P.. The Valders and Cochrane ice advances were not detected by the pollen analysis.

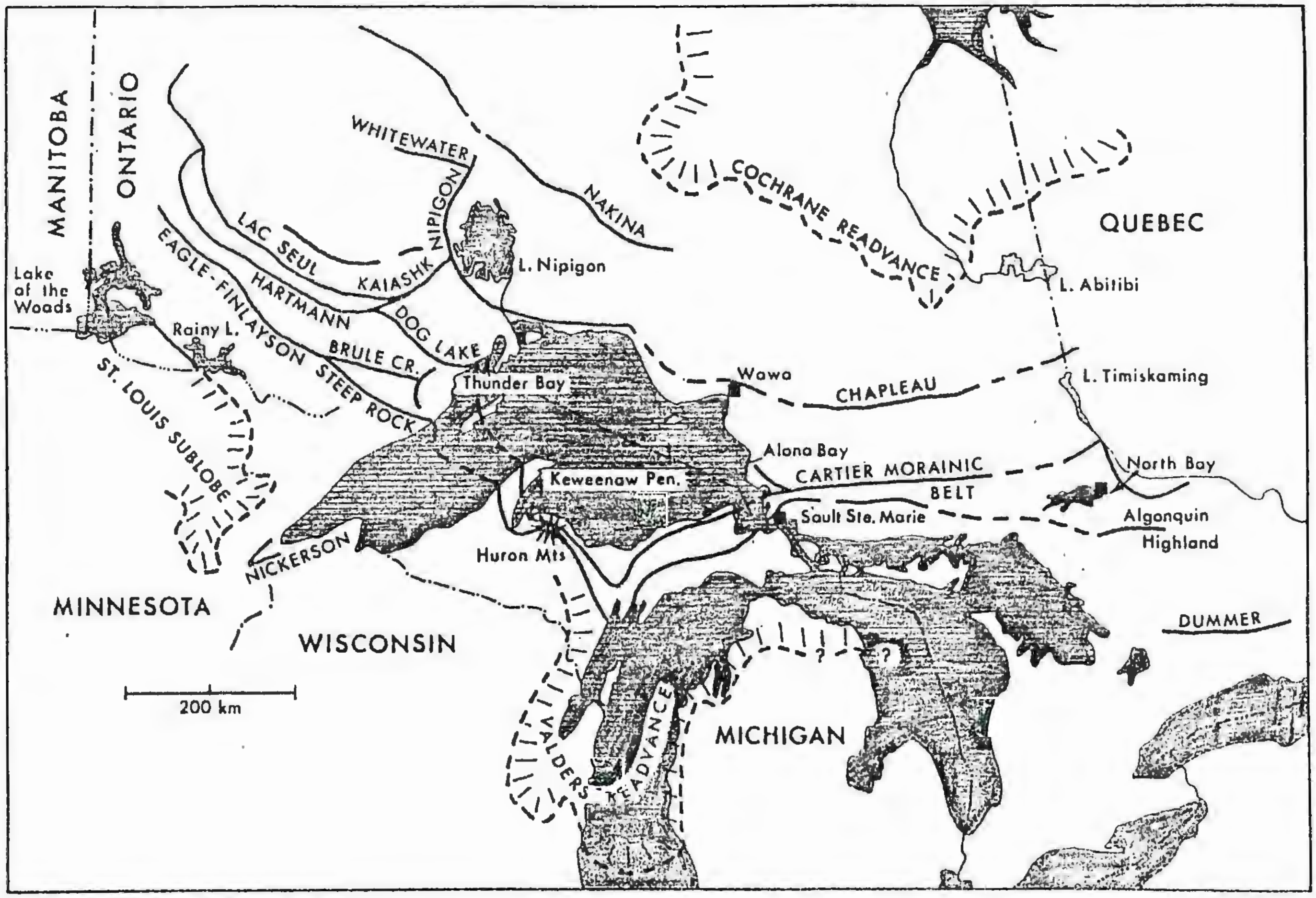


Figure 4. End moraines and ice marginal positions during the Late Wisconsin deglaciation, 12,000-8,000 years B.P., Great Lakes Region (from Saarnisto, 1974).

Saarnisto explained this by asserting that either: (1) suitable sites for pollen studies in critical areas have not yet been discovered or (2) pollen analysis is not a sensitive enough method to show climate changes of this magnitude.

Saarnisto also established a time-stratigraphic relationship between recessional moraine formation in the Lake Superior region and in northern Europe, at about 11,000 to 10,100 years ago. He concluded that the Algonquin Stadial of the Great Lakes region is comparable in age with the Younger Dryas Stadial of Europe.

In 1975 stratigraphic studies on the shoreline displacement of Lake Superior, along with earlier established morphological shorelines, enabled Saarnisto to work out the sequence of Late Wisconsin and Holocene lake levels. It is essentially the same as Farrand's (1960) shoreline model.

A regional study of the environmental geology of the North Shore of Lake Superior was carried out by Green, et al., (1977). Five types of maps (landforms, surfacial deposits, bedrock geology, depth to bedrock, and economic geology) were developed. They provide information on the geological character of the coastal zone of northeastern Minnesota, from Duluth to the Canadian border. In the Two Harbors area specifically, a lake plain, shoreline features, and ground moraine were mapped. Sediments are differentiated into lacustrine clay and silt, nearshore sand and gravel, and unsorted glacial deposits. They are attributed to the Superior Lobe advance and the formation of Glacial Lake Duluth.

Moss (1977) described in detail the Quaternary sediments of the French River region, just northeast of Duluth, and southwest of the Two

Harbors area of this study. She recognized lodgement till attributed to two distinct advances of Superior Lobe ice. Moss, in agreement with Leverett and Farrand, concluded that proglacial lakes formed around the retreating Superior Lobe margin, eventually coalescing to form Glacial Lake Duluth, which reached an elevation of 350 m (1150 feet). Moss concluded that the clay-rich surface unit of the southern part of the French River quadrangle is of lacustrine origin.

Zarth (1977) studied the Late Wisconsin glacial deposits of the Wrenshall and Frogner quadrangles southwest of Duluth. She distinguished two sedimentary environments: an ice-disintigration environment and a glaciolacustrine environment associated with Glacial Lake Duluth. Prominent shoreline features in this area ultimately enabled Zarth to trace the highest strandline of Glacial Lake Duluth, occurring at elevations near 330 m (1080 feet).

T. C. Johnson (1980) investigated the late-glacial and post-glacial sedimentation in Lake Superior using seismic reflection profiles. He concluded that during the final retreat of the Laurentide Ice Sheet, varved glaciolacustrine clays were deposited preferentially in the deep basins in northern Lake Superior and in other deep basins throughout the lake. Johnson was also able to detect that the post-glacial sediment accumulating on the lake floor is non-uniform, influenced by bottom currents, slumping, dewatering, and faulting.

In 1982, another study of end moraines and associated stratified drift beneath Lake Superior was carried out by C. W. Landmesser, T. C. Johnson, and R. J. Wold (1982). They used seismic reflection methods to trace subbottom geomorphic and sedimentary features. These features suggested deposition adjacent to a partially submerged ice margin, and were identified as prominent end moraines. Patterns of sedimentation reflected an offlapping glacial and glaciolacustrine sequence. These workers concluded that the moraines mark ice-margin shorelines of major proglacial lakes that formed during the retreat of the last ice sheet from the Lake Superior basin and tentatively correlate with Glacial Lake Duluth, Glacial Lake Washburn, and Glacial Lake Beaver Bay (Figure 5).

Most recently, Lee Clayton and Mark Johnson are investigating the glaciogenic sediments of Bayfield and Douglas Counties in Wisconsin. They have attempted to correlate the clay-rich unit of the south shore of Lake Superior, called the "Douglas till" (Johnson, 1980), to the red clay of the North Shore interpreted by others to be lacustrine (Leverett, 1929; Farrand, 1969; Moss, 1977; Zarth, 1977). Clayton (1982) in direct contradiction to Leverett and Farrand, proposed that the Marquette and Porcupine moraines (which are attributed to later Superior Lobe advances than those noted by Wright) climb above the Lake Duluth level just west of the Wisconsin/Michigan border, and should do the same straight across the lobe in Minnesota.

At the present time, as well as throughout the history of glacial studies of the Lake Superior region, distinguishing between a clayey till and a lacustrine clay has been problematical. The investigation of the Two Harbors area (this paper) sheds light on the problem, and adds to the present knowledge of the Quaternary history of northeastern Minnesota.

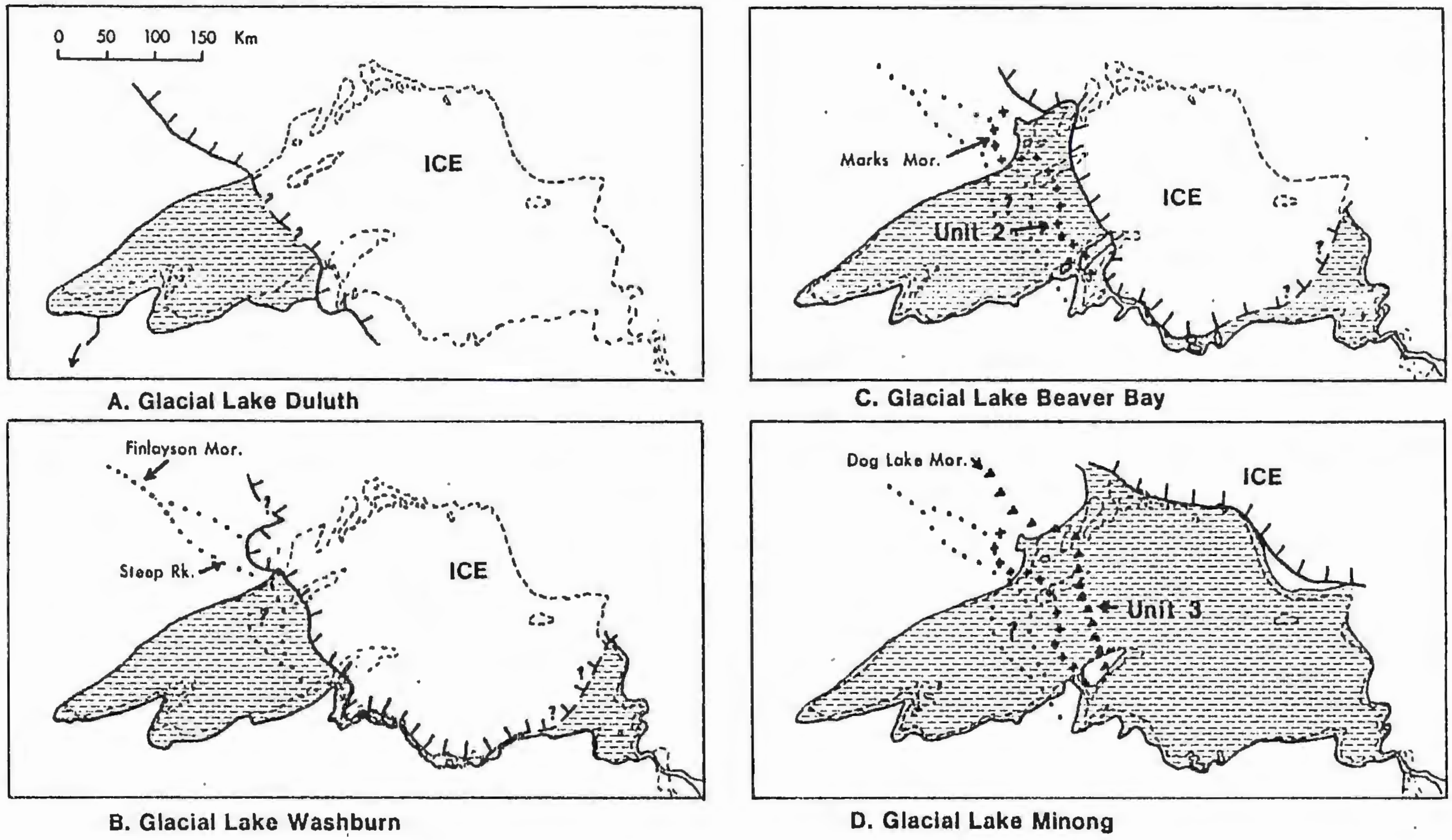


Figure 5. Lake Superior deglaciation and location of recessional moraines (from Landmesser, Johnson, and Wold, 1982).

PLEISTOCENE SEDIMENTS

INTRODUCTION

Tills and a complex of other glacially derived sediments of the Two Harbors area were deposited by the advance and retreat of the ice front during the Wisconsin glaciation. Two distinct groups of depositional processes, primary and secondary, have been shown to exist in glacial environments from sedimentological studies of the Matanuska Glacier, Alaska (Lawson, 1977, 1979b, 1981a, 1981b, 1982) and at other glaciers (Boulton, 1968, 1970a, 1970b, 1971; Shaw, 1977b; Eyles, 1979; Boulton and Eyles, 1979; German, et al., 1979).

Primary processes deposit only the debris in the glacier, are generally unique to the glacial environment, and preserve properties derived from glacial mechanisms (Lawson, 1982). Thus, till is defined as sediment transported and deposited directly from glacial ice, and has not undergone subsequent disaggregation and resedimentation (Lawson, 1979b). Debris eroded at the base of a glacier or which has fallen upon the glacier is transported in three different ways: as basal, englacial, or supraglacial debris, drift, or load (Figure 6). The basal 1 to 3 m of a glacier contains most of the rock debris carried by the glacier. The sediment is concentrated along closely spaced dark dirt bands. Compressive flow and regelation at the base moves the dirt bands upward from the base into englacial positions. At the glacier terminus, owing to the melting of the upper surfaces of debris-rich ice, the upward rising englacial debris becomes supraglacial (Dreimanis, 1977).

Most classifications of tills are based upon the depositional

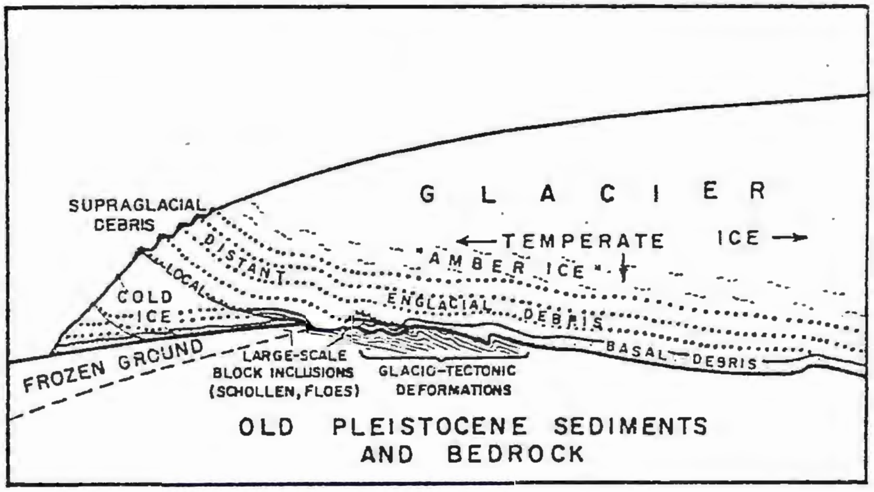


Figure 6. Schematic profile of an ice sheet (from Dreimanis, 1977).

processes that produced them and stratigraphic positions at the time of deposition. Table 1 is one such classification.

Subglacially deposited tills, or basal tills, are formed by a process of lodgement or plastering underneath actively moving glaciers; hence, the term lodgement till. Geothermal heat, as well as heat of friction, (from 35 to 80 cal/cm^2/yr; Andrews, 1975), may melt up to 1 cm/yr of ice at the base of a temperate glacier, thus enabling debris to be slowly let down, producing a basal melt-out till.

Characteristically, subglacially derived debris is uniformly distributed, with little or no size sorting. In exceptional cases, basal meltout may result in some sorting. Clasts are rounded to angular and align parallel and/or transverse to the direction of glacier movement, depending on the local stress systems prevailing within the glacier (Boulton, 1971). Lodgement and basal meltout tills are also moderately to very highly compact. This is attributed to the lodgement process, whereby fine rock flour is forcibly pressed into voids between larger particles during the gradual plastering on and shearing underneath a slowly moving glacier, or by the lithostatic pressure of overlying glacial ice during the deposition of the till. This compactness is referred to as preconsolidation or overconsolidation and is generally associated with high bulk density, high seismic velocity, high shear strength, low porosity, and low void ratios (Dreimanis, 1977).

Fissility is commonly developed in subglacially derived tills that are rich in silt and clay. It is physically an alignment of platy fragments, commonly giving the lenticular flaky quality of light pastry

Table 1.

Genetic classification of primary and secondary deposits based upon the relationship between process and location of deposition, and debris source and location.

a. Primary processes

Debris (sediment in glacier transport)	*Process of release/deposition*	*Position of deposition*	*Primary deposit classification*	*Preservation potential*
Supraglacial	Settlement by ice melt	Subaerial	Lowered till	Generally reworked
Englacial	Ablation	Subaerial		Reworked
	Melt-out	Subsurface	Melt-out till	Generally reworked
Basal	Ablation	Subaerial		Generally reworked
	Melt-out	Subsurface	Melt-out till (upper, lower)	Possible reworking
	Sublimation	Subsurface	Sublimation till	Possible reworking
	Tractional/frictional impairment or pressure melting	Subsurface (subglacial)	Tractional lodgement till (Clasts) ↕ to (Fines) Regelation lodgement till	Generally not reworked but may be glacio-tectonically deformed

b. Secondary processes

Processes of transport/ resedimentation	*Secondary deposit classification*	*Preservation potential*
Sediment gravity flow	Sediment flow deposit	All secondary deposits may be reworked several times before final deposition.
Spall collapse	Slope colluvium	
Gravitational settling or falling through air or water	Ice-slope colluvium Waterlain colluvium	
Meltwater sheetflow	Sheetflow deposits	
Fluvial processes	Various glacio-fluvial deposits	
Lacustrine processes	Various glacio-lacustrine deposits	
Eolian processes		
Thermal erosion and degradation		

(from Lawson, 1981b)

(Flint, 1971). This "schistosity" is thought to be induced by accretion of successive layers of drift from the base of the glacier during ice movement and/or by shearing of overriding ice (Flint, 1971).

Supraglacial till is deposited from debris-rich ice on, or from, the terminal zone of a wasting glacier. As the ice melts back from the terminus, top and base, drift melts out and then slides, flows, or is simply let down onto the ground (Flint, 1971). The result is a supraglacial till that is both lithologically and texturally more variable than a subglacially derived till of the same glacial advance. Its clasts are angular, and have no preferential alignment. The till is loose and not compact, and the fines are washed away selectively, leaving a coarse-textured deposit.

Englacial till is released by ablation and melt-out in subaerial and subsurface positions near the margin of the glacier. The deposit is generally reworked and not compact.

In contrast to these primary glacial processes, secondary processes are not restricted to a glacial environment. Secondary processes rework and redeposit glacially-derived debris and modify or destroy the properties derived from glacial mechanisms.

Sediment flow is one such a process of resedimentation. It mobilizes, transports, and deposits sediment that, in the glacier terminus environment, may be derived from debris, till, or other resedimented materials (Lawson, 1982). These sediment flow deposits (often called "flowtill") are deposited by a non-glacial sedimentary process, indirectly derived from the glacier, and thus should not be called till, although they may be difficult to distinguish from "primary" till.

Sediment flows are thought to be initiated by three mechanisms: (1) slumping of sediment covering stagnant or active glacier ice, (2) backwasting of slopes composed of sediment and stagnant glacier ice, and (3) ablation of debris-laden ice in the glacier's active margin (Lawson, 1982) (Figure 7).

Complications in interpreting stratigraphy

Distinguishing the various types of subglacially and supraglacially derived sediments and interpretating the glacial stratigraphy in the Two Harbors area is challenging. Though glacial sedimentation can be ideally classified, it is truly a complex phenomenon. This is the result of (1) the melting of glacial ice, which produces another geological agent - water; (2) the effect of gravity, which often remobilizes glacial debris as soon as it melts out of the glacier ice; and (3) stress exerted by glacial movement and/or weight, which may deform its own sediment and the pre-existing substratum.

Role of water in the formation of till

The volume of water released by melting glacier ice during the formation and deposition of till may vary considerably from one place to another. It may be minimal, so that it barely fills pore spaces of debris-rich ice and does not cause any sorting. Or, it may be abundant, moving through channels, fractures, and cavities, causing considerable washing and sorting.

Ideally, till is formed without the influence of water, yet size sorting is commonly present to some degree (Flint, 1971). Some sorting a.

b.

c.

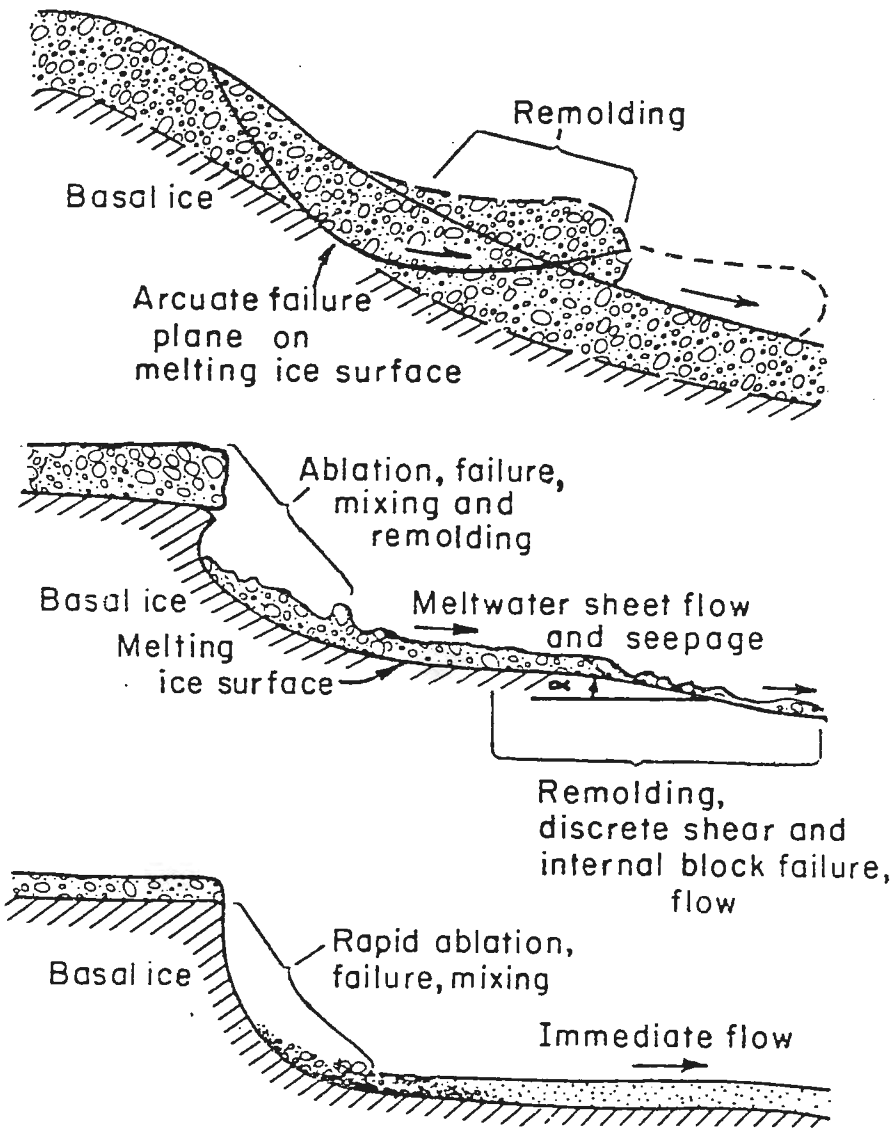


Figure 7. Conditions for sediment flow initiation (from Lawson, 1982).

a. Slump of sediment along arcuate failure plane at ice interface.

b. Backwasting of an ice-cored slope.

c. Initiated directly from an ablating slope when availability of meltwater is high and the availability of sediment is low.

is relict, owing to the incorporation of water-sorted sediments en masse by the glacier prior to the deposition of till (Lundqvist, 1977).

Lenses, fracture fillings, interbeds, and other macro- to microscopic bodies of water-sorted sediments appear in many tills. Though they are not till by themselves, they are considered to be constituents of till sheets, deposited during one episode of glacial sedimentation, and referred to as a "till complex" (Boulton and Eyles, 1979).

Temperature regime is a controlling factor in the presence or absence of water in a glacier (Andrews, 1975). Hooke (1977) proposed that the steady-state temperature distribution in a polar ice sheet of a given geometry is determined by the rate of influx of geothermal heat at the base of the ice sheet, the temperature near the surface (to a depth of 10 m), and the vertical and horizontal components of velocity at every point in the glacier.

The following conditions, considered by Weertman (1961) and Boulton (1972), bear important implications in the role of basal freeze-thaw mechanisms.

(1) If the thermal gradient is greater than the supply of heat to the sole of the ice, then no melting occurs, and the ice sheet is frozen to its base, hence a dry-based glacier. There is no erosion of the substrate and very little debris is incorporated into the glacier.

(2) If the thermal gradient is equal to the supply of heat at the base, then again, no melting occurs, and the conditions previously specified are applicable.

(3) If the thermal gradient in the ice sheet is zero or very small,

then geothermal and frictional heat supplied at the base will cause melting, hence a wet-based glacier. Abrasion will occur at the base of a glacier that is sliding over its bed.

"Deposition" by definition indicates that the debris within the glacier has come to rest and the intergranular ice and underlying ice have melted. Thus, essentially, subglacial deposition by melt-out is restricted to a wet-based glacier (Clayton and Moran, 1974), and deposition by lodgement will only take place where the basal ice is at or near the pressure melting point (Boulton, 1975).

Role of gravity flow and sliding

The role of gravity flow in producing diamictons in the terminal zone of present day glaciers has been discussed by Boulton (1968, 1971, 1972) and Lawson (1979b, 1981a, 1981b, 1982). Lawson estimates that only 5% of the sediments in his principal study area, the ice terminus region of the Matanuska Glacier, Alaska, are true tills. The remaining 95% of the material is resedimented, with sediment gravity flow as the predominant process.

These glacially related gravity and debris flow sediments are considered to be allo-tills, and differentiated from ortho-tills, deposited directly from glacier ice (Dreimanis, 1981).

Deformation by glacial stress

Stress exerted by the movement of a glacier and the weight of the ice may produce a variety of glaciotectonic features (1) in the glacier ice, (2) in the substratum beneath the glacier, and (3) along the front of the glacier, by bulldozer-like action (Dreimanis, 1981). Elson

(1961) has applied the term deformation till to those glacially deformed plastic sediments.

Three types of glaciotectonic structures generally occur throughout Pleistocene glacial sequences (Moran, 1971).

(1) Small-scale folds and faults in till, stratified drift, and bedrock, contorted by ice push and bed shear, are produced by simple in situ deformation. The resultant landforms are ice-thrust ridges or ice-pushed ridges (Andrews, 1975).

(2) Ridges are also produced when large, frozen or consolidated, intact masses of bedrock or pre-existing glacial drift are incorporated into the ice. True end moraines form in this manner, as well as by ice bulldozing of loose material, and delimit the former position of an ice front. Washboard moraines, expressed as a series of transverse ridges and trenches, result from the greater concentration of glacial sediment along periodically spaced transverse zones of shearing (Clayton and Moran, 1974).

In many places thrust masses form conical hills. Upglacier from the hills are typically depressions of the same size and shape from whence they came (Clayton, _et al_., 1980). These hills are commonly misidentified as kames or in place outliers of bedrock.

(3) Transportational stacking within single till sheets by sporadic differential movement and overthrusting along shear planes often occurs in the debris-charged basal zone of the ice (Moran, 1971). As a result, slices of sediment which originally formed at the base of a drift zone may occur anywhere throughout the till sheet.

Failure to recognize large-scale block inclusions and transportational thrust faulting can result in the creation of spurious local units and can also lead to erroneous models of thickness and glacial drift sequences where older beds are encountered near the surface (Moran, 1971).

Lastly, a combination of any of the above-mentioned factors (volume of water, influence of gravity flow, deformation by glacial stress) can erase boundaries, create transitory contacts, and cause interbedding, lensing, and fracture filling. This contributes to the complexity of glacial sedimentation and complicates the interpretation of sediment stratigraphy.

PROVENANCE REGIONS IN THE TWO HARBORS AREA

Surficial sediments of the Two Harbors area can be broadly grouped into two lithologic types, based on the bedrock source of the clasts they contain. Provenance region I produced glacial sediments that comprise the surficial deposits of the northwestern half of the Whyte quadrangle (Rainy Lobe drift). Provenance region II was the source of deposits encountered in the southeastern half of the Whyte quadrangle and all of the Two Harbors quadrangle (Superior Lobe drift) (Figure 8).

Provenance region I sediments

In general, the till derived from Provenance region I is gray to brown, and sandy to stony. The clasts and surface boulders are predominantly granite, granophyre, gabbro, and greenstone, indicating derivation primarily from the Duluth Complex which underlies much of the area where the drift is found. Other igneous and metamorphic sources to the north and northeast also contributed clasts. Stratigraphic relations show that these sediments are older than those from Provenance region II. They are the result of the Rainy Lobe advance from the northeast and are here referred to as the Sullivan Lake Formation.

Provenance region II sediments

The glaciogenic sediments of Provenance region II are a distinct reddish brown in color, and range from sandy to clayey. They are rich in rock fragments eroded from the Late Precambrian North Shore Volcanic Group (basalt and rhyolite) and from Keweenawan red sandstone from the Lake Superior basin to the east and northeast. Granite, granophyre, and

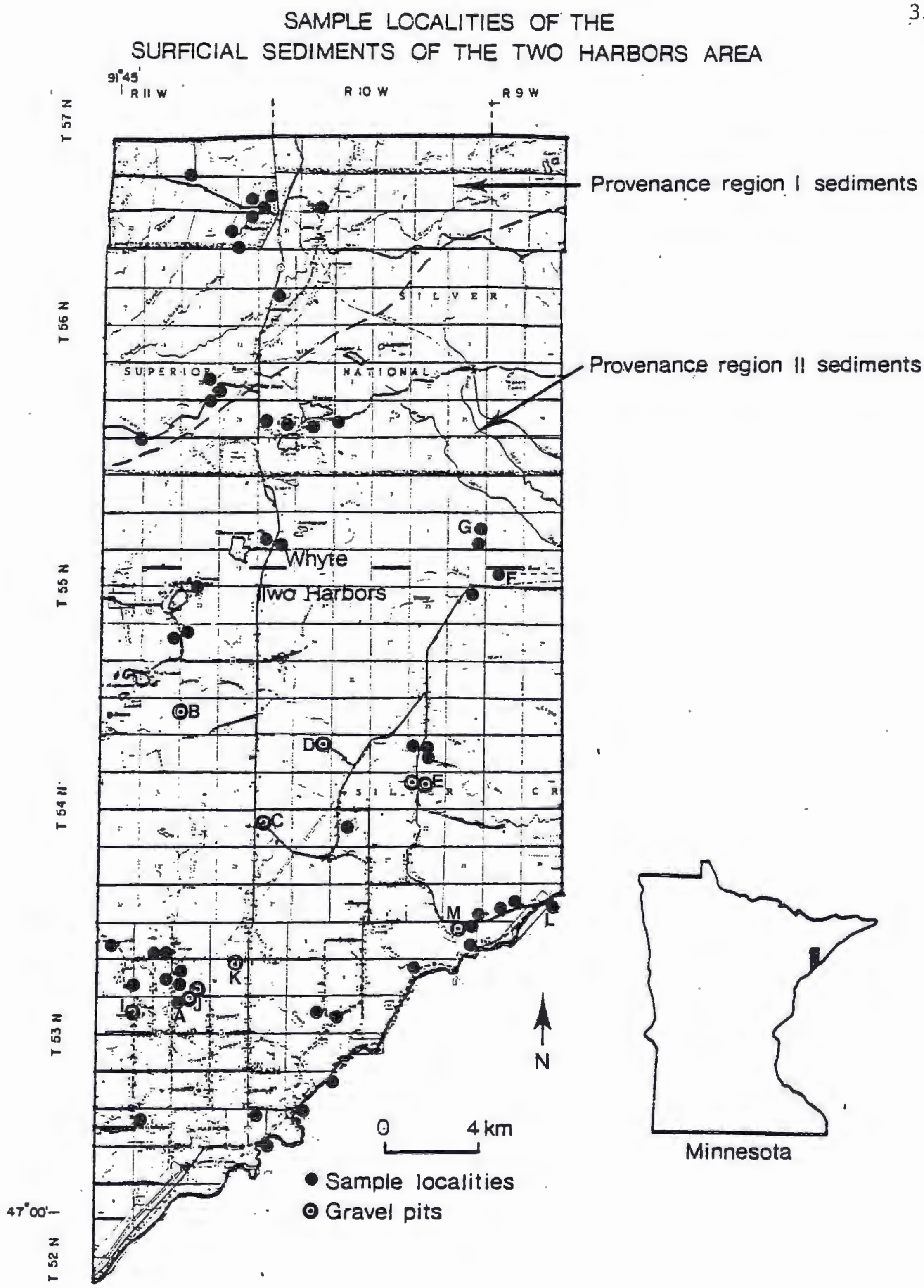


Figure 8. Sample localities of Provenance region I and II sediments.

gabbro clasts are also found, though less common. Their source is the gabbro and diabase dikes and sills locally intruded into the lava flows of this area, as well as older Precambrian terrane to the north of Lake Superior. Sandy to silty ortho-tills and associated sediments which cover much of the central and northern parts of the map area are ascribed to Provenance region II. These sediments were deposited during the advance, retreat, and stagnation of the Superior Lobe as it moved westward and southwestward out of the Lake Superior basin. They are defined as the Cromwell Formation (Wright, *et al*., 1970).

Glaciofluvial sediments and glaciolacustrine red clay are distributed near the southernmost edge of Provenance region II. They are associated with the formation of Glacial Lake Duluth and the glaciolacustrine sediments are identified as the Wrenshall Formation (Wright, *et al*., 1970).

SULLIVAN LAKE FORMATION

General characteristics

The name "Sullivan Lake Formation" is here introduced for the numerous exposures of grayish-brown till and outwash near Sullivan Lake, in Lake County, northeastern Minnesota (approximately 40 km north of Two Harbors). The type section is a 3 m-thick exposure along a roadside cut 0.8 km off of County Road 2, on County Road 15, en route to the village of Toimi. At this locality the drift is sandy and texturally similar from the base to the top of the section. The Sullivan Lake Formation presumably rests on bedrock, however no basal contacts are found at the type locality. Clasts greater than 5 cm comprise 15% to 35% of the deposit, and boulders, up to 30 cm in diameter and commonly striated, are scattered randomly on the till surface. The main rock types are granite, granophyre, gabbro-diabase, and greenstone. Fabric orientation of elongate stones at the type locality yields a strong north-northeast to south-southwest trend which is parallel to the prominant southwest trending Toimi drumlins that characterize this area.

The unsorted facies of the Sullivan Lake Formation has been previously referred to as the Independence Till. This term was first introduced by Wright (1956) for the unsorted, grayish-brown drift exposed beneath younger, clayey drift in the Cloquet quadrangle (approximately 65 km southwest of Two Harbors).

The type section for the Independence Till is a 4.5 m-thick road cut in a drumlin 27 km north of Cloquet. There the Independence Till is capped by 0.6 m of clayey till from another source, presumably the

Cromwell Formation (Wright, et al., 1970). The general thickness of the Independence Till at this locality (approximately 5 meters) can only be inferred since depth to bedrock is not known. The Independence Till resembles that of the prominent southwest trending Toimi drumlins (located north of the Cloquet area), and is so correlated with the drift in the northwest half of the Whyte quadrangle of the study area. Its deposition is ascribed to an advance of the Rainy Lobe (Wright, et al., 1970). Thus, the name "Independence Till" is hereby abandoned, and subsequently redefined as the Sullivan Lake Formation.

The Sullivan Lake Formation of the Two Harbors area is generally grayish-brown (10 YR, 5/2-5/3), to dark brown (10 YR, 4/3), to dark yellowish brown (10 YR, 3/6) (Munsell Color designation, wet to moist, except where otherwise specified). Texturally, it is sandy, having an average sand:silt:clay ratio of 76:21:03 (data from 12 samples) (Figure 9). The till is bouldery and lithic fragments greater than 5 cm are abundant, comprising more than 30% of the total volume.

The clasts greater than 2 mm are predominantly granophyre (31%) and granite (28%). Although granophyre can be granite, a distinction is made between the two based on the relative percentages of alkali feldspars (orthoclase, perthites, microcline) predominating over calcium-bearing plagioclase feldspars (oligoclase or andesine). In the field, as well as under a binocular microscope, granophyre is identified essentially as a porphyritic "pink granite." Granite, on the other hand, is identified by more commonly containing a host of minerals (quartz, biotite, muscovite, hornblende, olivine, and plagioclase), with only minor amounts of alkali feldspars; essentially a "white granite".

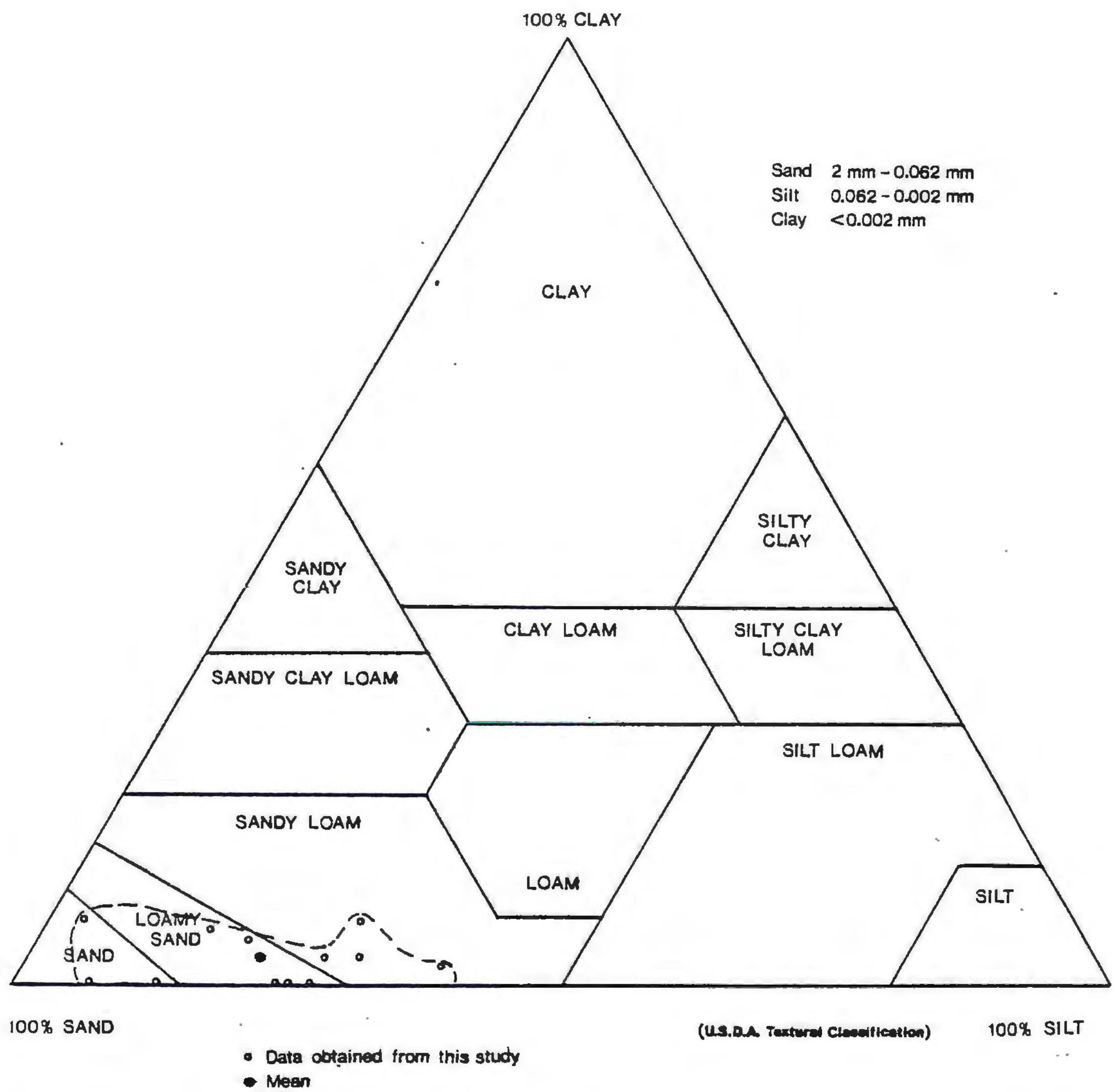


Figure 9. Textural composition of the Sullivan Lake Formation.

Other significant rock types include greenstone (15%), basalt (11%), and gabbro (10%). Lithic fragments of rhyolite, iron formation, quartzite, and conglomerate are minor components.

Granophyre and granite fragments together comprise greater than 50% of the 1-2 mm coarse sand fraction. Other coarse sand lithologies include gabbro (15%), basalt (12%), rhyolite (11%), and quartz (6%). Epidote, hornblende, pyroxene, and plagioclase sand-size grains were also identified. Red sandstone characteristic of the Lake Superior basin is rare (less than 1%). Table 2 summarizes the textural and lithological parameters measured.

The gabbro is locally derived from the Duluth Complex, as is the granophyre and granite, which occur as independent intrusive bodies, as well as the uppermost portion of diabase and gabbroic sills (Green, et al., 1977). Some of the granite may also be Archean in age, derived from the Giants Range and Vermilion batholiths in northeastern Minnesota. The quartz and iron magnesium bearing minerals (hornblende, pyroxene) are components of the granite and granophyre. The greenstone (essentially a metabasalt) may also have come from the Vermilion district in northeastern Minnesota (thus formally called the Ely Greenstone). Quartzite and conglomerate clasts could be far-traveled fragments of the Knife Lake Group in northeastern Minnesota. A probable source of the iron formation is the Gunflint Iron Range, also in northeastern Minnesota. Basalt and rhyolite are probably locally derived from the North Shore Volcanic Group.

The high percentage of gabbro (from the Duluth Complex), iron formation (from the Gunflint Iron Range), and slate and graywacke (from

Table 2

SUMMARY OF SEDIMENT CHARACTERISTICS

	Sullivan Lake Formation		Cromwell Formation			Wrenshall Formation
		Supraglacial debris	Subglacial debris (Sandy Loam Facies)	Subglacial debris (Loam Facies)		Clay Facies
Typical Color (moist)	10 YR, 5/2	7.5 YR, 4/6	5 YR, 3/4	5 YR, 3/4		5 YR, 4/4
Grain Size Distribution	(n=12)	(n=7)	(n=8)	(n=7)		(n=10)
Weight % sand	76	66	57	40		14
Weight % silt	21	30	32	39		16
Weight % clay	03	04	11	21		70
Greater than 2mm Clast Lithologies	(n=10)	(n=6)	(n=6)	(n=6)	Average	(n=19)
% basalt and amygdaloidal basalt	11	26	40	42	36	44
% rhyolite and amygdaloidal rhyolite	3	16	19	18	18	21
% "red" sandstone	0	1	.3	2	1	5
% granite	28	22	8	6	12	5
% granophyre	31	11	2	15	9	1
% gabbro and diabase	10	17	20	13	17	18
% quartz	0	0	0	0	0	.5
% agate	0	.3	1	2	1	1
% chert	.1	0	.3	0	.1	1
% iron formation	1.4	0	.6	0	.2	.1
% metamorphic (greenstone)	15	6	8	2	5	3
% quartzite	.8	.2	0	0	.1	.3
% conglomerate	.7	0	0	0	0	0
% shale	0	0	1	.3	.4	.3
% carbonates	0	0	0	0	0	.3
1-2mm Coarse Sand Lithologies	(n=9)	(n=8)	(n=7)	(n=8)	Average	(n=10)
% basalt	12	8	16	10	11	21
% rhyolite	11	14	14	18	15	9
% "red" sandstone	.2	.2	1	1	.7	1
% granite	42	44	47	42	44	22
% granophyre	11	11	12	9	11	9
% gabbro and diabase	15	18	6	16	13	14
% quartz	6	2	2	2	2	19
% agate	0	0	.1	0	.03	.2
% chert	.3	.4	.3	.7	.5	.1
% calcareous concretions	0	0	0	0	0	2
% iron formation	0	.06	0	0	.02	0
% metamorphic	.5	2	1	1.4	1	1
% epidote	.3	.1	.1	.2	.1	2
% hornblende	.03	0	.1	0	.03	0
% pyroxene	.07	.05	0	0	.02	0
% olivine	0	0	.2	.2	.1	0
% plagioclase	.6	.2	0	.1	.1	0
% carbonates	.03	0	0	0	0	0

the Rove or Virginia Formation), cropping out northeast of the study area, is what gives the Sullivan Lake Formation its grayish-brown color.

In the Two Harbors area the Sullivan Lake Formation is mostly a lodgement till, characterized by drumlins. Outwash, in the form of stratified drift, is commonly found in the cores of drumlins, with a cap of till. However, such a relationship was not observed in the study area. The presence of drumlins, whatever their mode of origin, indicates the existence of a wet-based glacier, easily able to slip over its bed (Clayton and Moran, 1974). Thus, the Sullivan Lake Formation was deposited by lodgement in the basal zone of an actively flowing glacier. Other evidence to support this mode of deposition is the relative compactness of the till, and the preferential alignment of elongate clasts. The orientation of long axes of elongate stones in the drumlinized till (measured at eight sites) shows a strong northeast-southwest trending fabric (Figure 10). This is parallel to the streamline form of the drumlins and to the inferred direction of ice flow. Macrofabric would not have been as well developed or preserved in sediment deposited from englacial or supraglacial positions.

Site-specific characteristics

The Sullivan Lake Formation is identified as surface exposures near the Langley and Cloquet Rivers, and near Sullivan Lake, Sec. 36, T 57 N, R 11 W, in the northwestern part of the map area. At the head of the lake, in the NW 1/4 of Sec. 36, T 57 N, R 11 W, a 3 m-thick section of gray, unsorted, gravelly outwash, capped by approximately 0.3 m of non-stratified sand is exposed. The most abundant rock types are

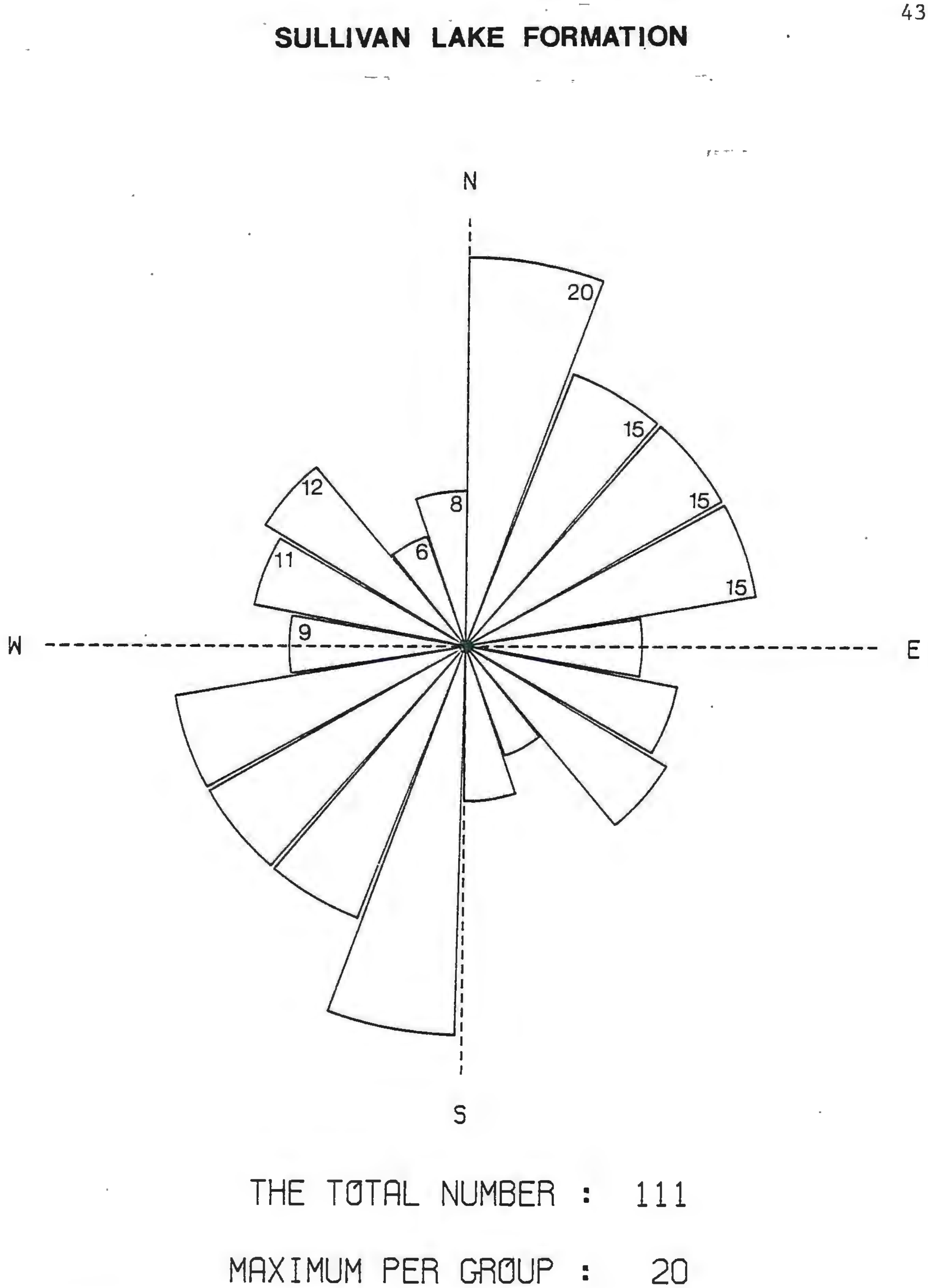


Figure 10. Fabric orientation of elongate stones of the Sullivan Lake Formation, showing a strong northeast-southwest trend. (Composite of measurements from eight sites.)

granite, granophyre, basalt, greenstone, and gabbro. The nature of this deposit is interpreted to be debris deposited in a meltwater channel.

Near Murphy Creek, NE 1/4, Sec. 27, T 57 N, R 11 W, a 1.5 m-thick section of a grayish-brown, sandy till is exposed. It is texturally and lithologically similar to the previously mentioned type section, located 4 km to the east, along County Road 15.

Geomorphic features

Morphologically, the Sullivan Lake Formation is represented primarily by the northeast-southwest trending Toimi drumlins. Several eskers and a tunnel valley, partially occupied by Sullivan Lake, also decorate the landscape.

The Toimi drumlins are asymmetrical in long profile and streamlined, with the blunter, higher end upglacier (to the northeast). Directional measurements of 12 drumlins (from a topographic map) ranges from S 31° W to S 62° W, with an average trend of S 43° W. The details of their origin, whether erosional, depositional, or a combination of both, are speculative. In one view, drumlins result from subglacial shearing in the thawed bed zone of a glacier where the ice can slip over basal obstructions (Clayton and Moran, 1974). In this model, the Toimi drumlins formed in the basal zone of transportation where the basal ice of the Rainy Lobe was loaded with debris, and the basal temperature was at the pressure melting point (Wright, et al., 1973).

In a depositional model, favored by many others, debris-rich stagnant ice is deposited around the flanks of a subglacial obstruction, due to a local increase in the rate of shear as the glacier passes over the obstruction (Boulton, 1970b). Upon melting, a rock-cored drumlin may result.

Thus, if the drumlins are erosional, the Sullivan Lake Formation is older than the ice lobe that molded it. If, however, the drumlins are depositional, then they are of the same age as the Rainy Lobe advance.

Eskers are long, narrow, sinuous ridges composed primarily of stratified drift. A northeast-southwest trending esker is found near Sullivan Creek, NW 1/4, Sec. 11, T 56 N, R 11 W, and another near the Cloquet River, NE 1/4, Sec. 16, T 56 N, R 11 W.

The topographic low trend containing Sullivan Lake, just northeast of the eskers in Sec. 36, T 57 N, R 11 W, is interpreted to be a tunnel valley eroded by a high-velocity subglacial stream. This stream could have been driven by high hydrostatic pressure, resulting from the weight of a thick mass of still active ice (Wright, 1973). When the ice thinned to stagnation, the hydrostatic head was lost, and this subglacial stream changed its habit from erosional to depositional. Hence, the several small eskers found along its southern trenches were formed.

CROMWELL FORMATION

General characteristics

The Cromwell Formation was originally named by Wright, et al., (1970) for exposures of reddish-brown sandy till and associated stratified deposits containing Keweenawan red sandstone of the Lake Superior basin, which underlies most of the Cloquet quadrangle. The type locality is in the village of Cromwell in Carlton County, 29 km west of the Cloquet quadrangle (approximately 94 km southwest of Two Harbors) on U.S. Highway 210, where exposures of this till are numerous. Though the base of the Cromwell Formation is not exposed at the type locality, it presumably rests on the Sullivan Lake Formation. This stratigraphic relationship is noted in the NE 1/4, Sec. 13, T 49 N, R 17 W, in the Cloquet quadrangle, and more conspicuously in a roadcut 0.3 km north of Brookston (32 km northeast of Cromwell) (Wright, et al., 1970). It was deposited by the Superior Lobe and its associated meltwater streams in eastern Minnesota from Cook County to southern St. Louis County, west to Crow Wing and Todd Counties, and south to Dakota County (Wright, et al., 1970). In central Minnesota, west of the Mississippi River, it rests on Wadena Lobe till. In east-central Minnesota, from Pine County south to Dakota County and west to Hennepin and Stearns Counties, it is covered by Grantsburg Sublobe drift from the Des Moines Lobe (Wright, et al., 1970).

The Cromwell Formation exposed in the study area consists of lodgement and melt-out tills, and glaciofluvial and sediment flow deposits derived from subglacial, supraglacial, and ice marginal debris, respectively. The till is characterized by a distinct reddish- brown color (5 YR, 3/4).

Lithic fragments ranging from 2 mm to 16 mm comprise more than 21% of the total volume of the sediment. Clasts of the North Shore Volcanic Group (basalt, some amygdaloidal basalt, and rhyolite) dominate the greater than 2 mm-size clasts, contributing 36% and 18% of the fragments. Gabbro and diabase (17%), granite (12%), and granophyre (9%) are a minor portion of the lithic components. Keweenawan red sandstone constitutes only 1% of the clasts, though by definition, the Cromwell Formation is characterized by relatively high percentages of red sandstone from the Lake Superior basin (Wright, et al., 1970). Agates, the most resistant mineral of basalt amygdules, also contribute 1% of the rock fragments.

Granite (44%) is the most abundant rock type in the 1-2 mm coarse sand fraction. Amygdaloidal basalt and rhyolite combined account for 26% of the grains. Gabbro (13%) and granophyre (11%) are again minor components. Keweenawan red sandstone accounts for less than 1% of the sand-size grains. Table 2 summarizes these characteristics.

The Cromwell Formation is distinguished from the older Sullivan Lake Formation by the abundance of basalt and rhyolite pebbles, along with the presence of red sandstone of Keweenawan age, and "Lake Superior" agates. This reflects local derivation from the underlying North Shore Volcanic Group and from the Lake Superior basin to the east. Dikes cutting across the flows and other local occurrences of Keweenawan intrusions account for the substantial percentages of gabbro-diabase, granite, and granophyre.

Supraglacially derived debris

Site-specific characteristics

Supraglacially derived debris is identified in the northwestern part of the Two Harbors quadrangle and the southeastern half of the Whyte quadrangle. In general, the supraglacially derived debris is texturally variable. Data from seven samples analyzed yields an average sand:silt:clay ratio of 66:30:04 (Figure 11). Long axis orientation of elongate stones, from a composite of five sites, is weakly developed, to random, reflecting the local variation in fabric formed supraglacially (Figure 12).

A 3 m section of strong brown (7.5 YR, 4/6), sandy to silty till is exposed near Thomas Lake, SW 1/4, Sec.14, T 55 N, R 11 W. Basalt and granite are the dominant greater than 2 mm clasts, followed in abundance by gabbro, rhyolite, amygdaloidal basalt, greenstone, and red sandstone. Fabric shows a strong northeast- southwest trend, which is parallel to the inferred ice margin (Figure 13). A strong fabric trend is not typical in supraglacially derived debris. Commonly long axes orientation of elongate stones is not well preserved or is weakly developed to random, owing to the "collapsed" mode of deposition. Thus, the interpretation of the origin of this deposit is controversial. Dr. Charles L. Matsch (pers. comm., 1982) has suggested that this sediment is the basally-derived "Lower Cromwell Formation," the time-stratigraphic equivalent of the Sullivan Lake Formation. He sites the strong northeast- southwest fabric trend as major supporting evidence of deposition from an ice-lobe advance from the northeast.

Moss (1977) distinguished two tills of different ages (presumably

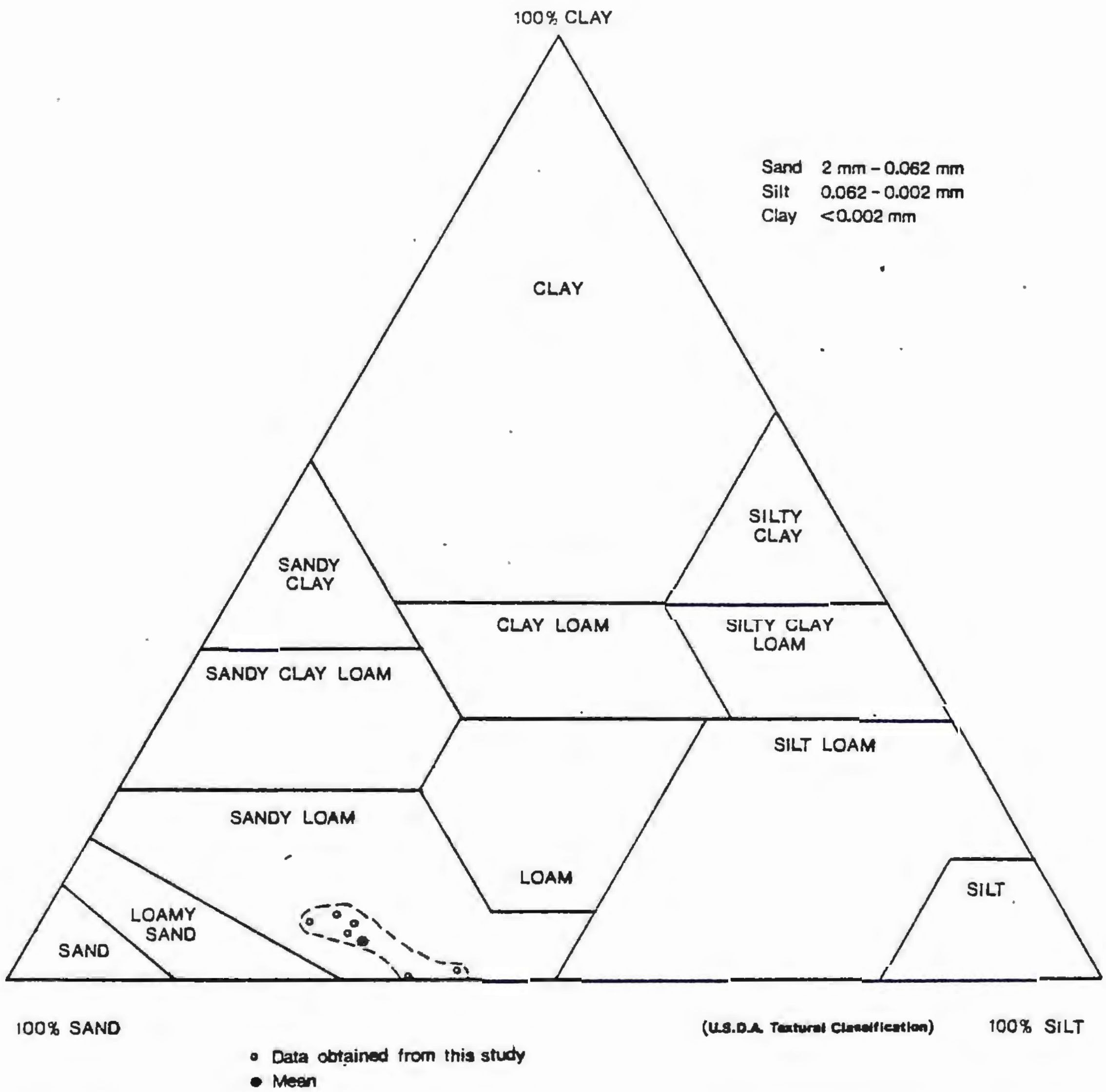


Figure 11. Textural composition of the supraglacially derived debris of the Cromwell Formation.

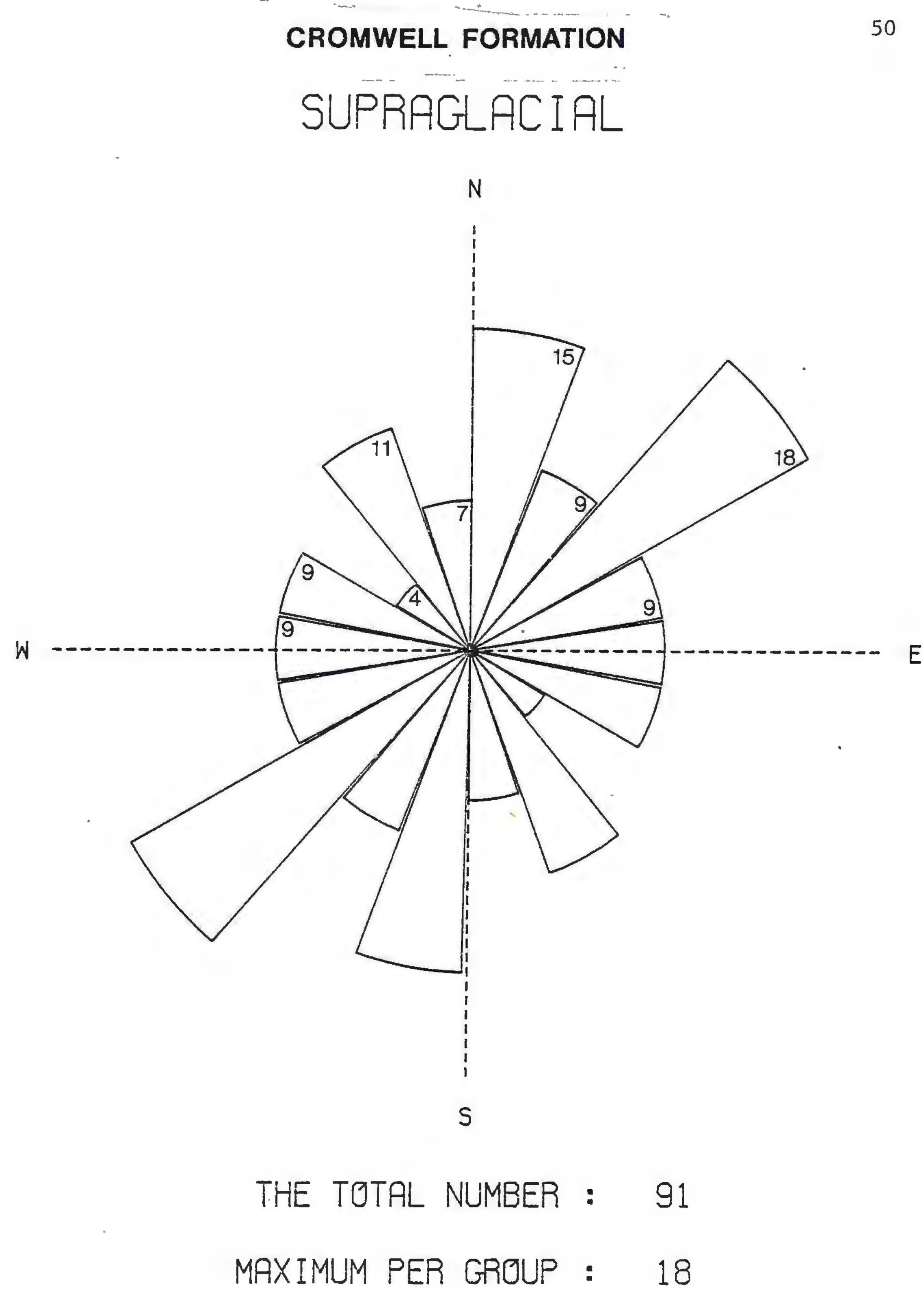


Figure 12. Fabric orientation of elongate stones, supraglacially derived debris of the Cromwell Formation. (Composite of measurements from five sites.)

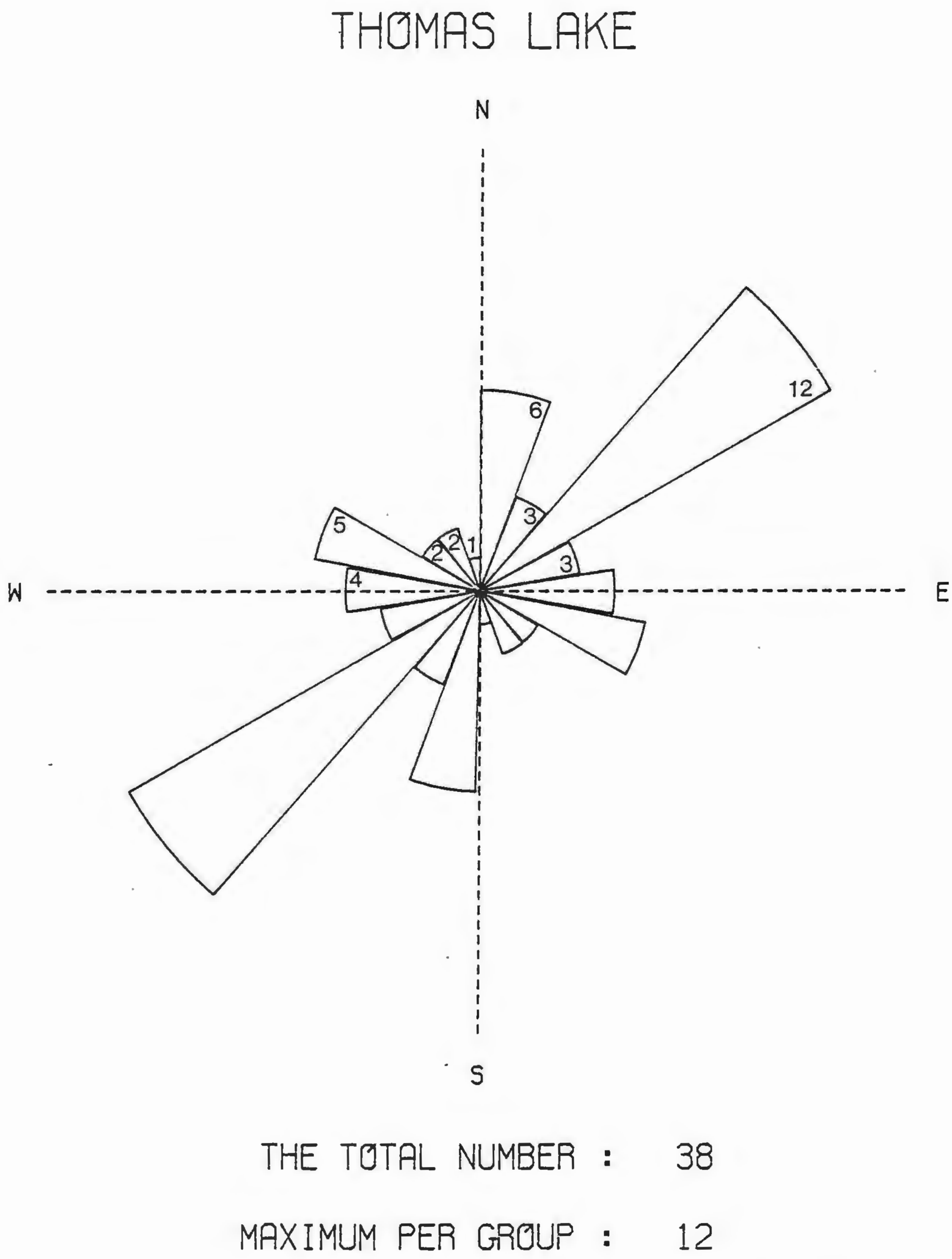


Figure 13. Fabric orientation of elongate stones, supraglacial melt-out till, Cromwell Formation. Thomas Lake, SW¼ Sec. 14, T55N, R11W.
Preferential alignment is northeast-southwest.

the Lower Cromwell and Upper Cromwell Formations) in the French River area, located approximately 16 km southwest of the Two Harbors area. When observed in stratigraphic sequence, the tills are easily distinguished by color, texture, and fabric. The contact between the two tills is generally sharp, rather than gradational, and there is commonly a stone line or gravelly layer between them. Such a relationship was not observed in the Two Harbors area.

The 3 m section near Thomas Lake is a surface exposure. No deposits lie above it, and no contacts were discerned. The sediment is not compact, sandy to silty, and has an average sand:silt:clay ratio of 64:36:00. Morphologically, the sediment is expressed by a hummocky topography, indicative of collapsed supraglacial sediment. It is for these reasons that the origin of this deposit is interpreted to be a supraglacial, or englacially derived melt-out till.

Fabric alignment is not always indicative of lodgement till. Preferential alignment of pebble fabric, inherited from the ice source with little change, can also occur in a melt-out till (Lawson, 1981b). Perhaps the strong upward component of movement in the terminal area of the glacier, owing to compressive flow, initiated the transverse alignment of elongate clasts, while the slow, melting in situ of the debris near the surface, without subsequent resedimentation, is responsible for the preservation of the englacial fabric.

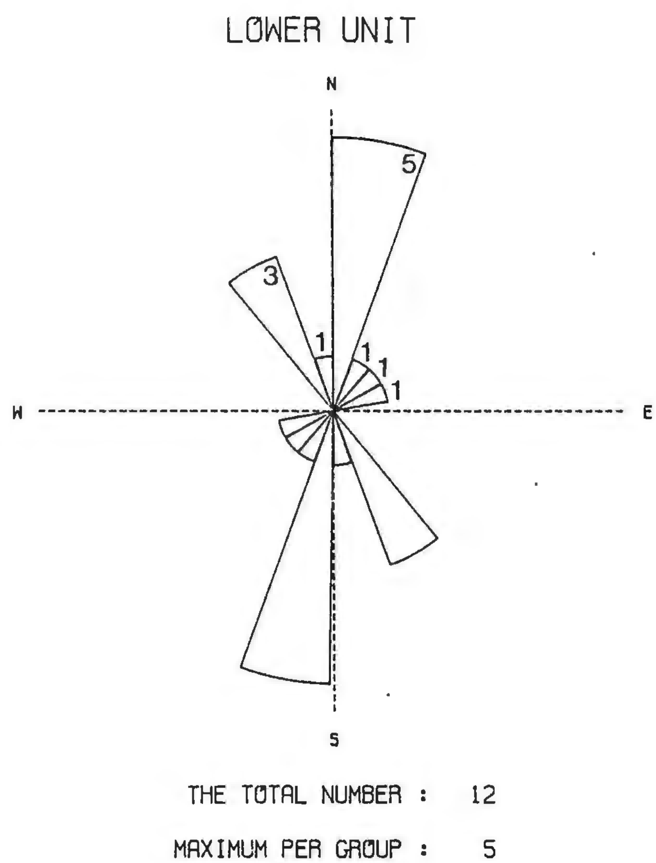
Supraglacial debris is also exposed near Kane Lake and Marble Lake Sections 29 to 32, T 56 N, R 10 W, and 5 km to the south, along County Road 2, SW 1/4, Sec. 7, T 55 N, R 10 W. A 2 m section along County Road 2 is composed of 1 m of a basal, silty till (67% sand, 27% silt, 6%

clay), and is overlain by approximately 1 m of a sandier, much stonier till (94% sand, 6 % silt, 0% clay). Both have a brownish hue (7.5 YR, 5/4, dry). The lower unit also shows a north-south fabric orientation, while the upper unit exhibits a northeast-southwest fabric trend (Figure 14). This variation in texture and fabric does not represent two phases of Superior Lobe ice movement, but rather could be the result of the constantly changing configuration of the till surface and is developed from differential ablation and till flow (Boulton, 1971).

The percentage of lithologic types is similar for both units; basalt, amygdaloidal basalt, and rhyolite are most abundant, followed by granite, gabbro, granophyre, greenstone, and agates.

Geomorphic features

The major landform composed of supraglacially derived debris of the Cromwell Formation is the Highland Moraine. It parallels the North Shore of Lake Superior along the crest of the North Shore Highland. Within the Two Harbors area the Highland Moraine has a width of approximately 9.4 km. It encompasses the northwestern most portion of the Two Harbors quadrangle and extends through the southeastern half of the Whyte quadrangle. It reaches an elevation of 488 to 549 m (1600 to 1800 feet). Northeastward from the study area the Highland Moraine forms an interlobate junction with the contemporaneous Vermilion Moraine of the Rainy Lobe, east of Isabella (Wright, et al., 1969). Southwestward from Two Harbors, the Highland Moraine is projected along its trend to the Cromwell and Wright Moraines (approximately 64 km southwest of Duluth). That moraine complex borders and encloses the Automba drumlin field (Leverett, 1932).



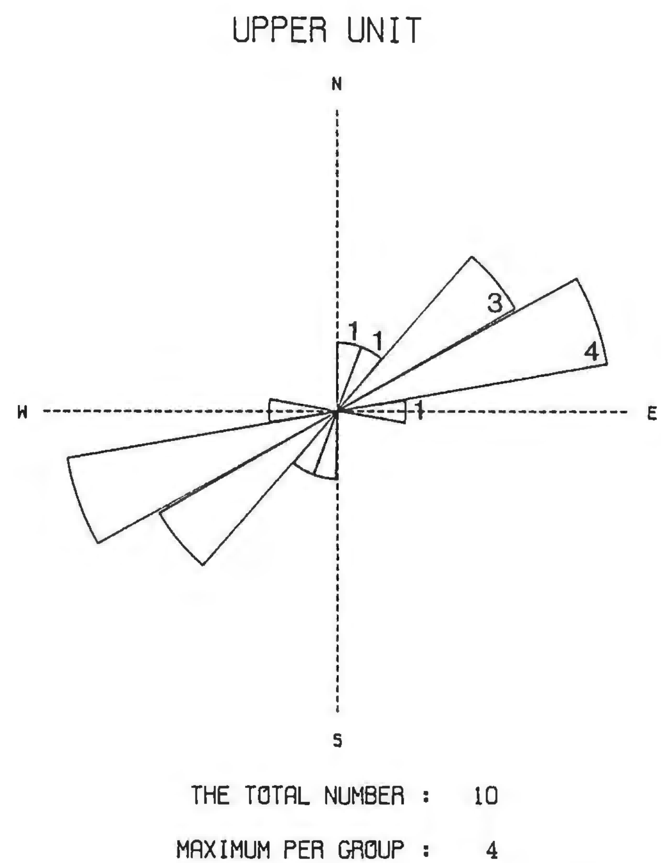


Figure 14. Fabric orientation of elongate stones, supraglacial debris of the Cromwell Formation, along County Rd. 2, SW¼, Sec. 7, T55N, R10W.

The northwestern limit of the Highland Moraine is bordered by a string of kettle lakes, from Lillian Lake, Sec.20, T 57 N, R 9 W, in the far east of the Whyte quadrangle, to Stewart Lake, Sec.9, T 54 N, R 11 W, in the northwestern corner of the Two Harbors quadrangle. Beyond this margin a thin veneer of supraglacial sediment covers the Toimi drumlins (composed of Sullivan Lake Formation).

The Highland Moraine formed as debris piled up on the leading edge of the glacier when forward movement (out of the Lake Superior basin and to the west and southwest) halted, and stagnation began. As ablation progressed, debris collected on, around, and between stagnating ice blocks that broke up from the edge of the ice sheet. Melting, slumping, collapse, and sediment transport all occurred in this area.

The moraine itself is expressed mainly as a hummocky kettle and kame collapse topography with intervening outwash bodies. It contains a variety of geomorphic features that attest to the changing nature of the supraglacial environment.

The most common feature recognized is the kames. They are conical hills or mounds of varying sizes, reaching maximum dimensions of up to 100 m in length and 15 m in elevation. They are an "uncontrolled" ice-disintegration feature formed by collapse and deposition from stagnant ice. Some of the kames have depressed tops, reflecting a doughnut or ring shape. This is interpreted to be the result of the incomplete filling of supraglacial sinkholes by mudflow (Clayton and Moran, 1974). Some of the kames are transversely elongated. They are considered to have formed where transversely elongated concentrations of englacial sediment (resulting from the shearing of subglacial sediment into the ice just behind the glacial terminus) is lowered to the ground as the underlying ice melted.

Texturally, the kames are composed of poorly-to moderately-sorted stratified sand and gravel. A small isolated kame (20 m in length), is exposed just north of Kane Lake, SE 1/4, Sec. 30, T 56 N, R. 10 W. The basal 2 m is a poorly sorted gravel with an abundance of striated boulders. This is capped by 0.5 m of moderately-sorted fine sand.

Kettles are another prominant feature associated with the hummocky terrane. They are small basins formed by the ablation of buried ice, and range from 0.2 km to 1.0 km in diameter. Small lakes may form in these depressions, hence, the northwestern most string of kettle lakes of the Highland Moraine.

An abandoned meltwater channel, trending northeast-southwest, is located near the southeastern margin of the moraine at an elevation of 488 m (1600 feet). Perhaps it marks an ice-margin position of minor significance.

Flutes also occur near this margin northwestward from the abandoned meltwater channel. They are determined largely by topographic interpretation and probably consist of glacial sediment (Green, 1982).

Eskers and esker-like ridges are also a common feature of the moraine. Their southeast-northwest trend parallels the general direction of ice flow (laterally out of the Lake Superior basin and to the northwest in this area). Their distribution is both near the margin of the moraine, in the area of the flutes, and also behind the margin, in the area of collapsed glacial sediment. The eskers attest to an abundance of meltwater and were probably deposited in subglacial tunnels near the terminal zone of the thin and stagnant glacier.

The general thickness of the supraglacial sediment in the Highland Moraine is 13 meters, yet sediment cover is estimated to be as thin as 3 meters in some areas, and can be as thick as 22 meters in others.

Clayton and Moran (1974), and Clayton, et al., (1980), have determined that the thickness (in meters) of supraglacial sediment of the rolling to gently undulating hummocky topography of North Dakota is roughly equal to the maximum slope angle (in degrees) of the hummocks. This observation can be explained by the following line of reasoning. Slope angle of collapsed debris is related to fluidity of supraglacial sediment at the time of deposition. Fluidity is controlled by the water content of the sediment, which is in turn controlled by the rate of ice melt. Ice melt is influenced by the thickness of the insulating blanket of supraglacial sediment. Thus, gentle slopes are the result of rapid melt due to a thin cover of supraglacial sediment, while steep slopes are the result of a thick cover of supraglacial sediment.

This concept was applied to the Highland Moraine and maximum slope angles of the hummocks were calculated. The undulating to hilly topography (slope angles 3° to 22°) of the moraine is thus interpreted to be the result of several episodes of post-depositional collapse of a supraglacial sediment pile inferred to be 3 to 22 meters thick.

Subglacially derived debris

Site-specific characteristics

Subglacially derived debris of the Cromwell Formation is exposed southeast of the Highland Moraine, near Bud Creek, SW 1/4, Sec.18, T 55 N, R 9 W and SE 1/4, Sec.12, T 55 N, R 10 W, Stony Creek, NW 1/4, Sec.24, T 55 N, R 10 W, and the Encampment River, SW 1/4, Sec.21, T 54 N, R 10 W. This area is characterized by southeast-northwest trending flutes.

Near the Gooseberry River, NW 1/4, Sec.11, T 54 N, R 10 W, approximately 8 m of reddish brown (5 YR, 3/4) lodgement till is exposed and is chosen as the type section for the Cromwell Formation in the Two Harbors area. It is finer-textured than the melt-out till, with an average sand:silt:clay ratio of 57:32:11 (Figure 15). Lithic fragments ranging from 2 mm to 16 mm comprise more than 26% of the total volume of the debris. Basalt and rhyolite are the most abundant clasts greater than 2 mm. Granite dominates the 1-2 mm coarse sand fraction (Table 2). Long axis orientation of pebbles yields a southeast-northwest fabric trend, which is parallel to the direction of fluting, a north-south fabric trend, which is transverse to implied ice flow, and an east-west fabric trend (Figure 16). Thus, the long axes of the streamlined forms of the flutes are a more reliable indicator of the general direction of ice flow than are the till fabrics, which are commonly influenced by local topography (Boulton, 1971; Flint, 1971).

In general, the preferred orientation of elongate pebbles from the lodgement till shows a stronger, more consistent fabric than the melt-out till. Elongate clasts contained within the basal debris are

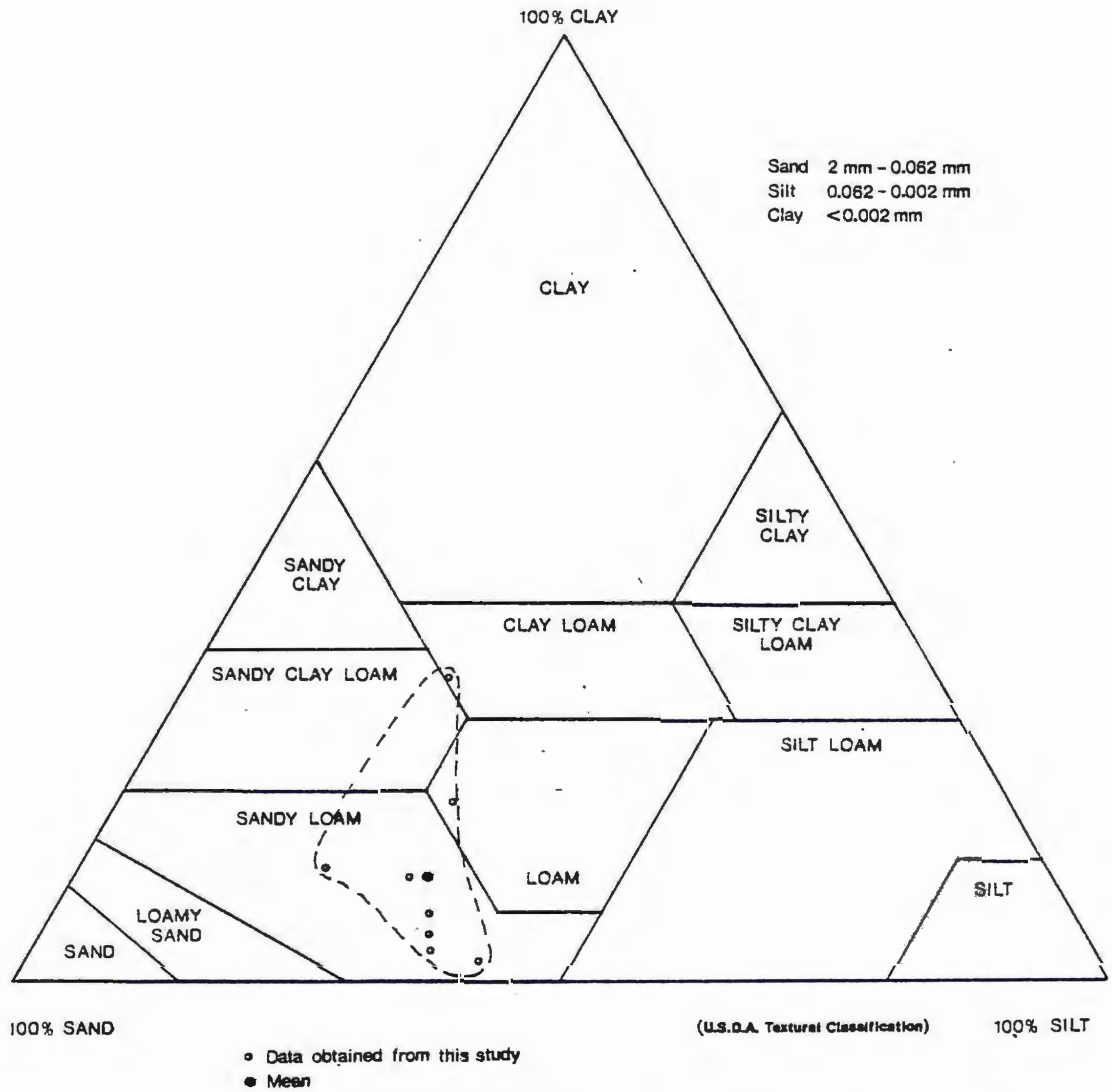


Figure 15. Textural composition of the subglacially derived debris of the Cromwell Formation (Sandy Loam Facies).

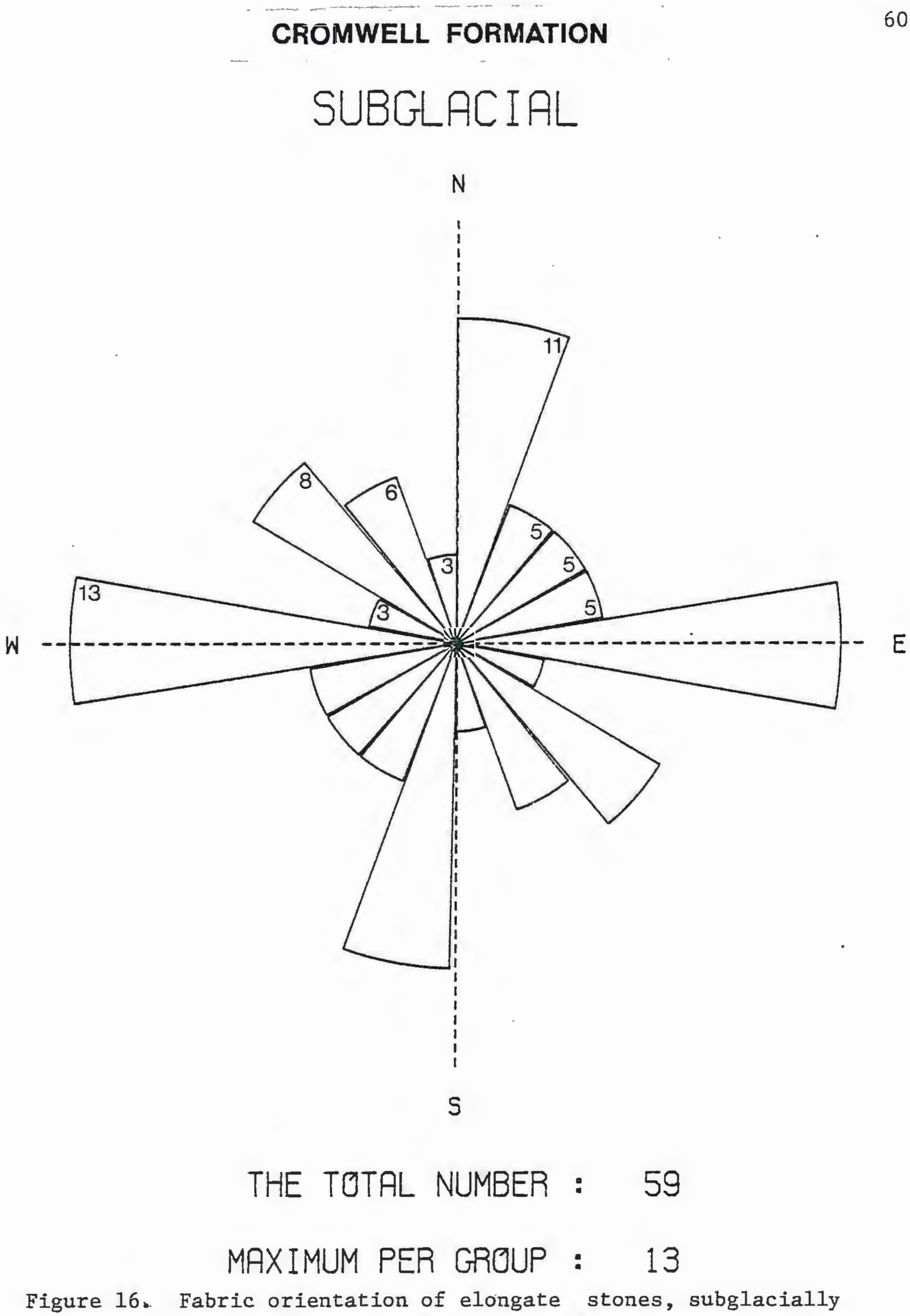


Figure 16. Fabric orientation of elongate stones, subglacially derived debris of the Cromwell Formation. Gooseberry River, NW¼, Sec. 11, T54N, R10W. Preferential orientation is north-south, and east-west.

generally lodged into the substrate with their long axes parallel to the direction of local ice flow (i.e. the direction of least resistance) due to the pressure melting from an actively moving glacier.

Under certain conditions, when debris-rich ice is compressed against, and forced to rise over the upglacier flank of a bedrock obstruction, the forward movement is blocked and the ice becomes essentially stagnant. There is commonly a well-marked plane of décollement separating the stagnant and active ice, and the former may well undergo further folding and deformation as a result of shear stress transmitted across this plane (Boulton, 1971). Thus, fabrics normally characteristic of basal, highly sheared ice, may be changed as the ice becomes an essentially subglacial, stagnant mass. Fabrics may then reflect the bedrock configuration, rather than the direction of ice movement (Boulton, 1971).

A transverse orientation of elongate clasts is related to zones of compressive flow, while parallel orientations represent zones of extending flow (Boulton, 1971).

The areal extent of this debris, as well as its compactness, textural characteristics, fabric, and the presence of flutes suggests deposition by lodgement processes.

Along County Road 13, Sections 2, 3, 10, 11, T 53 N, R 11 W, a clay-rich sediment (the loam facies) of the Cromwell Formation is exposed. At one locality, NW 1/4, Sec.11, T 53 N, R 11 W, the till overlies a 1.5 m-thick lacustrine sand and silt unit (Figure 17). The diamicton is dark reddish brown (5 YR, 3/4) and has a sand:silt:clay ratio of 40:39:21 (average of seven samples) (Figure 18). Clasts

Figure 17. Photograph of the clay-rich (Loam) facies of the Cromwell Formation overlying lacustrine deposits.

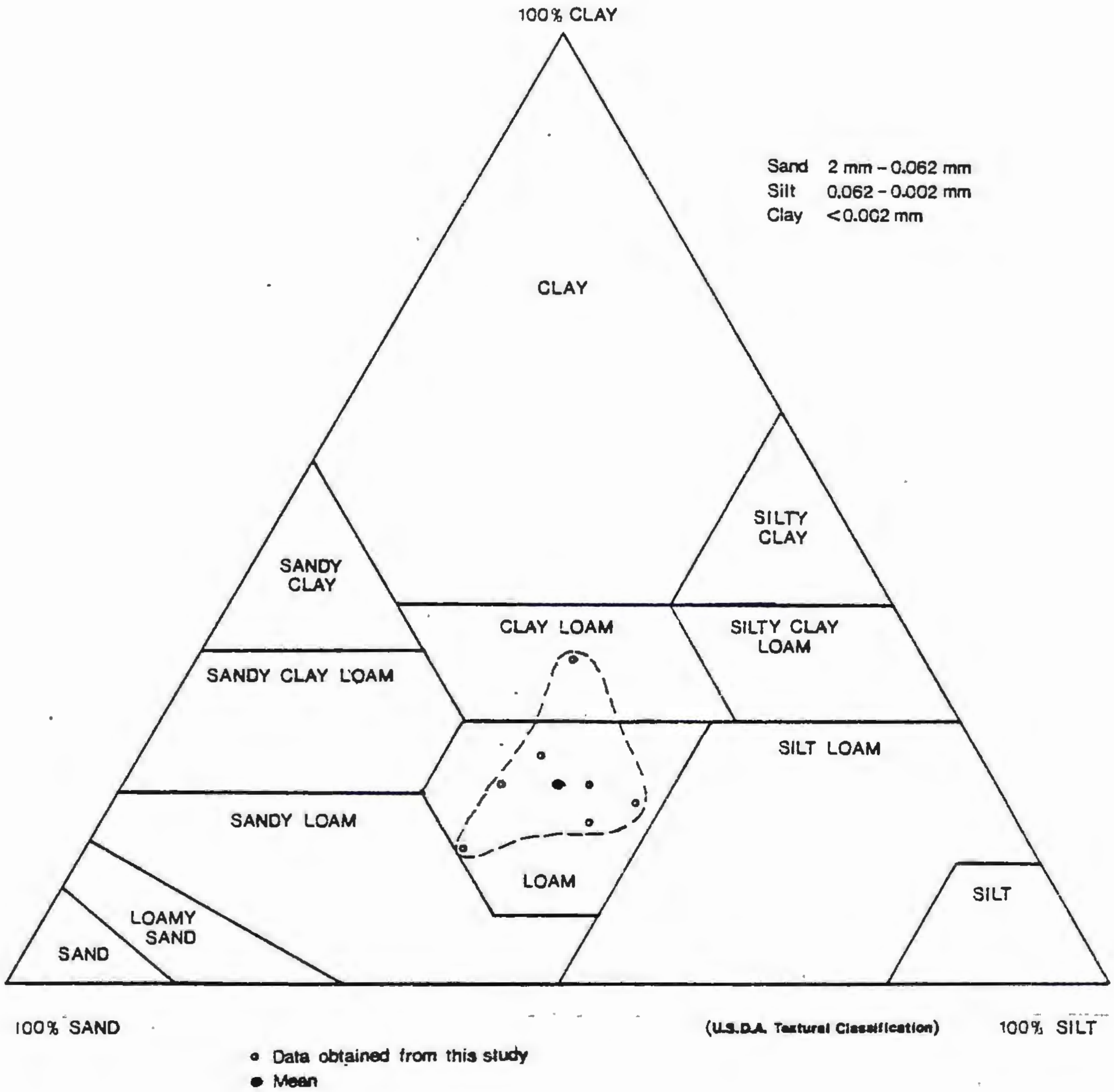


Figure 18. Textural composition of the subglacially derived debris of the Cromwell Formation (Loam Facies).

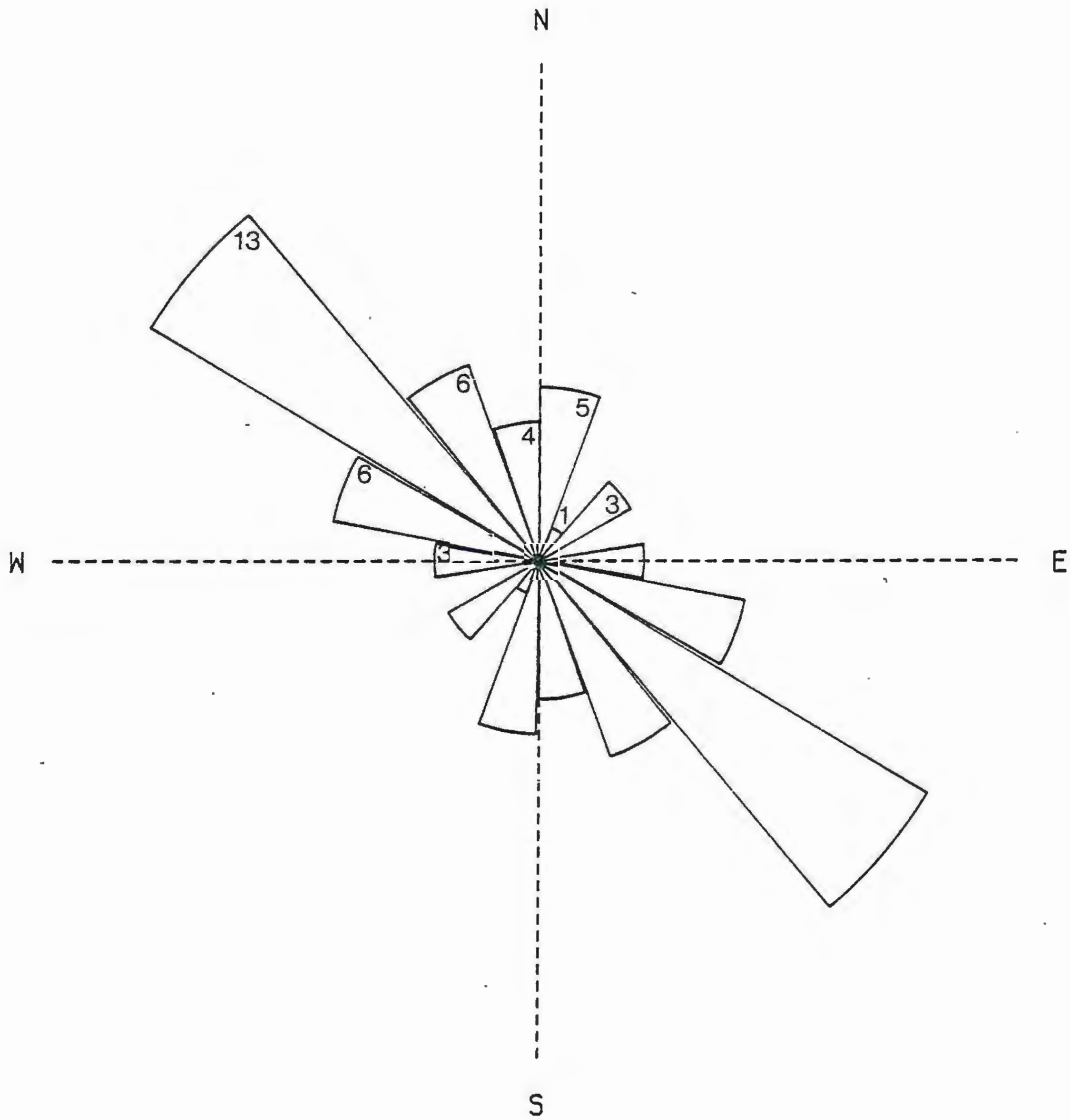
ranging from 2 mm to 16 mm comprise more than 28% of the total volume of the debris. Lithic fragments greater than 2 mm are predominantly basalt and rhyolite, along with granophyre, gabbro, granite, red sandstone, and a few agates. Granite (42%) dominates the 1-2 mm coarse sand lithologies, followed by rhyolite, gabbro-diabase, basalt, granophyre, quartz, and red sandstone (Table 2). The fabric trend of the elongated pebbles is southeast-northwest (Figure 19). This area is not fluted.

This diamicton is interpreted to be lodgement till deposited during the same ice advance responsible for the debris characterized by flutes. Overriding of proglacial lake deposits and incorporation of fine-textured sediment into the basal zone of the ice could explain this textural change.

Shoreward from this site, in Sec.14, T 53 N, R 11 W, a 7 m section of a clay- and silt-rich diamicton is exposed along the southern bank of the Stewart River (Locality A; localities are referenced on Figure 8). Figure 20 is a stratigraphic section of this unit. Though massive in appearance, it contains discontinuous layers, lenses, and pods of texturally distinct material. Pebble fabric is strongly developed in a north-south and northeast-southwest direction, which is transverse to inferred flow direction. This diamicton is interpreted to be colluvium overlying a lodgement till. Colluvium, a term applied to any slope sediment, is a typical cover produced by frost action and mass wasting processes originating under periglacial conditions (Shilts, 1981). Lawson (1981b) applies the term ice-slope colluvium to sediment that accumulates in a pile along the base of an ice slope. The resulting deposit is a structureless and heterogeneous dispersal of clay to

CROMWELL FORMATION

LØAM FACIES



THE TØTAL NUMBER : 41

MAXIMUM PER GRØUP : 13

Figure 19. Fabric orientation of elongate stones, subglacially derived debris of the Cromwell Formation (Loam Facies), SE¼, Sec. 3, T53N, R11W. Preferred orientation is southeast-northwest.

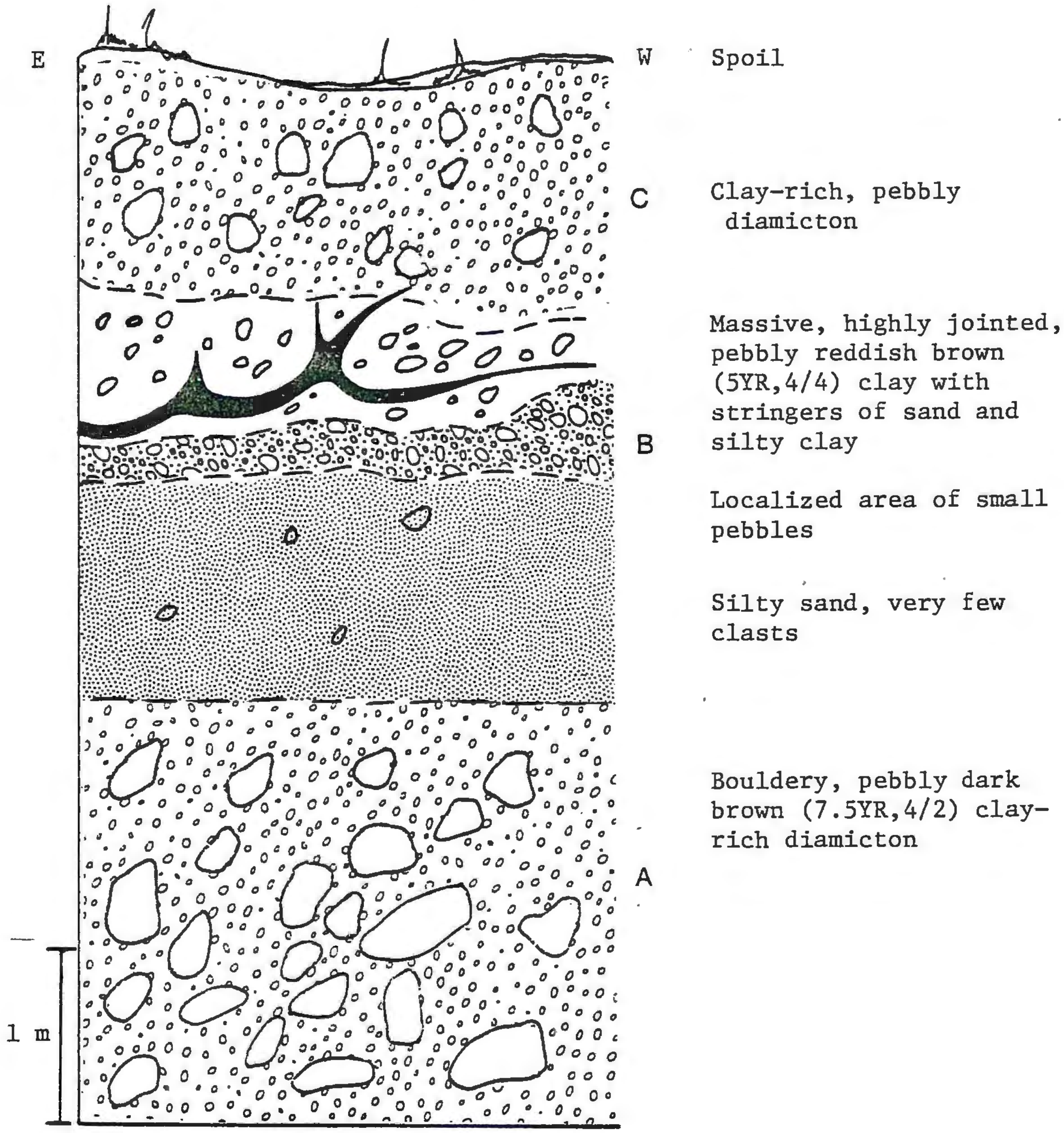


Figure 20. Stratigraphic section of colluvium overlying lodgement till. Locality A (southern bank of the Stewart River) NW¼, Sec. 14, T53N, R11W.

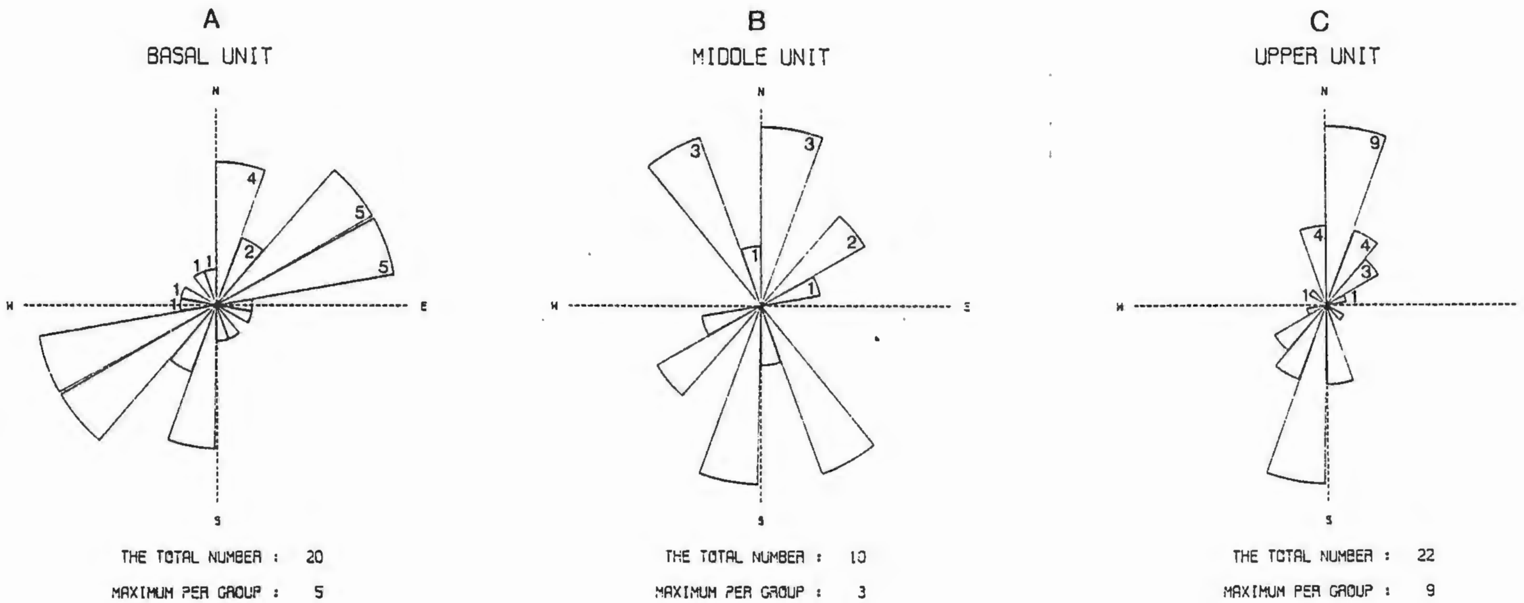


Figure 20 (continued). Fabric orientation of elongate stones from diamicton units A, B, and C of the stratigraphic section, Stewart River, NW¼, Sec. 14, T53N, R11W.

boulder size particles that looks as if it was simply dumped in place.

Geomorphic features

The subglacially derived debris of the Cromwell Formation is generally characterized by southeast-northwest trending flutes. Flute orientations were measured directly from a topographic map and the average trend (from 14 flutes) is N 53° W, with a range from N 40° W to N 66° W. The flutes are about 0.8 km long, 0.4 km apart, and generally only 1.5 to 6 m high. They consist of linear ridges in bedrock as well as linear accumulations of lodgement till.

Flutes have been suggested to form (1) by a process similar to drumlin formation; subglacial shearing from the drag of the glacier sole over a till surface (Boulton, 1971; Flint, 1971) and (2) by a process of ice pressing, whereby water-saturated till beneath active ice is pressed into cavities which formed in the lee of fixed boulders (Galloway, 1956; Stalker, 1960a). Whatever their origin, the presence of these forms establishes the existence of an actively flowing glacier at the time of formation.

Wright, *et al.*, (1969) propose that the flutes of the Two Harbors area formed when the western flank of the Superior Lobe rose laterally out of the basin, moving at right angles to the present shore and perpendicular to the axis of the ice lobe.

Glaciofluvial and sediment flow deposits

Site-specific characteristics

Isolated occurrences of outwash in the form of fans, braided stream deposits, and deltaic deposits, along with resedimented deposits of till, are found in the northwestern half of he Two Harbors quadrangle. Their regional distribution encompasses an area approximately 10 km wide, which borders upon the hummocky Highland Moraine to the northwest, at an elevation of 488 m (1600 feet), and the strandlines and lake plain of Glacial Lake Duluth to the southeast, at an elevation of about 366 m (1200 feet). These deposits form conspicuous topographic highs invariably situated near present- day swamplands, and are predominantly surrounded by the Highland flutes.

A large deposit of stratified outwash is found at Locality B (the "Ready Mix II" pit), SW 1/4, Sec.2, T 54 N, R 11 W. Cross-bedded, ripple cross-laminated and parallel-stratified gravels and sands are exposed in a 30 m section. They are interpreted to be the result of deltaic sedimentation. The stratified deposits are interfingered with clayey and silty, pebble-rich diamictons, as well as overlain by 2 m of a light brown, sandy, stony diamicton. There is a sharp contact between the outwash and the overlying diamicton. The diamictons are interpreted as sediment flows or slumps from an ablating ice surface (Lawson, 1981b). The presence of these sediment flows indicates that this delta was clearly ice-marginal and formed in a high energy environment (Cohen, 1979). Figure 21 is a rose diagram of planar crossbed measurements of the stratified sands, indicating a southerly current direction of the outwash at this site.

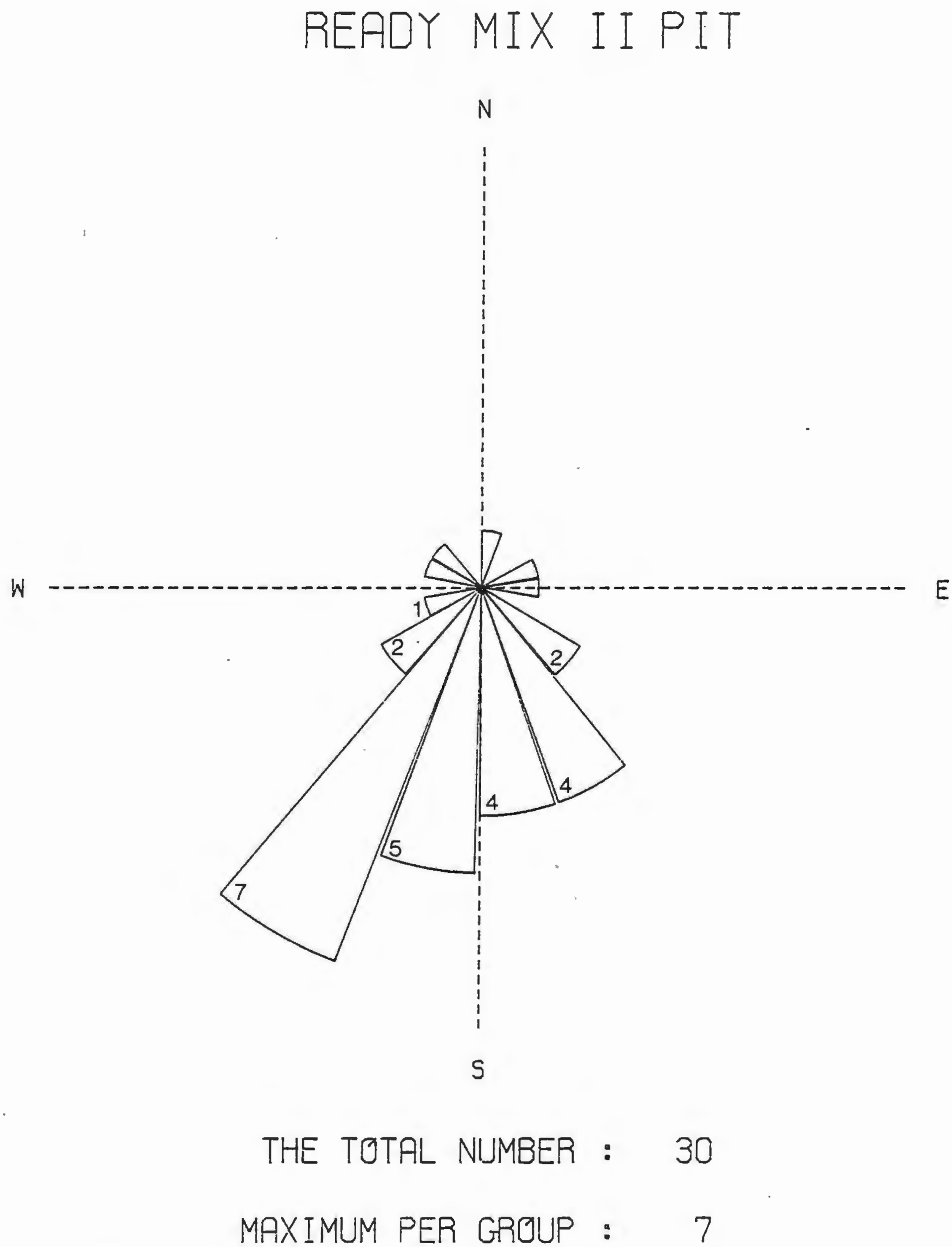


Figure 21. Measurements of planar crossbedding from the Ready Mix II gravel pit, SW¼, Sec. 2, T54N, R11W. Paleocurrent direction is to the south.

Along the North Shore Trail Road, at an elevation of approximately 415 meters (1360 feet), two gravel pits expose complex sedimentary sequences of differing materials. Locality C (the "North Shore Trail Pit I"), NW 1/4, Sec.19, T 54 N, R 10 W, exposes a 1.8 m section. The basal unit is composed of 0.5 m of lenses and discontinuous layers of silt- to sand-size sediment and gravel horizons. Zones alternate from clast-rich to clast-poor. This unit is overlain by 0.7 m of a structureless, silty to clayey, pebble-rich diamicton, which is in turn capped by 0.3 m of silty to sandy, pebble-rich diamicton. The contact between these two units is difficult to distinguish, though a slight clustering of cobble-size clasts, along with a change in texture mark the interface. There is no strong preferential alignment of pebbles in these upper two diamictons. Figure 22 illustrates the complex internal organization of this deposit.

The origin of this deposit is interpreted to be a sediment flow, resulting from the disaggregation and resedimentation of source materials (perhaps a basal lodgement or melt-out till).

The mechanics of flow are complex; several different mechanisms of grain support and transport can operate simultaneously within the same flow during movement. The following mechanisms are proposed for this deposit, adapted from Lawson (1981). Traction and saltation in the lowermost part of the flow transported coarse bedload material and accounts for the occurrence of the basal, gravel-rich horizons interspersed with sandy to silty layers of the deposit. Localized liquifaction, the transformation of a granular material from a plastic state into a liquid state due to increased pore-water pressures (Youd,

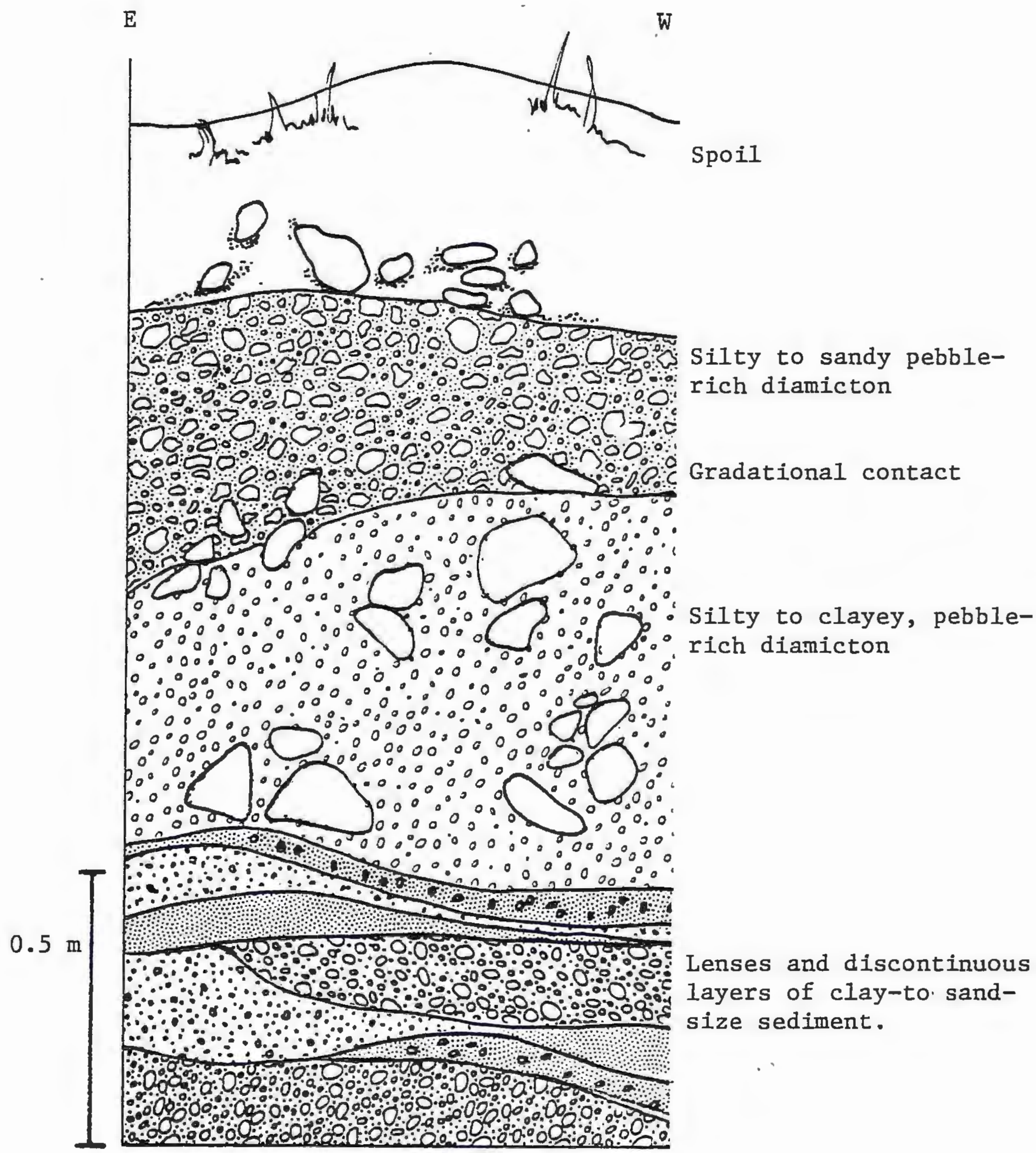


Figure 22. Sedimentary sequence of a sediment flow deposit resulting from the disaggregation of a basal lodgement or melt-out till. Locality C (North Shore Trail Pit I), NW¼, Sec. 19, T54N, R10W.

1973), controlled clast settlement during flow and deposition. This mechanism produced both clast-rich and clast-poor horizons. Where sediment flows are deposited on other freshly deposited flows not covered by meltwater deposits, contacts are difficult to distinguish. This could account for the gradational contact and coarsening texture between the two uppermost units of this deposit.

At Locality D (the "North Shore Trail Pit II") NE 1/4, Sec.8, T 54 N, R 10 W, approximately 2 m of a sediment flow deposit is exposed. Here, only two units are recognized: a basal gravel-rich unit, which grades upward into a texturally heterogeneous, massive, pebbly, sandy unit. This deposit possesses a very poorly defined southeast- northwest pebble orientation, which is inferred to be parallel to flow movement.

Complex interbedding of different sediment types can also be seen in the easternmost section of the Two Harbors quadrangle at an altitude of 378 m (1240 feet). Locality E ("Gravel Pit 301") is located in the NW 1/4, Sec.14, T 54 N, R 10 W, just south of the Gooseberry River. A 35 m section exposes cross-stratified sand and gravel interbedded with silty, clayey, pebble-rich diamictons (Figure 23). Measurements of planar crossbedding indicate paleocurrents to the northwest and southwest (Figure 24). The contacts between the diamictons and the well sorted units are sharp. As ice wastage occurred, debris accumulating on stagnant, dirty ice masses, may have slumped or flowed off the ice and onto the well sorted sands and gravels concurrently being deposited in a small proglacial lake.

Laminated, convoluted beds of fine- and coarse-grained sand draped around 4 to 10 cm boulders is exposed in a 3 m section at the west side

Figure 23. Photograph of a fining-upward sequence of coarse-grained sand and gravel at Gravel Pit 301, NW¼, Sec. 14, T54N, R10W. Shovel for scale.

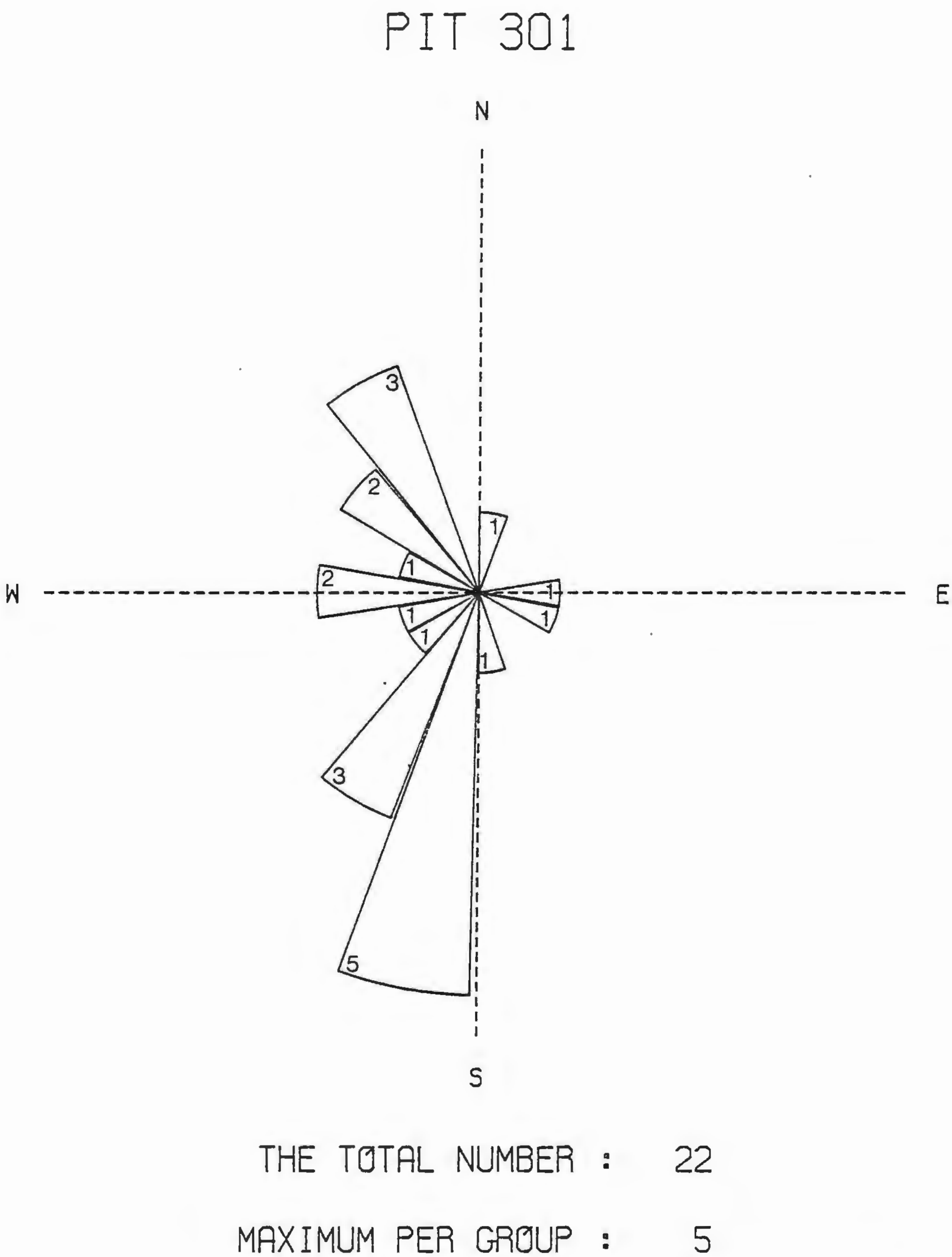


Figure 24. Measurements of planar crossbedding from Gravel Pit 301 NW¼, Sec. 14, T54N, R10W. Paleocurrent direction is to the northwest and southwest.

of this pit (Figure 25). "Draped lamination," a term introduced by Gustavson, et al., (1975), consists of parallel laminae of sand, silt, and/or clay draped over an underlying bedform. In a fluvial environment draped lamination is found in overbank deposits and mantling channel deposits. It is attributed to the decrease in velocity of overbank floodwaters, which enables deposition from suspension.

An opposing interpretation is that the large boulders and aggregates are a late introduction, released by ice, and subsequently deforming the underlying parallel laminae (Lawson, 1981b).

A most intriguing site is found in the northeasternmost part of the Two Harbors quadrangle, at an elevation of 415 m (1360 feet), at Locality F ("Silver Creek 9"), SW 1/4, Sec.18, T 55 N, R 9 W. Here, a basal gravel zone, 0.2 m-thick, is overlain by a 1 m-thick unit of several bands and layers of texturally-, compositionally-, and color-contrasted sediment. This sequence includes a lowermost pebbly, yellowish- red (5 YR, 4/6) clay, 21 cm-thick, overlain successively by a dark brown (7.5 YR, 3/4) silty-sand layer, 18 cm-thick, that contains stringers of gray clay; a pebble-free, dark yellowish-brown (10 YR, 3/4 clay, 15 cm-thick; a dark yellowish-brown silty-sand layer, 9 cm-thick; a dark brown pebble-free clay, 6 cm-thick; and 43 cm of a silty sand of the same hue. This unit is in sharp contact with and overlain by 0.8 m of a highly jointed, very compact and stony, reddish brown (5 YR, 3/4), silty to clayey diamicton. Figure 26 illustrates this sequence.

This deposit is identified as a sediment flow, which possibly remobilized a melt-out till, formed by the gradual in situ melting of upper and lower surfaces of stratified debris-rich ice. The origin of

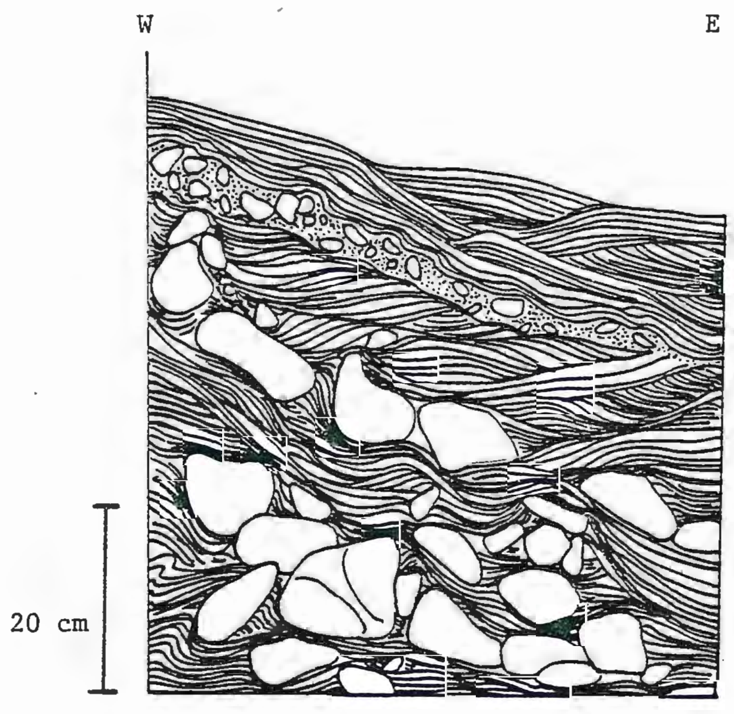


Figure 25. Illustration of "draped lamination," exposed at Locality E (Gravel Pit 301) NW¼, Sec. 14, T54N, R10W.

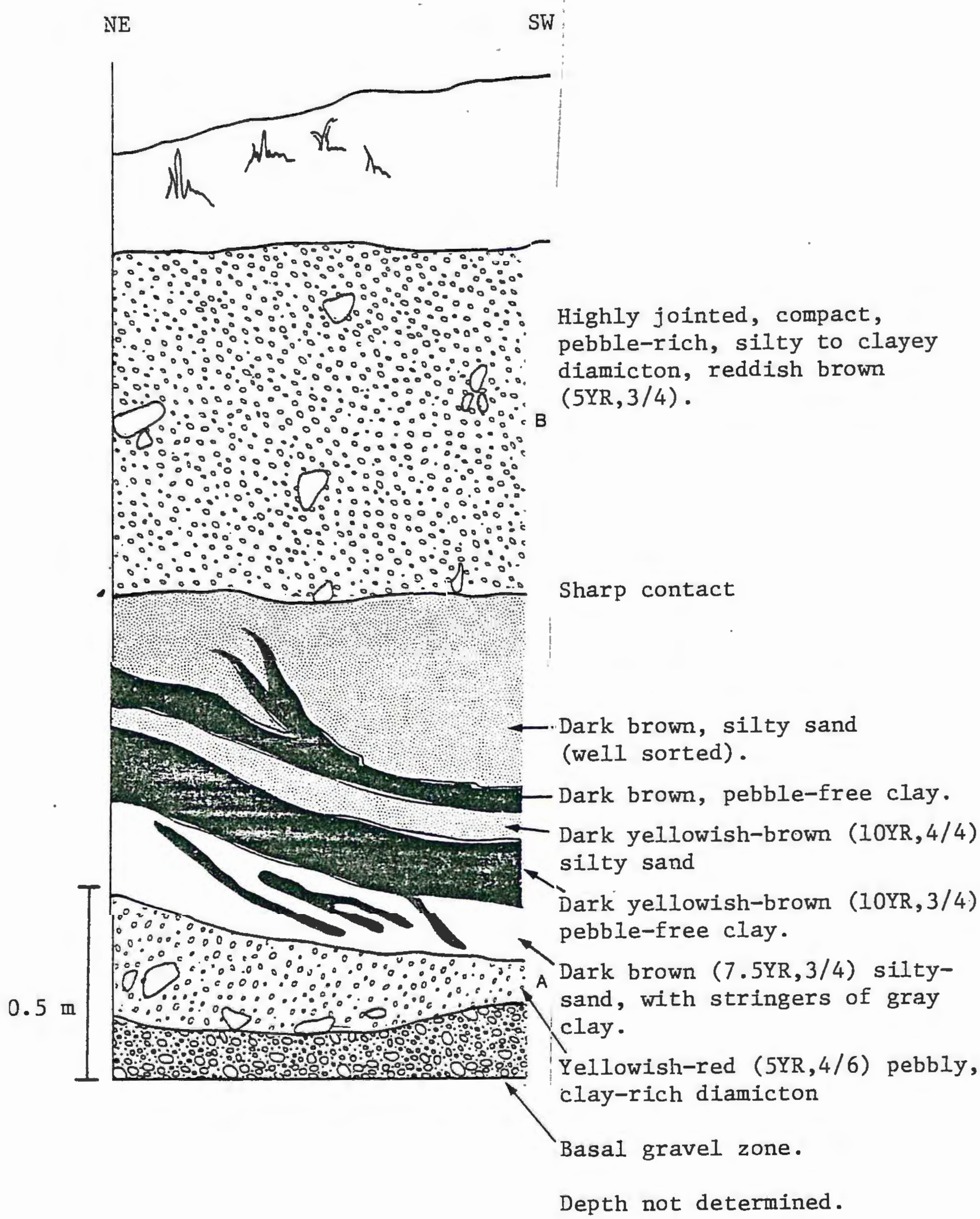


Figure 26. Sedimentary sequence of a sediment flow deposit. Locality F ("Silver Creek 9"), SW¼, Sec. 18, T55N,R9W. Possibly the result of interplay between fluvial, lacustrine, and mud-flow deposition.

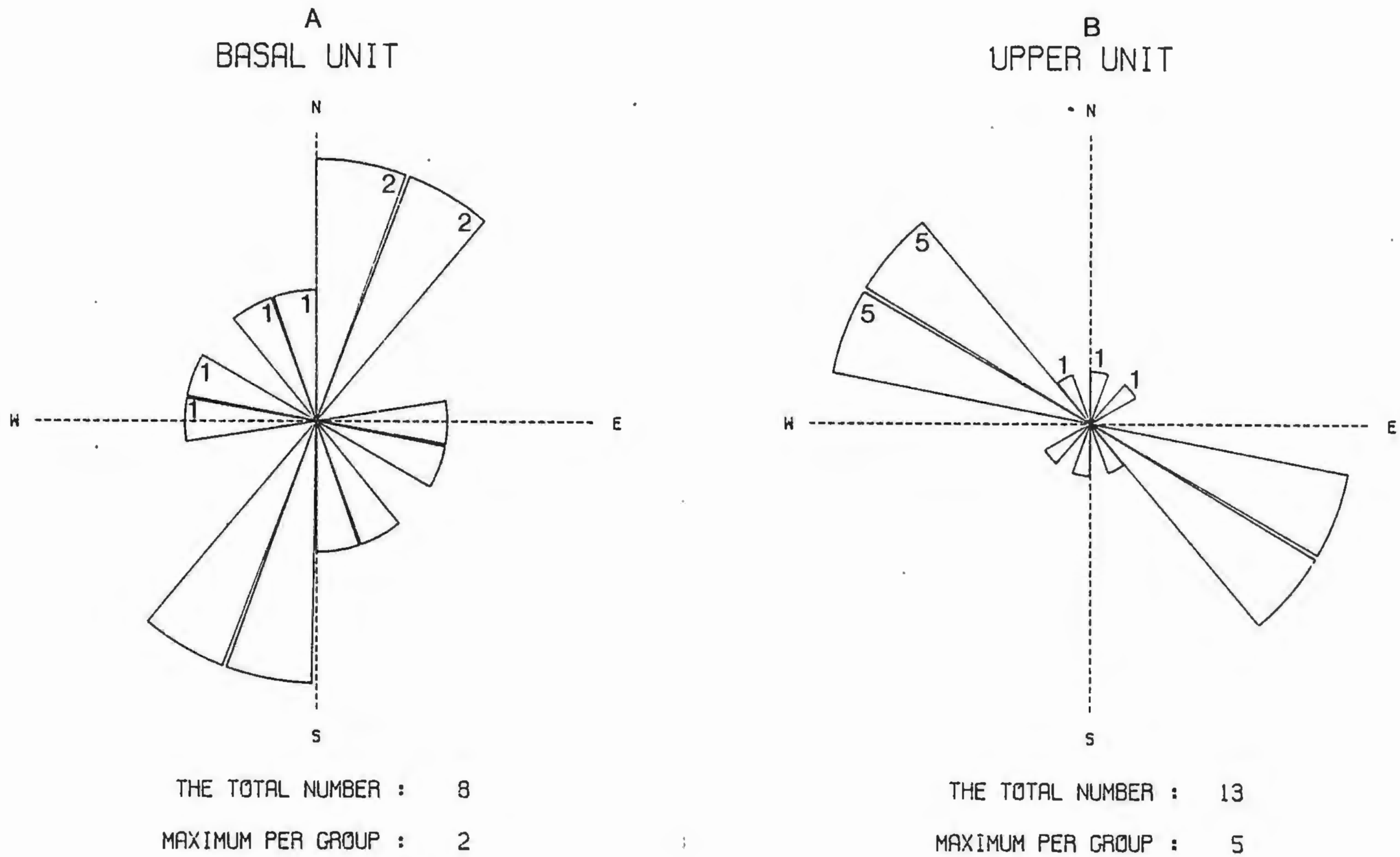


Figure 26 continued. Fabric orientation of elongate stones from diamicton units A and B of the stratigraphic section of a sediment flow deposit, in the SW¼ of Sec. 18, T55N, R9W.

the uppermost diamicton may be a later sediment flow deposit.

Just north of this deposit, at an elevation of 448 m (1470 feet), in the SE 1/4, Sec.12, T 55 N, R 9 W, a 3 m section of distinctly varying sediments is exposed at Locality G ("Silver Creeek 10"). A basal gravel-rich 0.4 m layer is in sharp contact with and overlain by 1 m of sandy to silty fluvial materials. This is in turn overlain by 1.3 m of a sandy, unsorted, non-compact till-like sediment (Figure 27). This deposit is attributed to the processes of slump, and meltwater and sediment flow.

These intricate sedimentary sequences are the result of a complex of secondary glacial processes operating in an ice- disintegration environment. The following model of deposition is proposed. As the Superior Lobe began to stagnate and thin, the ice margin began to "shrink" back to the main body of the ice lobe, which was situated in the Lake Superior basin. During this time, large blocks of dirty, dead ice were left scattered on the basal till surface. When the stranded ice blocks began to melt, supraglacial streams, issuing from the surface and subsurface of the ice, carried sand and gravel (and melt water) into adjacent low-lying areas, commonly occupied by lakes. Debris was deposited in the form of fans, deltas, and braided and meandering stream deposits. As downwasting of the ablating ice masses continued, supraglacial drift slumped and flowed intc these basins also. This accounts for the thin layers of sediment flow deposits in close association with the stratified deposits.

This model accounts for the complex deltaic deposits at Locality E (Gravel Pit 301) and the sediment flow deposits at Localities C and D

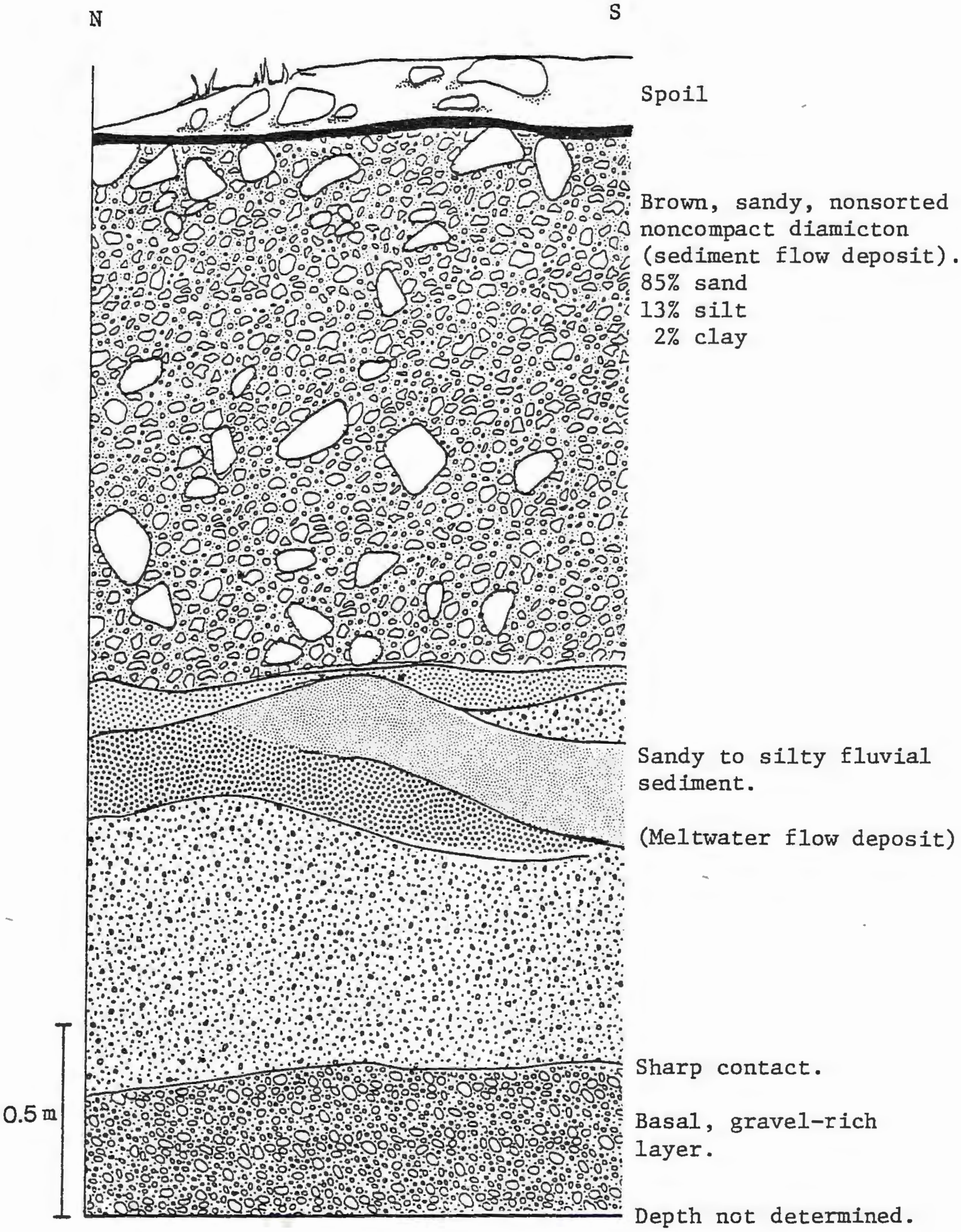


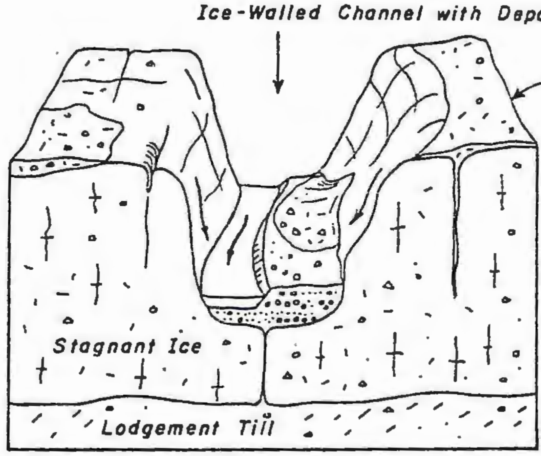
Figure 27. Sedimentary sequence of meltwater and sediment flow deposits. Locality G ("Silver Creek 10"), SE¼, Sec. 12, T55N, R9W.

(the North Shore Trail Pits I and II).

Locality B (the Ready Mix II pit), which borders on the hummocky terrain of the Highland Moraine, might possibly have been the site of an ice-walled channel. Melt waters draining the upland to the north may have deposited the glaciofluvial sediments, while ablating ice from the channel walls could have initiated contemporaneous sediment and mudflows (Figure 28).

In both of these models, an inversion of the topography, owing to the ablation of exposed ice, along with subsequent episodes of flow, slump, meltwater sheet and rill flow, and fluvial and lacustrine activity, is a major factor in the creation of these complex stratigraphic relationships.

In essence, these deposits attest to the complex interaction between ice, water, and sediment in an ice-disintegration environment.



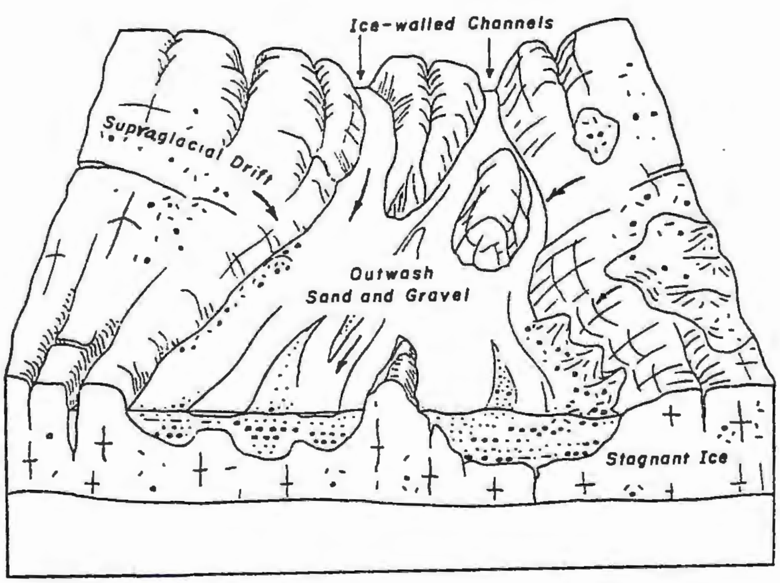


Figure 28. Idealized sketches of ice-walled channel development on stagnant ice (from Parizek, 1969).

WRENSHALL FORMATION

General characteristics

The Wrenshall Formation is generally a thick silt-clay unit that lies above the Cromwell Formation at altitudes below 360 m (1180 feet). It was deposited in Glacial Lake Duluth, a proglacial lake that formed during the final retreat of the Superior Lobe.

The Wrenshall Formation was named by Winchell (1899) for the lacustrine red and gray clay, oxidized yellow silt, and red sand which occurs within 1.6 to 3.2 km of the former shoreline of Glacial Lake Nemadji. Winchell distinguished two lake levels in the western Lake Superior region: (1) Glacial Lake Nemadji, at 324 m (1060 feet), and (2) Glacial Lake Duluth, at 320 m (1050 feet). Zarth (1977) reinterpreted the linear northeast trending scarp along the 300 to 309 m (980 to 1010 foot) altitude in the Wrenshall quadrangle to be the basinward leading edge of a prograding coarse-grained shelf, deposited into Glacial Lake Duluth, as it stood near its highest stage at 330 m (1080 feet), rather than the abandoned shoreline of Glacial Lake Nemadji. Thus, what Winchell had considered as two stages, Glacial Lake Nemadji and Glacial Lake Duluth, is now accepted as a single stage, that of Glacial Lake Duluth.

The abandoned clay pits at Wrenshall, exposing 12 m of fine-grained, varved, sediments, were originally designated by Winchell (1899) as the type locality for the Wrenshall Formation. An alternative type section was proposed by Wright, et al., (1970) north of the Village of Wrenshall, along the St. Louis River gorge, where U.S. Highway 210 crosses the 293 m (960 foot) topographic contour. The Wrenshall Formation stratigraphically lies above the Cromwell Formation at this exposure. The Cromwell Formation here consists of 6.7 m of sand, containing thin interbeds of silt, overlain by 0.4 m of coarse gravel. Above this lies 4.6 m of the Wrenshall Formation. It consists of 0.8 m of gray silt, overlain by 2.8 m of yellow silt, containing thin red clay interbeds and regular carbonate concretions, which is in turn overlain by 1 m of red clay, with irregular carbonate concretions.

A maximum thickness of 42 m of offshore sediment of the Wrenshall Formation has been noted by Zarth (1977). It is exposed along the banks of the Nemadji River and the Red River, which deeply dissect the lake plain in the southeastern section of the Wrenshall quadrangle.

Two facies of the Wrenshall Formation are recognized in the Two Harbors area and are here defined: (1) Nearshore facies: where major streams entered Glacial Lake Duluth at altitudes of 350 to 366 m (1150 to 1200 feet), forming glaciolacustrine deltas due to rapid sedimentation into a low energy lake environment, and where masses of sediment flowed off the wasting ice margin. (2) Deep-water (clay) facies: this facies includes massive, jointed, and sometimes laminated silt or sand and clay sequences deposited in an offshore lacustrine environment, as well as silt and clay sequences interfingering with fine- and coarse-grained sand, representing a transitional to nearshore environment.

Nearshore facies

Site-specific characteristics

The nearshore facies has been recognized at several exposures in the southwestern part of the Two Harbors quadrangle. It commonly occurs at elevations of 360 m (1180 feet), apparently marking the uppermost water plain of Lake Duluth.

A well-developed prograding glaciolacustrine delta is recognized in a 9 m exposure at Locality H (Ed Hanson's gravel pit), NW 1/4, Sec.29, and NE 1/4, Sec.30, T 53 N, R 11 W (McCarthy Creek quadrangle) (Figure 29). The lowermost 3 m of this deposit appear to be one large deltaic foreset complex.

The foreset bedding is inclined up to 25 and consists of multiple graded beds of coarse and fine sand, as well as planar crossbedded and ripple crosslaminated sands (Figure 30). Pinch and swell features and lag deposits of pebbles within a fine sand bed are common in this unit (Figure 31). Planar crossbed measurements indicate a paleocurrent direction to the south, which is also the direction down the paleoslope (Figure 32).

Approximately 3.6 m of poorly sorted and crudely bedded gravel unconformably overlie the delta foresets. This is interpreted as a deltaic topset bed. Gravel deposition is common on the upper reaches of outwash fans, and usually occurs as sheet and longitudinal bars (Gustavson, *et al*., 1975).

The gravel is composed mainly of subrounded to rounded lithic fragments of gabbro, greenstone, amygdaloidal basalt, rhyolite, and granite. The clasts range in size from 2 to 20 cm.

Figure 29. Photograph of a well-developed delta at Ed Hanson's gravel pit, NW¼, Sec. 29, T53N, R11W. Exposure is 9 meters high.

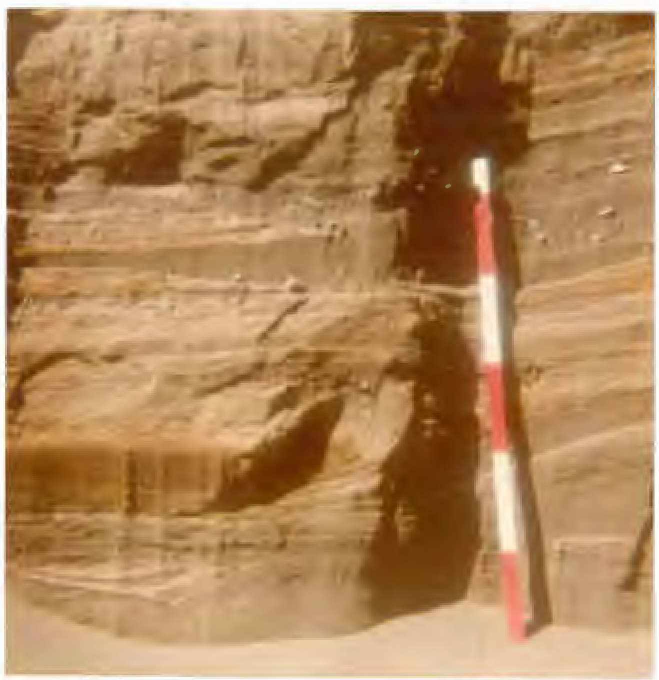


Figure 30. Photograph of foreset beds consisting of multiple graded beds of coarse and fine sand and planar crossbedding. Ed Hanson's gravel pit.

Figure 31. Lag deposits in fine-grained sand, at Ed Hanson's gravel pit, NW¼, Sec. 29, T53N, R11W.

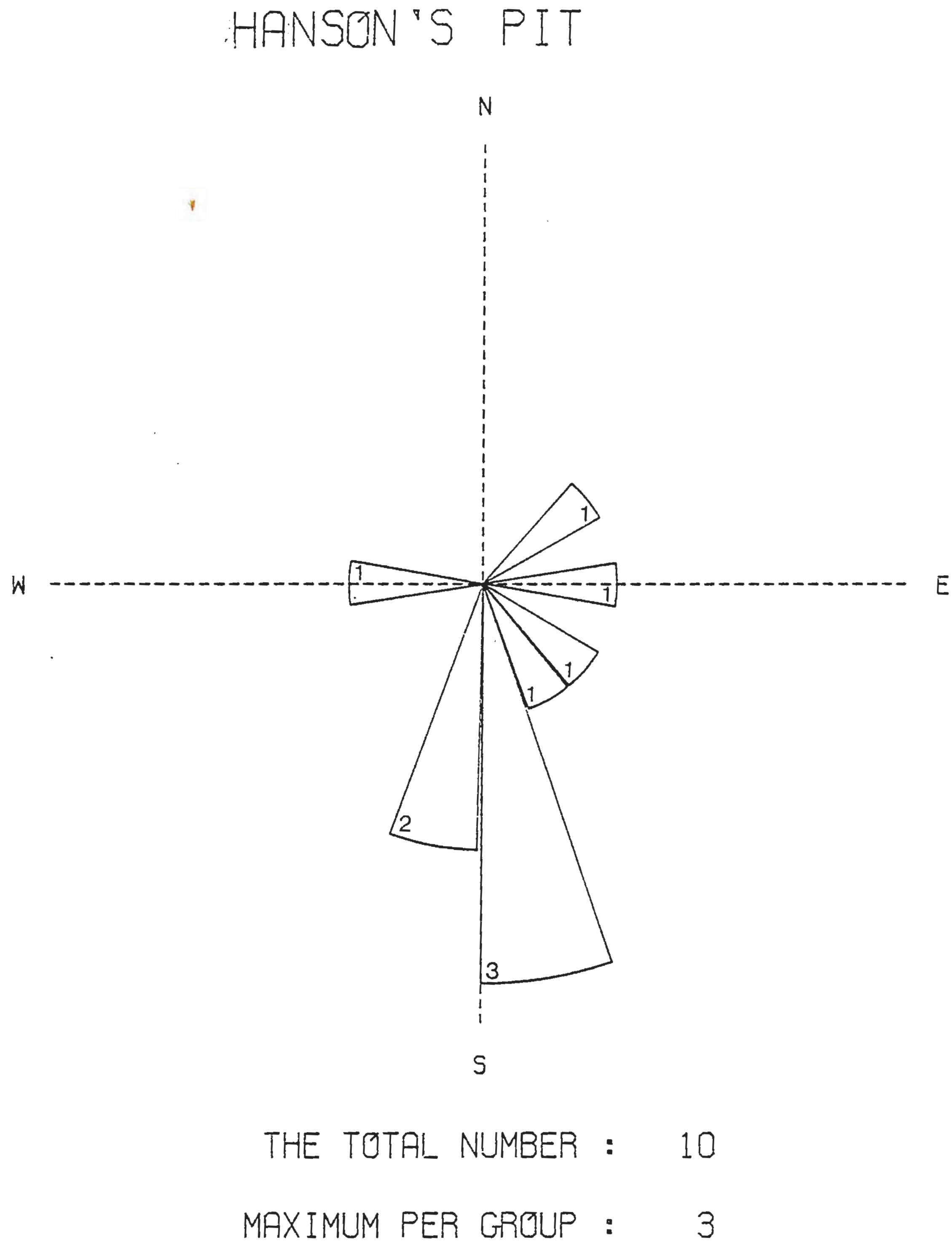


Figure 32. Measurements of planar crossbedding, Ed Hanson's gravel pit, NW¼, Sec. 29, T53N, R11W. Paleocurrent direction is to the south.

In this sequence, there is a definite distinction between the proximal channel deposit, characterized by the nearly featureless gravel, and the more distal environment, characterized by the fine-grained, well-sorted, and crossbedded sand. This distal environment could correspond to the lower portions of a deltaic outwash fan, which commonly progrades by frontal avalanching of sediments, leaving fine cross-sets and preserving lags on bar surfaces.

The gravel deposit is capped by about 2.5 m of a very compact, fine-grain sediment flow. The basal contact of the flow is sharp, indicating deposition on older consolidated sediments (Lawson, 1979). The flow itself is probably the result of slumping of a semi-fluid till from nearby stagnant ice. Poorly sorted, angular fragments of gabbro, rhyolite, and basalt are dispersed throughout the fine-grained matrix (Figure 33). Pebble fabric is very weak to absent. Texturally, this diamicton is a sandy to silty loam. Clay and sand stringers also occur locally within the sediment flow.

To the east, at Locality I (the "Ready Mix I" pit), NW 1/4, Sec.15, T 53 N, R 11 W, multiple units of cross-bedded sand and silt interfingered with clay stringers are exposed in a 1.5 m section. Measurements of crossbedding indicate an easterly current direction (Figure 34). The lack of coarse-grained gravel outwash at this site possibly indicates a glaciolacustrine prodelta slope environment (Gustavson, 1975). Underflows or turbidity currents deposited laminated, commonly graded or rippled sand and silt. When the underflows ceased, fine silt and clay was able to settle to the bottom.

Further northeast of this unit, within the same gravel pit, is a 3

Sediment flow in sharp contact with gravel. Field of view is 1 meter square.

Figure 33. Sediment flow deposits at Ed Hanson's gravel pit, NW¼, Sec. 29, T53N, R11W. Field of view is 1 meter square.

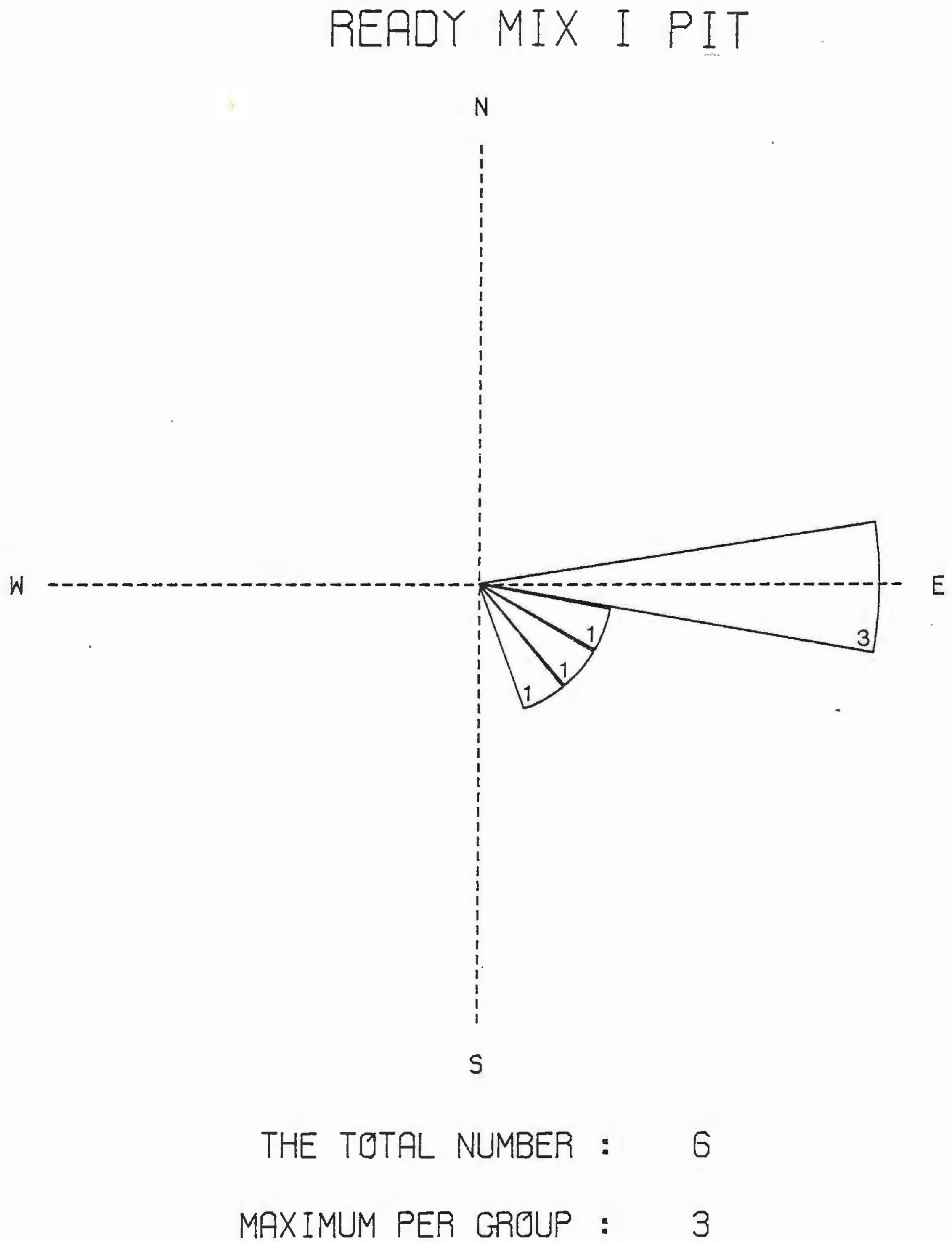


Figure 34. Measurements of planar crossbedding from the Ready Mix I gravel pit, NW¼, Sec. 15, T53N, R11W. Paleocurrent direction is to the east.

m glaciofluvial deposit of stratified sand and gravel. This unit is different in that the internal structures of the various types of crossbedding are cut by high-angle reverse and normal faults (Figure 35). Internal faulting has been described in fluvial gravels that were deposited on or against glacier ice (McDonald and Shilts, 1975). Collapse caused by melting of buried ice blocks results in the formation of high-angle reverse faults, whereas melting of a confining ice wall causes slumping and the formation of gravity (normal) faults.

Stratified sediments (chiefly coarse sand and gravel) are exposed in a 4 m section 2 1/2 km northeast of the previously mentioned gravel pit, at Locality J ("Gravel Pit 13"), SW 1/4, Sec.11, T 53 N, R 11 W. The pebbles, cobbles and boulders range in size from 1 to 30 cm. They are commonly subrounded to rounded, and are mainly lithic fragments of rhyolite and basalt, gabbro, and granite. Figure 36 is a sketch of a coarse gravel lag occurring between the crossbedded detritus.

The occurrence of stratification within the gravel attests to the influence of water, which disaggregated and sorted the outwash during deposition.

This unit can be traced 1 1/2 km further northeast and occurs again at a large open gravel pit, Locality K (the "5M Pit"), NE 1/4, Sec.12, T 53 N, R 11 W, at an elevation of 366 m (1200 feet).

In the far western section of the pit, a 10 cm-thick unit of cross-stratified sand, indicating a southerly paleocurrent direction, is preserved in a 4.6 m gravel exposure (Figure 37). Horizontally bedded sand, in units as thick as 25 cm, is also preserved in the gravel at some localities (Figure 37).

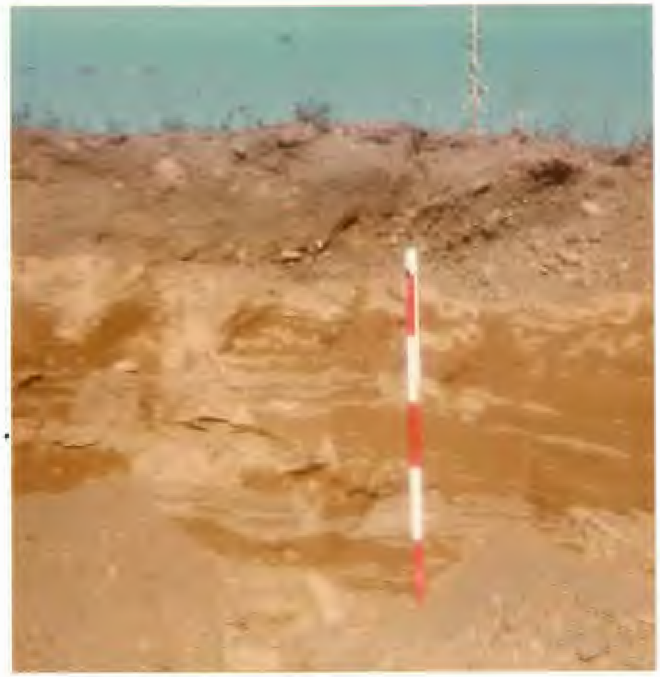


Figure 35. Photographs of high angle reverse and normal faults, the Ready Mix I gravel pit, NW¼ Sec. 15, T53N, R11W.

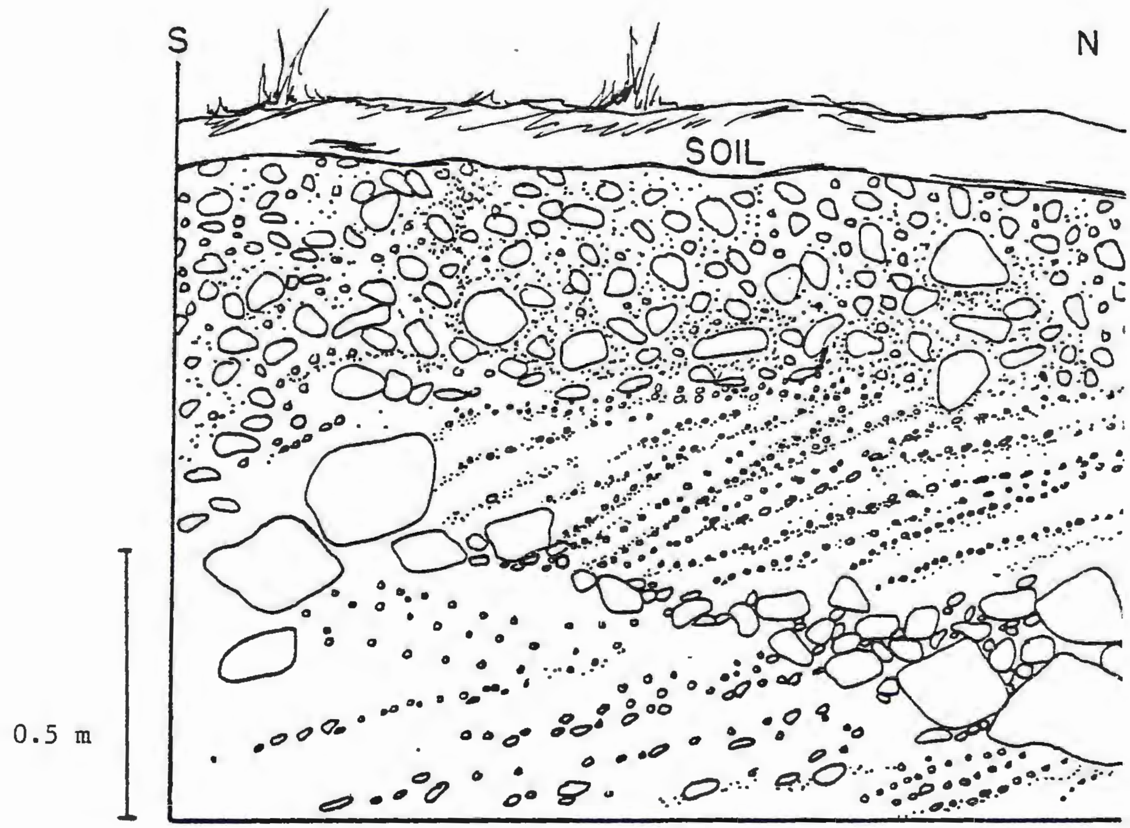


Figure 36. Illustration of disaggregated and sorted outwash, exposed at Locality J (Gravel Pit 13), SW¼, Sec. 11, T53N, R11W.

Figure 37. Photographs of cross-stratified and horizontally bedded sand, preserved in gravel at the 5M Pit, NE¼, Sec. 12, T53N, R11W.

The poor sorting and rudimentary bedding of the gravels at Gravel Pit 13 and the 5M Pit are probably the result of rapid deposition of bed load at the mouth of a distributary channel (Shaw, 1975). The finely laminated sand and silt at the Ready Mix I pit may represent the more distal reaches of this meltwater channel and nearshore sedimentation into Glacial Lake Duluth.

In the southwestern part of the Two Harbors quadrangle ice wastage and delta formation appear to have been concurrent processes. Whether these deltas were built into Glacial Lake Duluth, or into smaller proglacial lakes that preceded the formation of Lake Duluth is uncertain. It is probable that blocks of stagnant ice were stranded along the 360 m "strandline" (1180 feet, as defined by Farrand, 1960). These dead ice blocks may have been the chief contributors of sediment for the building of the deltas. Upland streams could have also supplied large quantities of sediment from subaerial erosion of the drift and from other stagnant ice sources further north. Unsorted sediments may have slumped from these areas of dead ice directly onto the deltaic sands; this would account for the sediment flow deposits and diamicton units.

Near the deltas, between an elevation of 360 to 366 m (1180 to 1200 feet), there is a definite break in slope and a change in the regular, undulating pattern of the contours. The extensive development of sand and gravel deposits, as well as this notable change in slope, supports the idea that this discontinuous northeast-southwest trending linear zone represents abandoned beaches or strandlines. As the lake level progressively dropped and intermittent still-stands occurred, fine-grained silts and clays were washed out, leaving behind concentrations of the coarser sand and gravels. However, there is a comparative lack of strong beach development in other parts of the Two Harbors quadrangle at similar elevations. Perhaps stranded blocks of ice at the shoreline level in other areas prevented the washing of fine sediments, or a beach may have formed on the ice, later to be destroyed, as the ice collapsed and melted (Moss, 1977).

Deep-water (clay) facies

The dominant surficial deposit of the southeastern half of the Two Harbors quadrangle below elevations of 350 m (1150 feet) is the eminent red clay of the North Shore of Lake Superior. It is exposed extensively along the lakeshore and in stream valleys, and is commonly found in association with silt and fine sand. The depositional environment of this red clay is controversial. This section presents current data and a discussion that clarifies the origin of the clay-rich diamicton of the Two Harbors area.

Massive lake clay, deposited in the absence of current action, and receiving ice-rafted sand and pebbles, could have the same grain size distribution and mineralogy as lodgement till derived primarily from overridden lake sediment (Johnson, 1980). Therefore, in the Lake Superior region, distinguishing between a lake clay and a clayey till is problematical.

Numerous workers have suggested a lacustrine origin for the deposits of red clay that lie basinward of abandoned shorelines on the North Shore of Lake Superior, and on the Wisconsin south shore of Lake Superior (Taylor, 1897; Leverett, 1929; Moss, 1977; Zarth, 1977). The fine texture of the red clay and its occurrence below high-level strandlines has been noted as primary evidence. The presence of boulders within the clay has been attributed to ice-rafting (Moss, 1977; Zarth, 1977). The massive, non-laminated character of the red clay is interpreted to be due to deep water origin where current has played no part in deposition (Moss, 1977; Zarth, 1977). In parts of northeastern Minnesota, laminated clay commonly overlies the massive clay, and is interpreted as a near-shore lacustrine facies (Moss, 1977; Zarth, 1977).

Fewer workers have suggested a subglacial origin, citing areas in northern Douglas and northwestern Bayfield Counties of Wisconsin (Leverett, 1929; Johnson, 1980; Clayton, 1982). The presence of boulders (some striated) in the red clay is held to indicate an advance of ice over clayey lake deposits. It is thus assumed that the lake clay has been redeposited by ice with erratic boulders incorporated, and is essentially a lodgement till (Johnson, 1980).

Through detailed stratigraphic mapping of the Wisconsin shoreline of Lake Superior, a red sandy till, the "Jardine Creek till," and two red clay units, the "Hanson Creek till" and the "Douglas till," have been defined (Johnson, 1980; Need, 1980). The Jardine Creek till is the oldest of the stratigraphic units. It was named by Need (1980) for exposures along the shoreline bluff near the mouth of Jardine Creek, Bayfield County, Wisconsin. It is dark reddish brown to reddish brown (2.5 YR, 3-4/6), is massive, and has a sand:silt:clay ratio of 64:21:15. This unit is clearly a till because of its poor sorting, lack of stratification, strong macrofabric, and striations on the underlying bedrock (Johnson, 1980).

The Hanson Creek till is the older of the two red clay units and was named by Need (1980) for exposures near the mouth of Hanson Creek, Douglas County, Wisconsin. It is dull to dark reddish brown (5 YR, 3-4/3, 3/4) and has a sand:silt:clay ratio of 11:32:57. Pebbles are present but scarce. A distinctive feature is the presence of gray clay stringers, 1 to 10 cm-thick, often giving this unit a banded appearance in outcrop (Johnson, 1980).

The youngest unit of Wisconsin's Lake Superior shoreline is the Douglas till, the red clay of Douglas County, after which it is named (Need, 1980). It is dull reddish brown (2.4 YR, 4/4) and is composed largely of clay, having a sand:silt:clay ratio of 11:26:63. Pebbles, some striated, are present, but very sparse. The Douglas till is massive and is distinguished from the Hanson Creek till by its lack of distinct color bands.

A clay, very similar to the Douglas till, was described southwest of Duluth (Zarth, 1977) and along the Minnesota North Shore near the French River (Moss, 1977), and interpreted by them as lacustrine. This clay unit (correlated with the Wrenshall Formation) was originally assumed to be correlative with the Douglas till based on similarities of color, texture, structure, bulk density, engineering properties, and stratigraphic position (Johnson, 1980).

The clay-rich unit of the Two Harbors area in northeastern Minnesota also bears resemblance to the Douglas till. It is commonly reddish brown (5 YR, 4/4) and is composed largely of clay. Grain size determinations show that clay content typically ranges from approximately 43% to 92%, while silt content varies from about 0% to 36%. The remaining material, from about 0% to 27%, falls into the sand category (except for small stones). The average sand:silt:clay ratio of 10 samples is 14:16:70 (Figure 38). This is comparable to lacustrine deposits of the French River area that have an average composition of 5% sand, 26% silt, and 69% clay (Moss, 1977). The grain size distribution of the Douglas till is also similar having a textural composition of 11% sand, 26% silt, and 63% clay (Johnson, 1980).

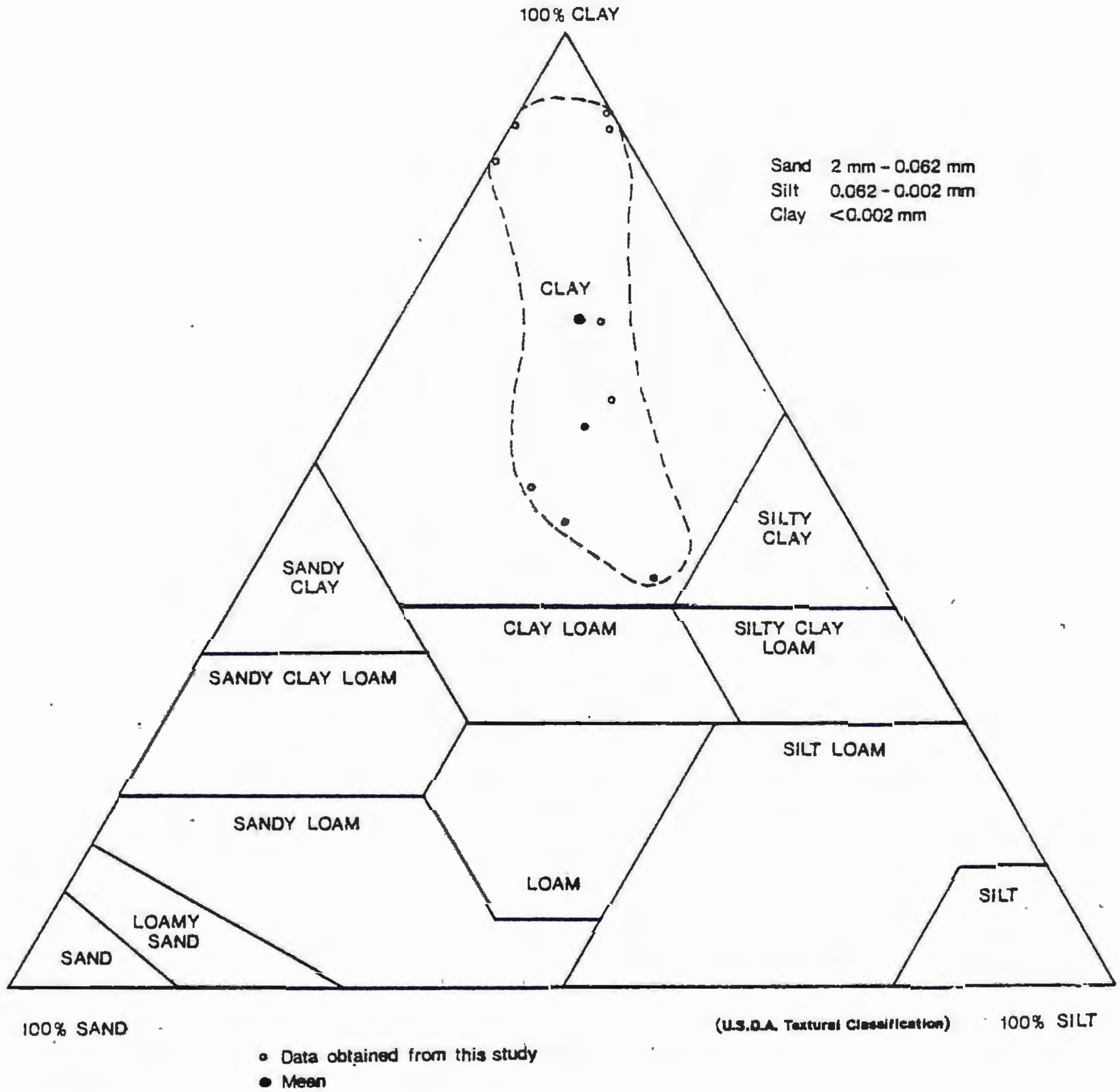


Figure 38. Textural composition of the clay facies of the Wrenshall Formation.

The clay facies of the Wrenshall Formation of the study area ranges in character from massive and highly jointed, to finely laminated with pockets of "sand nests." The clay varies from pebble-free to pebble-rich, where lithic fragments ranging from 2 mm to 16 mm comprise more than 20% of the total volume. The clasts are mainly basalt and rhyolite from the North Shore Volcanic Group, which comprise 44% and 21% of the pebbles, respectively. Keweenawan red sandstone (5%) and granite (5%) also contribute to a minor portion of the clasts. "Lake Superior" agates represent 1% of the pebbles. Coarse sand fragments 1-2 mm are rare.

The paucity of coarse sand fragments in the red clay of the Wrenshall Formation is far different from the Sullivan Lake Formation and Cromwell Formation where these grains are abundant. Granite, basalt, and quartz are the most abundant coarse sand grains, contributing 22%, 21%, and 19% to the total. Rhyolite (9%), granophyre (9%), epidote (2%), and calcareous concretions (2%) are relatively minor contributors (Table 2).

Mineralogical analysis of the less than 2 μm fraction of the Wrenshall Formation indicates that the clay facies contains (1) quartz, (2) illite, (3) chlorite, (4) corrensite (vermiculite), (5) kaolinite, (6) k-feldspar, (7) plagioclase, (8) calcite, and (9) dolomite.

This mineral group is consistent with those determined by Zarth (1977) for the clay samples in the Wrenshall quadrangle.

These minerals were derived from weathered bedrock and older glacial sediments. The presence of calcite and dolomite could be attributed to concretions, vein fillings and amygdules in the flows of the North Shore Volcanics (Zarth, 1977).

Clay mineralogies of the Douglas till (clay facies) indicates the relative percentages of illite (54%), smectite (32%), vermiculite (9%), and kaolinite/chlorite (5%) (Johnson, 1980). All but the smectite are found in the Wrenshall Formation.

Mode of deposition

Johnson (1980) proposed that a subglacial, rather than lacustrine, origin for the clay-rich sediment of the Lake Superior region would be confirmed if the red clay (1) is overconsolidated and (2) has a preferred grain orientation, both of which are features associated with subglacial deposition.

Evidence for a lacustrine, rather than subglacial, origin of the clay-rich unit would be confirmed if this unit (1) is normally to underconsolidated, (2) exhibits features associated with lacustrine and glaciolacustrine deposition (varves, till pellets and other ice-rafted material), (3) is confined to the basin below elevations of 350 m (1150 feet), as defined by Glacial Lake Duluth (Leverett, 1929), and (4) is stratigraphically the highest and youngest of the Quaternary deposits of the area.

Consolidation and bulk density

The origin of overconsolidation in till may be attributed to overriding ice, desication, or a fluctuating water table (Dreimanis, 1977). Both the Douglas till and the Hanson Creek till are shown to be overconsolidated, as indicated by conventional consolidation tests on undisturbed samples (Johnson, 1980). Consolidation tests were not performed on the clay facies of the Wrenshall Formation. Bulk density measurements were, however, obtained.

Density relates to consolidation in that as a deposit is compacted or consolidated, it becomes more dense. Numerous workers have used bulk density measurements as a practical method of distinguishing till from glaciolacustrine and glaciomarine drift, and other diamictons which have not been overridden by glacier ice. There are notable differences in the density of glaciogenic sediments relating to methods of deposition and the subsequent degree of compaction (Easterbrook, 1964; Moss, 1977; Kemmis, et al., 1981).

Easterbrook (1964) used bulk density measurements to differentiate glaciomarine drift (1.6 to 2.1 g/cc, which is "normally consolidated") from till (2.1 to 2.6 g/cc, which is "overconsolidated") in the Puget Lowland, Washington. Moss (1977), used bulk density values to differentiate massive, pebble-free, lacustrine lay (1.2 to 1.5 g/cc) and pebble-rich, compact lacustrine clay (1.4 to 1.5 g/cc) of the Wrenshall Formation, from sand- and silt-rich tills (1.6 to 1.9 g/cc) of the Cromwell Formation. Bulk density figures for the clay-rich Douglas till range from 1.2 to 1.5 g/cc (Johnson, 1980). The concurrence in values obtained from the Douglas till and from the lacustrine red clay of the French River area led Johnson (1980) to suggest that even bulk densities as low as 1.2 to 1.5 g/cc can occur in subglacially deposited clay-rich materials.

Bulk density measurements for the clay facies of the Wrenshall Formation in the Two Harbors area and in the Silver Bay area are summarized in Figure 39. The bulk density values range from 1.67 to

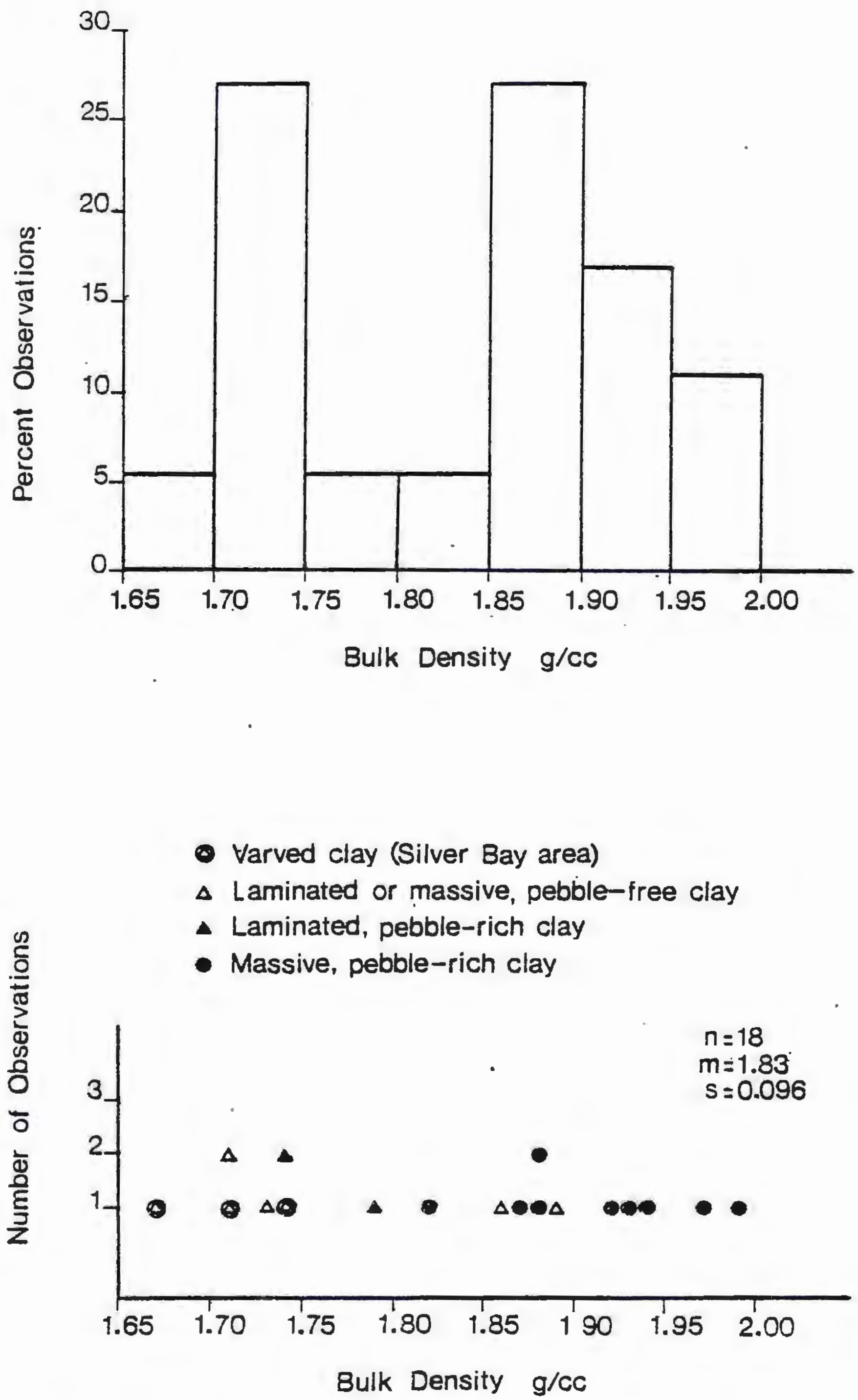


Figure 39. Lab analysis and histogram of bulk density measurements of the clay facies of the Wrenshall Formation.

1.89 g/cc for the laminated or massive, pebble-free clay, and from 1.82 to 1.99 g/cc for the pebble-rich, compact clay. These data are bimodal and highly variable. They are much lower in value than the basal till of Easterbrook (1964) and very similar in value to the glaciomarine drift. This red clay is thus "normally consolidated," which supports a lacustrine rather than basal till origin. It is also interesting to note that these bulk density data are greater in value than the lacustrine clay deposits of the French River area. This discrepancy may be due to methods of analysis.

Bulk density is dependent upon grain size because texture limits to what density a given particle assemblage can be consolidated. The Douglas till and the lacustrine clay of the Wrenshall Formation are texturally similar and thus their bulk density measurements are directly comparable. It is quite disconcerting to note however, that the Douglas till has an even lower bulk density value than the Wrenshall Formation, yet is still believed to be of subglacial origin.

Preferred grain orientation

The parallelism of silt-sized grains within till, known as microfoliation, is a useful tool for determining ice flow direction (Sitler and Chapman, 1955; Harrison, 1957; Ostry and Deane, 1963; Sitler, 1968 Evenson, 1971; Johnson, 1980). Microfoliation is generally concordant with coarse fabric orientation and is assumed to be caused by subglacial shearing and the smearing action of ice (Holmes, 1941; Evenson, 1971).

Johnson (1980) did extensive microfabric analysis of the red clay along the south shore of Lake Superior. Support for a subglacial origin for the Douglas till was based largely on these results. Horizontally and vertically oriented samples of the Douglas and Hanson Creek tills were made into thin sections. Measurements were made using a petrographic scope and enlarged projections of the thin sections. All but 2 of the 25 samples of the massive red clay had a preferred orientation of elongate sand grains. Due to the paucity of greater than 2 mm clasts, no macrofabric analysis was carried out for a comparison of results. Microfabrics in two of the clay samples also corresponded well with underlying boulder striae. The plunge of the sand grains in all of the samples was variable. Though the absolute ice flow direction for the Douglas till is unclear, it is assumed to be from the northeast (Johnson, 1980).

Johnson considered many possibilities that could disturb the samples and produce the observed fabrics. He has confirmed that the fabrics were not produced by forces operating on the bluff face, by the coring device, by drying in the lab, or by thin section preparation.

However, preferred grain orientation within a sediment should not be used to determine the origin of the deposit. It is not unlikely that lacustrine and marine sediments can exhibit a parallelism of silt-sized particles that has been influenced by currents and the earth's magnetic field (Ellwood and Ledbetter, 1977, 1979; Shaw and Archer, 1979; Johnson, Carlson, and Evans, 1980). Ellwood and Ledbetter (1977) studied the fabric and texture of deep-sea sediments of the Vema Channel in the southwestern Atlantic Ocean. Long axis alignment of silt-sized grains was detected by a method that determined the anisotropy of magnetic susceptibility for these grains. The factors that influence particle alignment are (1) gravity; which causes the long axes of grains to lie flat; (2) the earth's magnetic field; which causes magnetic particles in the water column to act as simple dipoles; and (3) bottom currents; which cause the long axes of settling grains to become aligned in response to current flow, with greater current velocities producing stronger alignment.

Johnson (1980) based his conclusions from his microfabric analysis on the assumption that preferred grain orientation is related solely to ice flow. In reality, he may have been the first to actually document preferred grain alignment of lacustrine sediments.

Horizontally and vertically oriented slabs of clay from the Wrenshall Formation of the Two Harbors area were also prepared for microfabric analysis. X-radiographic techniques were employed, using 1 to 2 cm-thick slabs of clay, instead of the thin section and petrographic methods of Johnson (1980). However, no silt- to sand-sized grains were shown on the x-ray pictures of the massive, pebble-free clay to measure, and microfabric analysis was abandoned.

The vertical sections of the clay did, however, reveal finely bedded laminae of dark colored clays and lighter fine silt. These laminations are often less than a millimeter in thickness (Figure 40). Figure 41 is a photomicrograph of the laminated sediments. Cleavage also tends to occur along the silt/clay interface. When these clay slabs were placed in water, they invariably flaked along parallel bedding planes (Figure 42).

Small scale deformation structures, which have been attributed to slumping, are also noted in a few of the massive clay samples. Figure

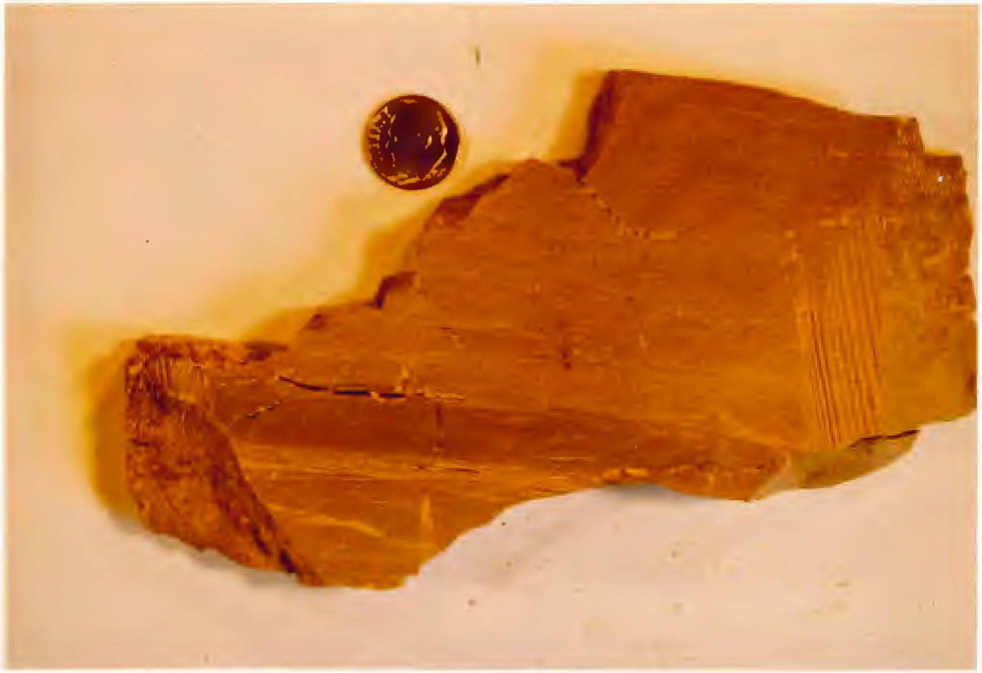


Figure 40. Photograph of a vertically oriented slab of laminated clay, Wrenshall Fm.

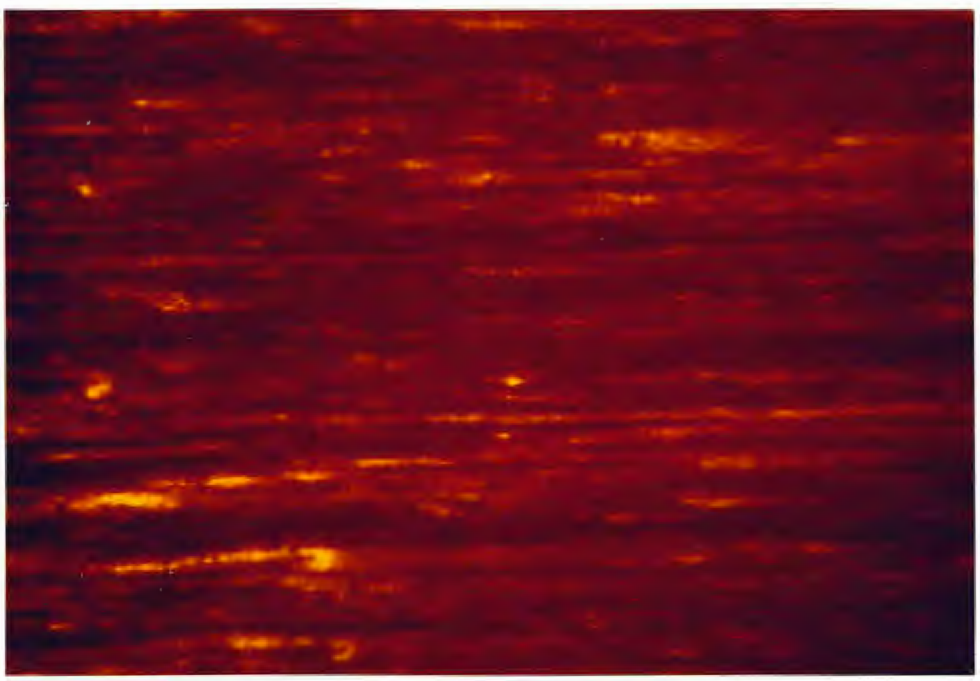


Figure 41. Photomicrograph of a vertically oriented slab of laminated clay, Wrenshall Fm. Field of view: 2.4 mm wide.

Figure 42. Photograph of 0.1 cm piece of laminated clay of the Wrenshall Fm., flaking along parallel bedding planes in a beaker of deionized water.

Figure 43. Photograph of folded, convoluted layers of fine silt and clay, overlying undisturbed laminae.

43 shows folded, convoluted layers of fine silt and clay overlying undisturbed laminae.

Some local deformation of the parallel bedding is also noted, and is generally seen in association with "sand nests" (Figure 44). "Sand nests," a term introduced for the clusters of coarse silt and sand particles found in the laminated clay, have been referred to by others as "till pellets" (Ovenshine, 1970; Ojakangas and Matsch, 1980). Ovenshine (1970) observed the formation of till pellets on icebergs in Glacier Bay, Alaska. Small pellets of poorly sorted sediment originally formed between clear ice crystals in the foliation bands of glacier ice. They owe their coherence to stress undergone during glacier flow. During iceberg-rafting processes, the pellets are freed by melting of the enclosing ice crystals and subsequently deposited in an aqueous environment by melting, tilting, fragmentation, and/or overturning of the iceberg.

The till pellets found in the Wrenshall Formation range from 0.3 to 1.5 cm in diameter. The individual sand grains and diamictite clusters are less than 1 mm in diameter. Their occurrence is a strong indication of the presence of glacier ice in a lacustrine environment.

In one of the laminated clay samples a pebble of basalt, 1 cm in diameter, was found on a horizontal bedding plane (Figure 45). It is interpreted to be a dropstone, introduced into a lacustrine sequence by melting out of a floating, debris-rich iceberg, for the following reasons. It is an "over-size" clast, exceeding the thickness of the stratification unit, and thus could not have been carried laterally into place contemporaneously with the sediment. The pebble is also randomly

Figure 44. Photograph of "sand nests" locally deforming parallel laminae, clay facies, Wrenshall Formation.

Figure 45. Photograph of a pebble on a horizontal bedding plane of laminated clay, Wrenshall Formation. Interpreted to be an ice-rafted dropstone.

oriented (not lying parallel to the bedding plane) and it slightly penetrates and distorts the stratification beneath it.

The presence of small-scale deformation structures, till pellets, and varying amounts of pebbles (dropstones) locally occurring in the laminated clays of the Wrenshall Formation strongly suggests a glaciolacustrine environment of deposition.

In general, the clay facies of the Wrenshall Formation is massive and pebble-rich. In only one area below 350 m (1150 feet) in elevation were laminated lacustrine sediments found (NE 1/4, Sec.17, T 53 N, R 10 W, where a foundation for a house is being excavated). These laminated sediments do not display a rhythmic, uniform alteration of sequences of laminae of similar color and composition, which is characteristic of true varves (Theakstone, 1976). The laminae are generally 0.5 mm to 1 mm thick.

Apparently water temperature, lake chemistry, changes of sediment supply, or rate of sedimentation were unfavorable for the formation of varves in the Two Harbors area. However, northeast of Two Harbors, near Silver Bay, varved couplets of clay and silt are extensively developed and are seen at the Reserve Mining tailings disposal site.

Site-specific characteristics

Massive, pebble-rich clay exposed along stream valleys reaches a maximum observed thickness of 10 m. In the Silver Bay area the maximum penetrated thickness of the clay is 14 m (Green, 1982). The best exposures are along Stewart River (Sec.29, T 53 N, R 10 W), Silver Creek (Sections 16 and 21, T 53 N, R 10 W), Encampment River (Sec.11, T 53 N, R 10 W), and Crow Creek (Sec.1, T 53 N, R 10 W).

An interesting feature exposed along Crow Creek, at approximately 220 m (720 feet) in elevation, is a "macro" varve-like clay and sand sequence. A 0.4 m section of pebble-free, reddish brown clay is located at the top of a 15 m cliff of pebble-rich clay resting on bedrock, high above the stream bed. Two sand layers, each 8 cm thick occur within the pebble-free clay, and give this unit a banded appearance that is commonly associated with glacial-lake rhythmite sequences (Ashley, 1975). Although the contacts between the clay and sand are sharp, the sand does not contain multiple graded bedding, a feature indicative of most varve sequences. Variation in water and sediment discharge, as well as differing rates of deposition in the lake basin can account for this clay and sand sequence.

Other interfingering clay and silt/sand sequences are found along the shoreline at an elevation of approximately 190 m (620 feet). They are exposed near the Gray Gull Motel, SW 1/4, Sec.21, T 53 N, R 10 W, and behind the Gooseberry Park Motel, SE 1/4, Sec.32, T 54 N, R 9 W. Figure 46 is a sketch of the 4 m section at the Gooseberry Park Motel (Locality L). The basal unit is an approximately 1 m-thick layer of non-stratified sand. It is overlain successively by 0.5 m of a clast-poor silty clay, and by another approximately 0.5 m of alternating and interfingering layers of silty sand, silt, and clayey silt. This is capped by about 1 m of a pebble- and cobble-rich, reddish brown, sandy unit.

A complex of glaciolacustrine sediments is also found at an elevation of 275 m (900 feet), at Locality M (the Sanitary Landfill Pit), NW 1/4, Sec.1, T 53 N, R 10 W. Figure 47 is a sketch of this 1.2

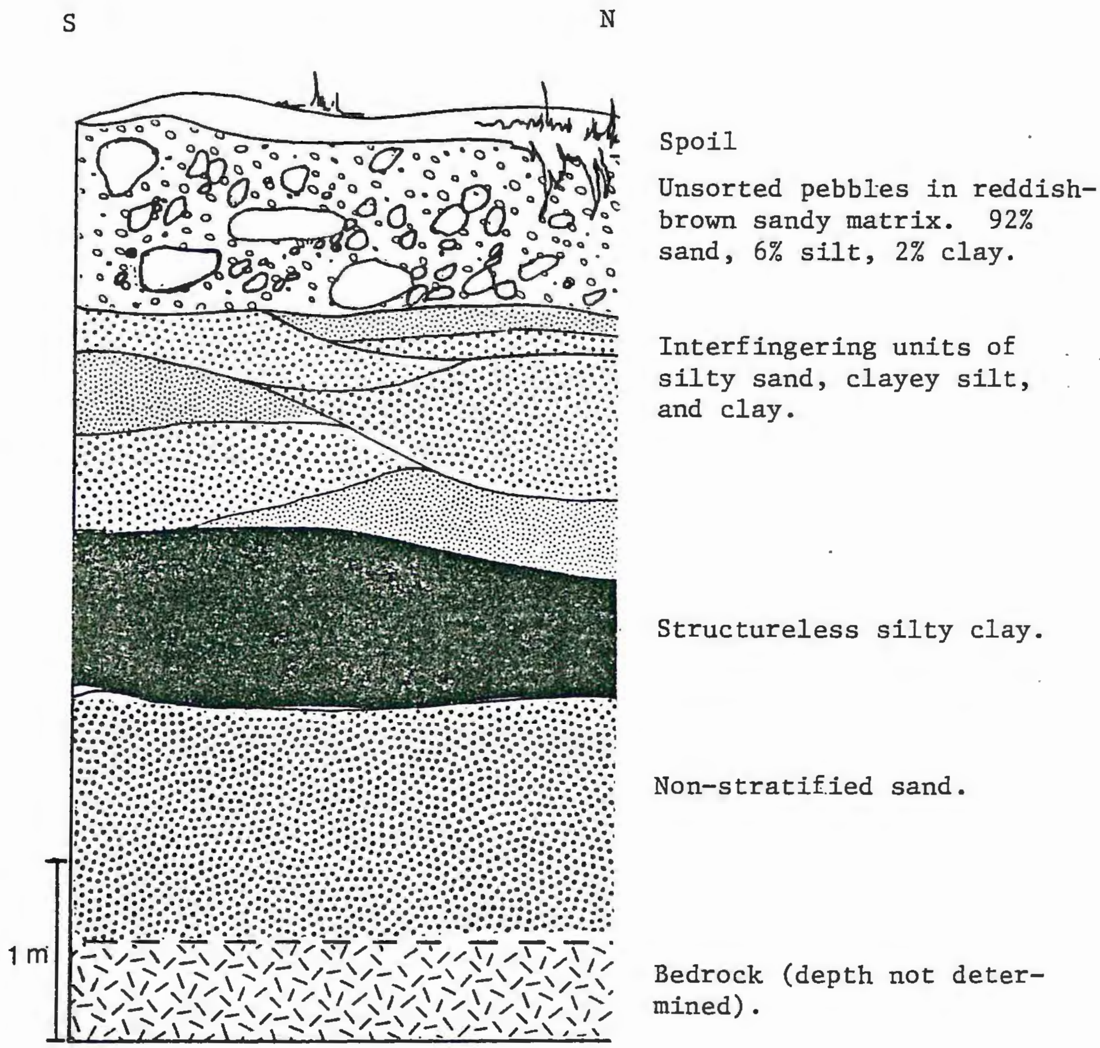


Figure 46. Glaciolacustrine sedimentary sequence. Gooseberry Park Motel (Locality L), SE¼, Sec. 32, T54N, R9W.

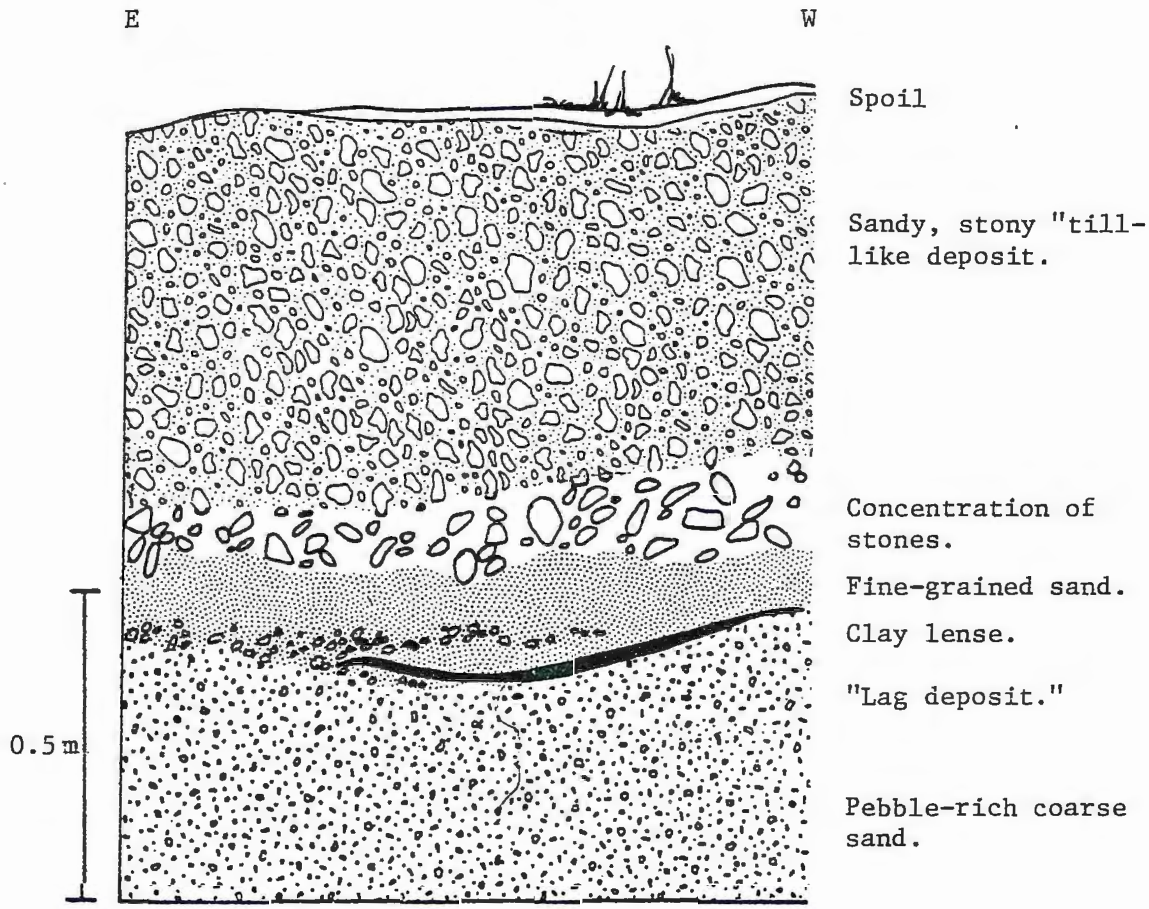


Figure 47. Glaciolacustrine sedimentary sequence exposed at Locality M (the Sanitary Landfill Pit), NW¼, Sec. 1, T53N, R10W.

m-high exposure illustrating a sandy, stony, till-like sediment, interfingered with clay lenses and finely bedded sand.

The origin of the pebble-rich massive clay, the interfingering clay and silt/sand sequences, and the occasional occurrence of till-like units within the Wrenshall Formation can all be explained in terms of iceberg- rafting processes in a glaciolacustrine environment. Deep-water deposition in Glacial Lake Duluth resulted in the formation of an offshore facies, consisting predominantly of massive clay and more rarely, finely laminated silt and clay. Icebergs were probably abundant in the lake, calving from the Superior Lobe as it wasted northeastward within the Lake Superior basin. Immediately after calving, the icebergs probably fragmented and turned over in the water, periodically dumping debris into the lake basin, until they attained a stable position.

Sediment having the texture of till is contained in about 1 percent of the icebergs and is released continuously from the submerged part as it melts while drifting through the water (Ovenshine, 1970); hence, the till-like units of the Wrenshall Formation. In contrast, stones and mud in the portion of the iceberg above the waterline are not released continuously, but accumulate on the upper surface of the iceberg. Eventually, this sediment leaves the iceberg by way of (1) tilting, fragmentation, or overturning of the iceberg, (2) mudflow and slumping, and (3) meltwater rivulets. The processes of overturning, mudflow, and slumping provide mechanisms for the sudden release of large quantities of stones that will settle rapidly to the bottom of the lake. This accounts for the abundance of clasts (some striated) that occur in the clay facies of the Wrenshall Formation.

Areal extent

Another line of evidence to support a lacustrine origin for the red clay of the Wrenshall Formation is the fact that it is confined to the basin below elevations of 350 m (1150 feet), as defined by Glacial Lake Duluth strandlines (Leverett, 1929; Farrand, 1960; Moss, 1977; Zarth, 1977). In the Two Harbors area it is confined to the basin below the 350 to 366 m (1150 to 1200 feet) northeast-southwest trending zone of stratified sand and gravel deposits, interpreted to be deltas and abandoned shorelines of Glacial Lake Duluth.

The Douglas till in Wisconsin does occur above the 340 m (1100 foot) Lake Duluth highstand as defined by Farrand (1960). Johnson (1980) cited one locality at which the Douglas till is found out of the lake basin at an elevation of 370 m (1210 feet). Elsewhere it occurs below the 340 m (1100 foot) contour. It is difficult to accept the conclusion that only subglacial deposition could account for the occurrence of the Douglas till above the highest lake level. It may be feasible to suggest that an ice advance or surge (not related to the Douglas till formation) over a clayey lake bed may have locally deposited a sediment which bears resemblance to the Douglas till. A clay-rich facies of the Cromwell Formation is noted in the Two Harbors area at elevations of 372 to 378 m (1220 to 1240 feet). It is proposed to be a redeposited lake clay resulting from an ice advance that overrode proglacial lake deposits and incorporated fine-textured sediment into its basal zone.

Stratigraphic relationships

Disregarding post-glacial sediments, the Wrenshall Formation is stratigraphically the highest and youngest of the Quaternary deposits of the Two Harbors area. Just to the southwest of the study area, in the French River area, this unit is in sharp contact with, and overlies the uppermost silt-rich till of the Cromwell Formation (Moss, 1977). The stratigraphic position of this unit supports a lacustrine origin of deposition in Glacial Lake Duluth. The Hanson Creek and Douglas tills of Wisconsin are also stratigraphically the highest and youngest Quaternary deposits of the region.

Geomorphic features

Geomorphic features such as flutes and drumlins, which are molded by subglacial activity and characterize the ground moraine surfaces of the Cromwell Formation and the Sullivan Lake Formation, are noticeably absent on the surface underlain by the Wrenshall Formation. Morphologically, the clay is expressed locally as a stacked terrace terrain (Figures 48, 49). Terraces could represent a stillstand during the lowering water levels of Glacial Lake Duluth. The terraces would thus be a depositional feature in which newly stranded ice blocks could furnish an abundance of till-like debris, ice-rafted pebbles, and sand.

In Douglas and Bayfield Counties, Wisconsin, faint traces of linear features trending to the northeast are molded on the clay surface. These features are interpreted as flutes (Johnson, 1980), and are only discernable on air photographs of the area. It is reasonable to argue that these flutes developed during an earlier ice advance and are only draped by a lacustrine red clay. These low ridges and shallow grooves could also be interpreted as ice- drag marks. Similar features are

Figure 48. Photograph of the "stacked terrace terrain" of the Wrenshall Formation, SE¼, Sec. 33, T54N, R10W.

Figure 49. Photograph of the "stacked terrace terrain" of the Wrenshall Formation, SW¼, Sec. 14, T53N, R11W.

noted on the offshore sediment of Lake Agassiz (North Dakota) and are attributed to gouging by the irregular bottoms of glacial icebergs (Clayton, et al., 1980).

Conclusions

Grain size analysis, bulk density measurements, sedimentary structures, the presence of ice-rafted material, areal extent, and stratigraphic position indicate a glaciolacustrine, rather than a subglacial origin for the clay facies of the Wrenshall Formation in the Two Harbors area. The Douglas till and the Wrenshall Formation exhibit similar characteristics and appear to be correlative units. Johnson (1980) had originally proposed this correlation, but he considered the clay facies of the Wrenshall Formation to be of subglacial origin. Johnson, et al., (1981) have subsequently abandoned this correlation, and now they attribute the Douglas and Hanson Creek tills to a later glacial advance, the Marquette advance, dated at 9,900 years B.P. That advance did not affect the North Shore of Lake Superior, according to my own work. However, the presence of the Hanson Creek and Douglas tills, and the marked absence of the lacustrine clay of the Wrenshall Formation on the south shore of Lake Superior is not feasible. According to Drexler (1982), there is no evidence of the Marquette advance filling the western end of the Lake Superior basin. No one has identified a moraine produced by this advance in the Upper Peninsula of Michigan, Wisconsin, or Minnesota, and thus the extent of the Marquette advance is poorly known.

Therefore, I propose that the Hanson Creek and Douglas "tills" are a misnomer. These units are part of the lacustrine clay deposits of the western Lake Superior region, and are a continuation of the clay facies of the Wrenshall Formation in Minnesota.

SUMMARY OF REGIONAL SEDIMENTOLOGY

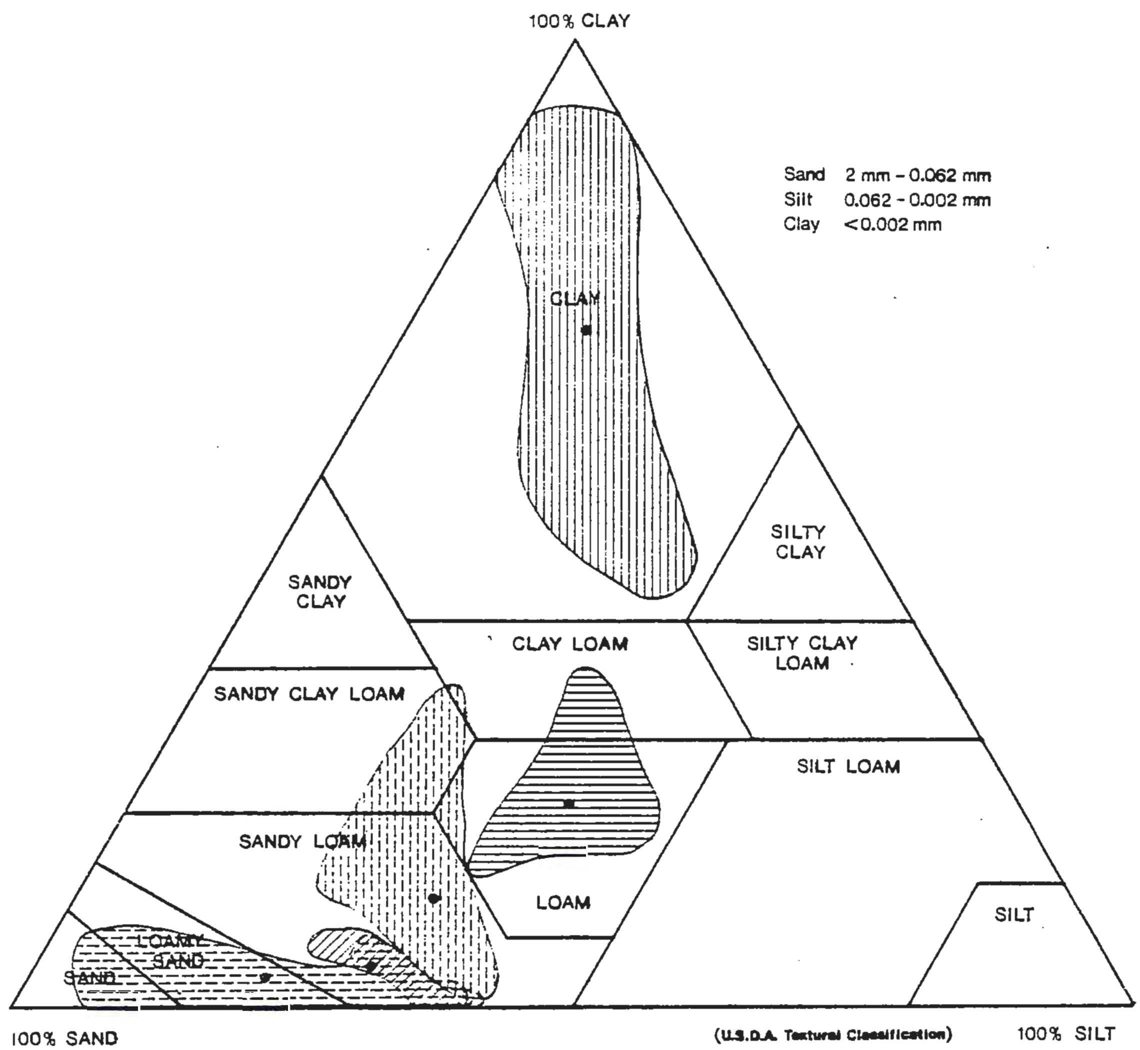
The Quaternary deposits of the Two Harbors area can be grouped into five texturally distinct units. These groups are differentiated on the basis of grain-size distribution, clast lithology, stratigraphic position, and regional distribution. Their specific physical properties are attributable to (1) bedrock sources, (2) conditions of glacier flow, and (3) methods and environments of deposition.

Unit 1

This unit contains the sand to loamy sand sediment (based on U.S.D.A. textural classification) of the Sullivan Lake Formation (Figure 50). It is the oldest of the sedimentary units, and underlies the northwestern most part of the study area. It is topographically expressed as the Toimi drumlin field.

The abundance of granophyre, granite, greenstone, basalt, and gabbro reflect derivation from the underlying Duluth Complex and from other igneous and metamorphic sources cropping out to the north and northeast. This implies deposition by the Rainy Lobe.

An actively moving, wet-based glacier deposited this sediment by the lodging of clasts and debris at the base of the glacier and by melting out of debris during ice movement (Lawson, 1981b). Hence, the Sullivan Lake Formation is a basally-derived lodgement till. This is confirmed by the strong northeast-southwest macrofabric of elongate clasts and the streamline trend of the drumlins, which parallels the inferred regional ice flow. The drumlins are attributed to the process of subglacial shearing. They formed in the thawed bed zone of the



Unit			
5	Wrenshall Formation (clay facies)	10 samples
2	Cromwell Formation, Supraglacial debris	7
3	Cromwell Formation, Subglacial debris (sandy loam facies)	8
4	Cromwell Formation, Subglacial debris (loam facies)	7
1	Sullivan Lake Formation	12
	● mean	

Figure 50. Composite ternary diagram of the textural composition of Quaternary sediments of the Two Harbors area.

glacier, where ice was easily able to slip over basal obstructions (Wright, et al., 1973). This topographic and fabric lineation is consistant with Rainy Lobe derivation. The abundance of meltwater within the glacier, moving through channels, and causing washing and sorting of the sediment, is also recorded by the presence of eskers, and a tunnel valley, partially occupied by Sullivan Lake.

Unit 2

The sandy loam sediments of this unit comprise the supraglacially derived debris of the Cromwell Formation (Figure 50). These sediments occur to the southeast of the Toimi drumlin area and are expressed mainly by the kettle and kame topography of the Highland Moraine. Isolated occurrences of this unit are also expressed as topographic highs in the area of fluted terrain southeast of the Highland Moraine.

The abundance of lithic fragments of basalt and rhyolite, gabbro-diabase, granite, granophyre, and red sandstone reflect local derivation from the underlying North Shore Volcanic Group and from the Lake Superior basin to the east. Local occurrences of the Duluth Complex account for the gabbro and diabase, granite, and granophyre. This provenance implies deposition by the Superior Lobe.

These sediments are the result of stagnation and compressive flow in the terminal zone of the glacier. Evidence for this is the transverse orientation of elongated clasts to inferred glacial flow (out of the Lake Superior basin and to the west) at the margin of the moraine. In other areas within the moraine the macrofabric is random. This reflects multiple episodes of collapse, sliding, and flowing of drift, as the ice melted back from the terminus (Flint, 1971).

Methods of deposition include the primary process of melt-out, forming ortho-tills by the melting in situ of the debris-rich body of the stagnant glacier (Dreimanis, 1981). Also, sediment released from ablation of the active and stagnant basal zone ice was commonly transported and deposited by one or more secondary processes, thus forming a variety of allo-tills (Dreimanis, 1981). These secondary processes include: sediment gravity flow, spall (outward failure and collapse of steeply sloping sediments on melting stagnant ice), and sheet and rill flow of meltwater. Fluvial and lacustrine processes were also operating simultaneously in the englacial and proglacial parts of the environment. This enabled gravitational settling out of fine sediment in water (Lawson, 1981b).

The various allo-tills of the Highland Moraine and the northern half of the Two Harbors quadrangle, include isolated occurrences of outwash in the form of fans, braided stream deposits, deltaic deposits, and resedimented deposits of till.

Processes of deposition in the terminal zone of the glacier were further complicated by the stress exerted by the glacier and the weight of the ice in this zone. A variety of glaciotectonic features were formed in the substratum beneath the glacier and along the front of the glacier. This includes thrust masses (or flutes) concentrated near the southeast margin of the moraine in the Two Harbors area. Eskers and esker-like ridges were deposited in subglacial tunnels near the margin of the thin and stagnating glacier. Their southeast-northwest trend parallels the general direction of ice flow as inferred from the flutes to the southeast of the Highland Moraine.

Unit 3

This sediment group contains the sandy loam to sandy clay loam subglacially derived debris of the Cromwell Formation (Figure 50). These sediments were deposited upglacier from the previously described terminus region (the Highland Moraine), and are expressed as the Highland flutes.

Bedrock source of materials for this unit is the same as for the supraglacially derived sediments of Unit 2. However, differing conditions of glacial flow and methods of deposition serve to separate these sediments as a different unit of the Superior Lobe drift.

The presence of a fluted topography establishes the existence of an actively flowing, wet-based glacier at the time of formation (Flint, 1971). Methods of till deposition include lodgement of debris into the substrate, and melting of basal debris during regelation. The lodgement process of forcibly pressing fine rock flour into voids between larger particles, and the loading of overlying glacial ice during deposition, as well as the lack of washing by meltwater, accounts for the finer texture of till formed subglacially. The processes of subglacial shearing from the drag of the glacier sole over a till surface (Boulton, 1971; Flint, 1971) and/or ice pressing of water saturated till into cavities both in front of and behind fixed boulders (Galloway, 1956; Stalker, 1960a), have been suggested for the formation of the flutes.

Unit 4

This unit contains the loam sediments of the Cromwell Formation (Figure 50). These sediments occur in an isolated area southward of the flutes and border the strandline of Glacial Lake Duluth in the southwest section of the study area.

The source of sediment for this unit includes debris from the underlying North Shore Volcanic Group, red sandstone from the Lake Superior basin, and clayey, proglacial lake sediments. Although these sediments are expressed by a non-fluted terrain, elongate clasts exhibit a strong southeast-northwest preferential alignment appropriate to the Superior Lobe.

The following conditions of glacier flow and methods of deposition are postulated for units 3 and 4. A thick mass of glacial ice was confined to the Lake Superior basin and frozen to its bed. This enabled a build up of subglacial meltwater behind a dam of frozen ice. Local melting and weakening of the ice front (perhaps owing to the presence of a proglacial lake) reduced basal friction in the toe of the glacier, and initiated a surge of the ice front (Wright, 1973). The sediments of these units are therefore attributed to a basal slip of the ice mass during a rapid glacial flow. They have essentially been deposited by lodgement and plastering processes. Overriding of proglacial lake deposits and incorporation of fine-textured sediment into the basal zone of the ice could explain the textural change between units 3 and 4.

Unit 5

The clay-rich unit of the Two Harbors area forms another texturally distinct unit (Figure 50). Stratigraphically, it is the highest and youngest of the sedimentary units and is the glaciolacustrine clay facies of the Wrenshall Formation. It is differentiated from the upland glacial deposits by its fine texture, sedimentary structures (laminations), and its restricted occurrence basinward of abandoned shorelines below elevations of 366 m (1200 feet). Methods of deposition include offlapping nearshore processes and the settling out of fine silt and clay in deeper water, unaffected by current action (Moss, 1977; Zarth, 1977).

Figure 51 is a diagrammatic cross-section summarizing the regional Quaternary sedimentology and stratigraphy of the Two Harbors area.

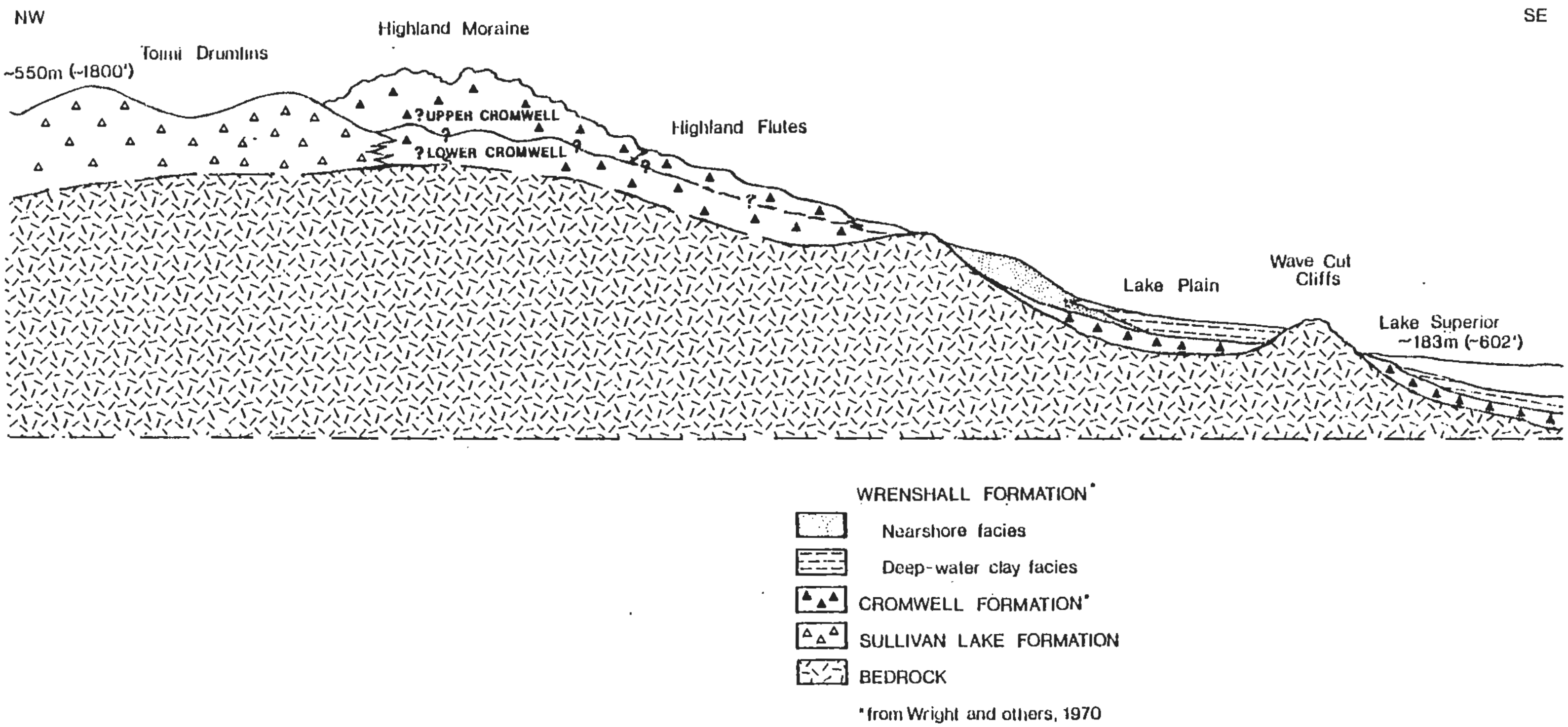


Figure 51. Diagrammatic cross-section of the Quaternary deposits of the Two Harbors area.

QUATERNARY HISTORY

The sediments and morphology of the Two Harbors and Whyte quadrangles record several distinct episodes of the Late Wisconsin glaciation. These sediments are attributed to ice lobe advances, ice stagnation, final retreat, and proglacial lake formation. The following glacial history is inferred:

(1) During the St. Croix Phase of the Wisconsin glaciation 20,500 ± 400 years B.P. (figure 52), the Rainy Lobe advanced from the northeast, along with the contemporaneous and parallel advance of the Superior Lobe. These two streams of ice, within the broad belt of the Laurentide Ice Sheet, were separated subglacially by the North Shore Highland. They coalesced downglacier forming the St. Croix (terminal) Moraine. Sandy to stony, gray to brown drift, and an abundance of gabbroic lithic fragments are attributed to the Rainy Lobe. In the northern half of the Whyte quadrangle the Rainy Lobe drift is expressed by a distinctive topography of the southwest-trending Toimi drumlin field, and tunnel valleys, which are partially occupied by lakes and eskers. The rock-stratigraphic name for the drift of the Rainy Lobe advance, the Independence Till, has been abandoned, and is now designated the Sullivan Lake Formation.

As the Rainy Lobe wasted from the St. Croix Moraine into Canada, the adjacent and thicker Superior Lobe just barely retreated into the Superior basin.

(2) When the ice readvanced during the Automba Phase, inferred to be younger than 20,000 years B.P. and older than 16,000 years B.P., the Rainy Lobe was confined to northeastern Minnesota and formed the

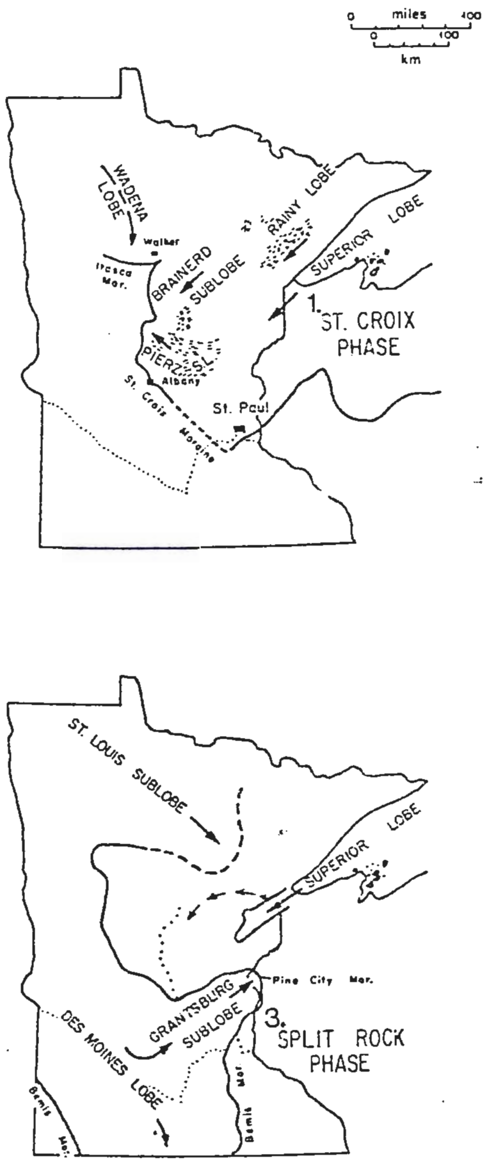


Figure 52. Ice movement during the Late Wisconsin glaciation (from Wright and others, 1973).

Vermilion Moraine (Figure 52). Meanwhile, the Superior Lobe moved southwestward and westward, overflowing out of the Lake Superior basin where it had thickened sufficiently to top the North Shore Highland. It molded a fluted terrain, partially buried the Toimi drumlins, and terminated at the Highland Moraine. Southwest of Duluth, the Superior Lobe formed the Automba drumlin field and the Wright and Cromwell Moraines, and reached its terminus at the Mille Lacs Moraine. Drift of the Superior Lobe, formally designated the Cromwell Formation, is typically reddish brown, sandy to clayey, and contains lithic fragments of the North Shore Volcanic Group and Keweenawan red sandstone.

(3) Stagnation and wastage of the Superior Lobe marked the end of the Automba Phase. At the Highland Moraine, debris-bearing horizons cropped out on the surface of the glacier. This supraglacial till cover reduced the ablation rate of the underlying ice, and debris concentrated to form an ice-cored moraine (Figure 53, phase 1). As ablation progressed and the buried ice began to melt, meltwater streams flowed from the retreating Superior Lobe and the ice-cored moraine. Outwash sediments and saturated slurries of debris accumulated locally in troughs and low spots on the stagnant margin.

(4) The Superior lobe retreated far enough into the Lake Superior basin at the end of the Automba Phase to bring about the formation of a proglacial lake between the ice front southwest of Duluth and a drainage divide near Sandstone. This lake was large and deep enough for the accumulation of red clay and silt. Small, isolated proglacial lakes also formed in front of the ice margin near the Two Harbors area.

(5) Readvances of the Superior Lobe over lake beds southwestward

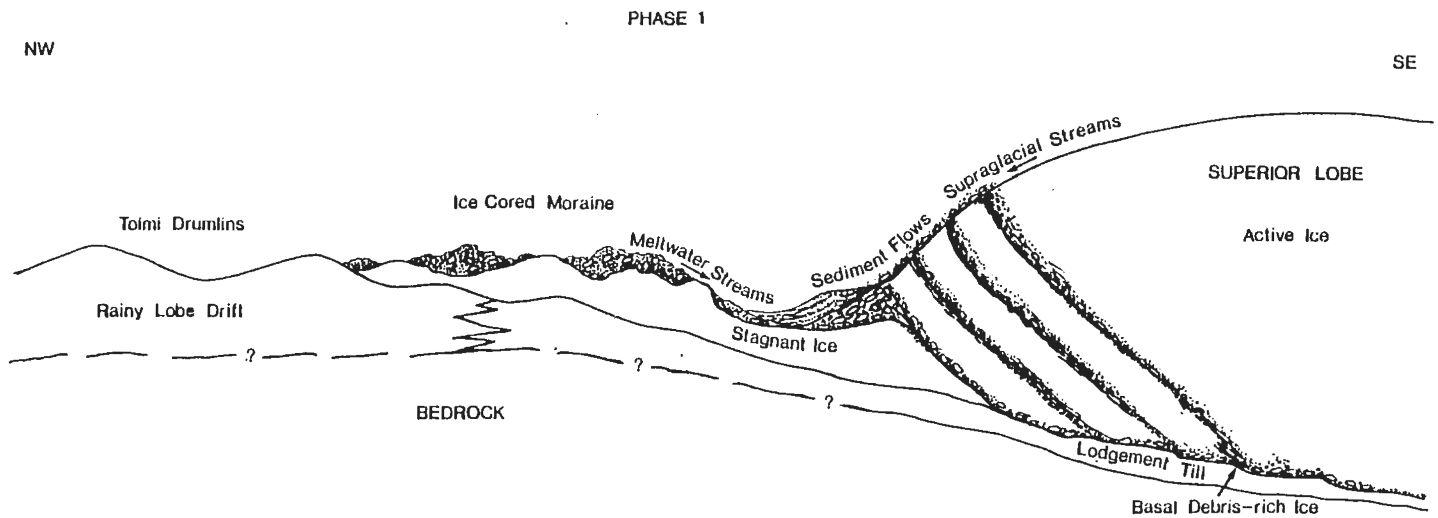


Figure 53, phase 1. Idealized model of stagnation and retreat of the Superior Lobe in the Two Harbors area.

of Duluth to the rim of the basin during the subsequent Split Rock and Nickerson Phases (figure 52), occurring 16,000 and 12,000 years B.P. respectively, produced a red clayey till in that area. These sediments were deposited from surges of ice that resulted from the buildup of basal meltwater behind the frozen toe of the Superior Lobe (Wright, 1973). The ice formed a narrow tongue only about 20 km wide, and extended to about 100 km beyond Duluth. The Two Harbors area was too far north to be affected by these major ice advances. However, a clay-rich lodgement till, the loam facies of the Cromwell Formation, does occur in the Two Harbors area. The age of the event that deposited this sediment is, however, interpreted to be the Automba Phase.

(6) With the final retreat of the Superior Lobe into the Lake Superior basin, after 10,800-10,400 years B.P., proglacial lakes formed in front of the ice marin at the southwest end of the basin.

In the Two Harbors area, meltwaters from the wasting ice were ponded in front of the retreating Superior Lobe during the formation of Glacial Lake Duluth (Figure 53, phase 2). Meltwater streams, laden with sediment, deposited gravel, crossbedded sands, and coarse silts as prograding deltas in a nearshore environment. As the deltas prograded into the basin, currents carried fine sand, silt, and clay particles into the deeper water. Massive clay and laminated silt and clay, settling out from suspension, were contemporaneously being deposited with the deltas, in an offshore environment. Floating icebergs sporadically supplied coarser ice-rafted sediments to the basin. Resedimented slurries of debris issuing from the retreating ice lobe were also introduced into the lacustrine environment.

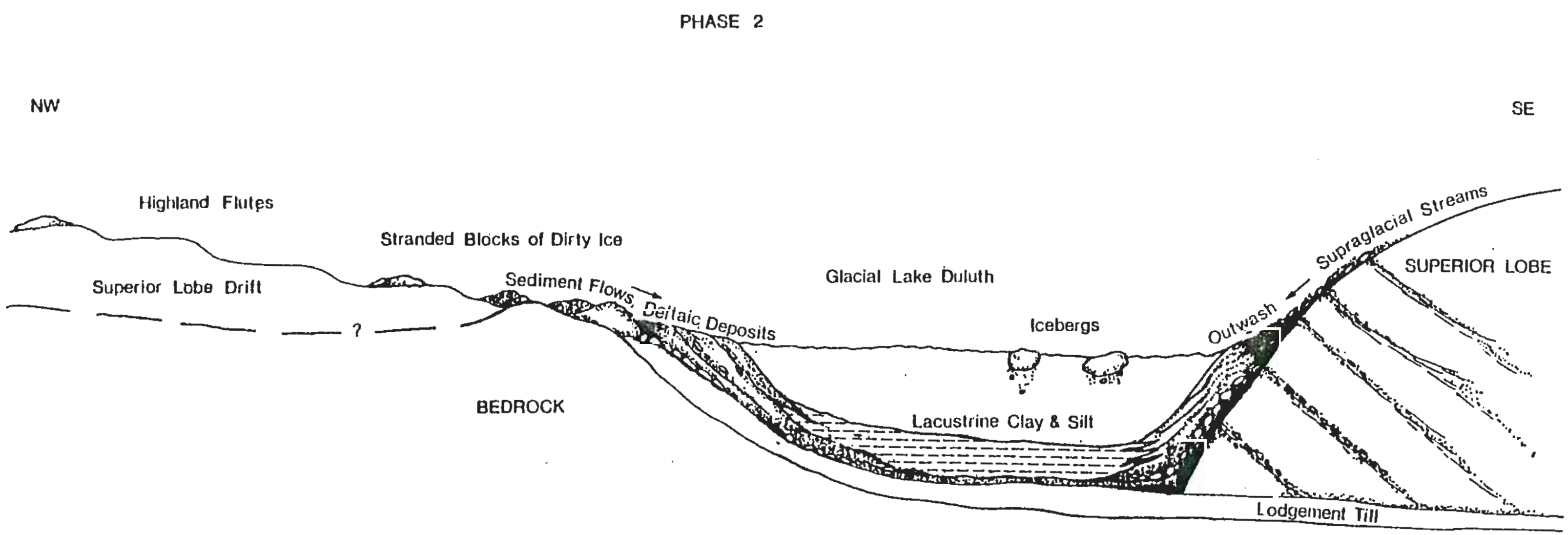


Figure 53, phase 2. Idealized model of stagnation and retreat of the Superior Lobe; and glaciolacustrine sedimentation in Glacial Lake Duluth.

The well-developed strandline at the 350 to 366 m (1150 to 1200 foot) elevation indicates a long period of stability of Glacial Lake Duluth in the southwestern part of Two Harbors area. During this time the lake was discharging into the Mississippi River System through two outlets: Solon Springs, Wisconsin, between the headwaters of the Brule and St. Croix Rivers; and through Moose Lake and the Kettle River, southwest of Duluth.

(7) A rapid drop in lake level occurred as the ice front retreated past the area of the Huron Mountains west of Marquette, Michigan, after about 10,100 years B.P. (Saarnisto, 1975), and uncovered a lower outlet in the Michigan basin. This new level is known as the post-Duluth Stage of Lake Superior.

Another period of rapid retreat of the ice front opened up the entire lake, which Farrand (1969) referred to as Glacial Lake Minong. At 8,500 years B.P. the lake drained to its lowest level, approximately 67 m (220 feet) below the present lake level (Farrand, 1969), forming Glacial Lake Houghton. This was followed by a 5,000 to 6,000 year period of slowly rising lake levels in the upper three Great Lakes as the outlet rose by isostatic rebound. Drainage was then transferred to outlets at North Bay, Ontario, Chicago, and Port Huron. This three-outlet stage, occurring around 5,000 years B.P., is known as the Nipissing Great Lakes Stage.

The post-Nipissing stages of Lake Superior have undergone only minor changes in lake level. The strandlines that record these lower lake levels are all inclined gently to the southwest in response to isostatic rebound due to the removal of glacier ice. Evidence of these later shorelines is not observable in the Two Harbors area.

Features of the modern lakeshore include wave-cut cliffs and scarps on the bedrock and surficial deposits, as well as coarse sand and gravel beaches. The present geological processes active along the shoreline in the Two Harbors area are wave erosion and the lateral movement and deposition of sediment below the 184 m (602 foot) waterline by bottom currents.

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APPENDIX I

WEIGHT PERCENTAGES OF SAND, SILT, AND CLAY OF GLACIOGENIC SEDIMENTS IN THE TWO HARBORS AREA

Sullivan Lake Formation	% Sand	% Silt	% Clay
8/21/81-1	87	13	0
8/21/81-2	76	19	5
8/21/82-3	93	7	0
8/21/81-4	60	38	2
8/24-81-1	67	30	3
8/24/81-2	65	28	7
8/24/81-3	75	25	0
8/24/81-4	79	15	6
8/24/81-5	70	27	3
8/24/81-6	76	24	0
8/24/81-7	90	3	7
8/24/81-8	73	27	0
Cromwell Formation			
Supraglacial Debris			
8/20/81-1	67	26	7
8/20/81-2	67	28	5
8/20/81-10	59	40	1
8/20/81-11	70	24	6
9/19/81-1	67	26	7
9/19/81-2	66	28	6
9/19/81-3	64	36	0
Subglacial Debris (Sandy Loam Facies)			
8/14/81-1c	57	41	2
8/14/81-2c	66	22	12
8/14/81-3c	61	36	3
8/14/81-4c	59	34	7
8/14/81-5c	60	35	5
8/14/81-6c	59	30	11
8/14/81-1d	45	23	32
8/14/81-2d	51	30	19
Subglacial Debris (Loam Facies)			
9/12/81-10	45	34	21
9/12/81-11	52	34	14
9/13/81-8	40	36	24
4/17/82-4	37	42	21
4/17/82-5	32	34	34
4/17/82-6	39	44	17
4/17/82-7	34	47	19
Wrenshall Formation (Clay Facies)			
8/11/81-9	26	25	49
8/12/81-4	13	0	87
8/12/81-4e	15	23	62
8/14/81-1e	1	9	90
8/17/81-7	21	36	43
8/17/81-8	19	22	59
8/23/81-3	9	0	91
8/27/81-6	27	20	53
8/28/81-3	12	18	70
8/28/81-4	0	8	92

APPENDIX II

PERCENT COMPOSITION OF PEBBLE AND COARSE SAND LITHOLOGIES OF THE GLACIOGENIC SEDIMENTS OF THE TWO HARBORS AREA

													"Other"								
	Basalt and Amygdaloidal Basalt	Rhyolite and Amygdaloidal Rhyolite	"Red" Sandstone	Granite	Granophyre	Gabbro and Diabase	Quartz	Agate	Chert	Calcareous Concretions	Iron Formation	Metamorphic (Green-stone) and Schist	Quartzite	Epidote	Hornblende	Pyroxene	Olivine	Plagioclase	Conglomerate	Shale	Carbonates
Sullivan Lake Formation																					
>2mm clasts																					
8/24/81-1	5	3	0	31	31	6	0	0	0	0	0	22	0	0	0	0	0	0	3	0	0
8/24/81-2	0	0	0	46	38	4	0	0	0	0	4	4	0	0	0	0	0	0	4	0	0
8/24/81-3	4	0	0	31	51	2	0	0	0	0	0	10	2	0	0	0	0	0	0	0	0
8/24/81-6	9	0	0	38	33	2	0	0	0	0	4	13	0	0	0	0	0	0	0	0	0
8/24/81-7	6	0	0	23	29	10	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0
8/24/81-8	6	0	0	24	30	12	0	0	0	0	6	21	0	0	0	0	0	0	0	0	0
8/25/81-1	15	11	0	31	26	7	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0
8/25/81-4	13	3	0	10	26	38	0	0	0	0	0	8	3	0	0	0	0	0	0	0	0
8/25/81-5	22	6	0	20	19	13	0	0	0	0	0	17	4	0	0	0	0	0	0	0	0
8/25/81-6	28	5	0	18	26	8	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0
1-2 mm coarse sand																					
8/21/81-1	4	13	0	45	12	23	2	0	.3	0	0	1	0	0	0	0	0	0	0	0	0
8/21/81-2	5	11	0	44	15	14	8	0	.4	0	0	0	0	0	0	0	0	2	0	0	0
8/21/81-3	12	12	0	47	12	13	3	0	.6	0	0	.6	0	0	0	0	0	0	0	0	0
8/21/81-4	12	16	0	43	6	16	4	0	0	0	0	1	0	.3	0	0	0	0	0	0	0
8/24/81-1	8	12	2	46	7	17	6	0	.3	0	0	.3	0	1.5	0	.3	0	.6	0	0	0
8/24/81-2	13	17	0	29	11	18	8	0	0	0	0	1	0	1.6	1	.3	0	.6	0	0	0
8/24/81-4	11	8	0	45	14	16	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/24/81-7	17	3	0	45	9	13	10	0	1	0	0	0	0	0	0	0	0	1	0	0	0
8/24/81-8	27	9	0	37	11	9	7	0	0	0	0	.4	0	0	0	0	0	.9	0	0	0
Cromwell Formation																					
Supraglacial debris >2mm clasts																					
8/20/81-1	31	14	0	28	0	17	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
8/20/81-3	35	5	0	16	19	13	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0
8/20/81-5	28	12	0	27	9	14	0	2	0	0	0	8	0	0	0	0	0	0	0	0	0
8/20/81-11	17	23	0	17	27	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9/19/81-1	23	30	6	11	10	11	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0
9/19/81-3	21	10	2	35	3	27	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0

	Basalt and Amygdaloidal Basalt	Rhyolite and Amygdaloidal Rhyolite	"Red" Sandstone	Granite	Granophyre	Gabbro and Diabase	Quartz	Agate	Chert	Calcareous Concretions	Iron Formation	Metamorphic (Greenstone) and Schist	"Other" Quartzite	Epidote	Hornblende	Pyroxene	Olivine	Plagioclase	Conglomerate	Shale	Carbonates
Supraglacial debris 1-2mm coarse sand																					
8/20/81-1	5	14	0	41	14	23	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8/20/81-2	5	12	1	46	10	24	2	0	0	0	0	.3	0	0	0	0	0	0	0	0	0
8/20/81-3	20	14	0	28	12	25	0	0	.4	0	0	0	0	0	0	0	0	.4	0	0	0
8/20/81-10	10	14	0	47	9	18	0	0	.8	0	0	0	0	.8	0	0	0	0	0	0	0
8/20/81-11	7	14	0	44	13	15	2	0	2	0	0	2	0	0	0	0	0	.5	0	0	0
9/19/81-1	5	17	0	42	16	10	3	0	0	0	.5	6	0	0	0	0	0	.5	0	0	0
9/19/81-2	9	17	.6	48	9	12	.6	0	.0	0	0	4	0	0	0	0	0	0	0	0	0
9/19/81-3	3	13	0	56	6	14	3	0	.4	0	0	4	0	0	0	.4	0	0	0	0	0
Subglacial debris (Sandy Loam Facies) >2mm clasts																					
8/14/81-6c	48	33	0	3	1	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/19/81-7	37	11	0	16	5	26	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
8/19/81-2	45	0	0	0	0	36	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0
8/19/81-8	42	28	0	9	0	5	0	2	0	0	2	12	0	0	0	0	0	0	0	9	0
8/19/81-13	35	16	0	5	5	18	0	5	0	0	0	16	0	0	0	0	0	0	0	0	0
8/19/81-14	31	26	2	13	0	17	0	0	2	0	2	7	0	0	0	0	0	0	0	0	0
1-2mm coarse sand																					
8/14/81-1c	19	16	1	48	8	7	1	0	0	0	0	.4	0	0	0	0	0	0	0	0	0
8/14/81-2c	18	10	2	57	5	5	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8/14/81-1d	6	6	1	52	17	10	3	0	0	0	0	5	0	0	0	0	0	0	0	0	0
8/14/81-2d	11	17	2	46	12	6	3	0	.5	0	0	.5	0	0	1	0	1	0	0	0	0
8/19/81-13	18	16	.4	43	11	7	2	.4	.4	0	0	0	0	.4	0	0	.4	0	0	0	0
8/19/81-14	20	20	0	39	12	6	2	0	0	0	0	.5	0	0	0	0	0	0	0	0	0
8/28/81-8	20	15	1	42	18	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Subglacial debris (Loam Facies) >2mm clasts																					
9/12/81-9	44	28	4	2	2	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9/12/81-10	39	16	4	3	18	13	0	3	0	0	0	4	0	0	0	0	0	0	0	0	0
9/13/81-1	57	15	4	6	4	10	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0
9/13/81-7	54	18	0	5	7	14	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
9/13/81-8	29	11	0	5	45	5	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0
9/13/81-9	29	22	0	15	12	15	0	5	0	0	0	2	0	0	0	0	0	0	0	0	0

	Basalt and Amygdaloidal Basalt	Rhyolite and Amygdaloidal Rhyolite	"Red" Sandstone	Granite	Granophyre	Gabbro and Diabase	Quartz	Agate	Chert	Calcareous Concretions	Iron Formation	Metamorphic (Green-stone) and Schist	"Other"								
													Quartzite	Epidote	Hornblende	Pyroxene	Olivine	Plagioclase	Conglomerate	Shale	Carbonates
Subglacial debris (Loam Facies) 1-2mm coarse sand																					
9/12/81-9	16	11	1	50	10	6	3	0	.1	0	0	2	0	0	0	0	0	0	0	0	0
9/12/81-10	14	21	0	44	10	6	2	0	1	0	0	2	0	0	0	0	0	0	0	0	0
9/12/81-11	5	21	1	34	6	28	2	0	1	0	0	.3	0	1	0	0	0	.3	0	0	0
9/13/81-8	7	14	.5	55	11	8	0	0	0	0	0	4	0	.5	0	0	0	.5	0	0	0
9/13/81-9	12	21	.3	40	6	18	3	0	.3	0	0	0	0	0	0	0	0	0	0	0	0
4/17/82-5	9	18	2	41	13	9	2	0	2	0	0	2	0	0	0	0	2	0	0	0	0
4/17/82-6	6	23	1	42	6	20	1	0	0	0	0	1	0	0	0	0	0	.4	0	0	0
4/17/82-7	9	16	2	31	9	32	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wrenshall Formation (Clay Facies) >2mm clasts																					
8/11/81-9	49	15	8	6	0	9	0	2	2	0	1	5	0	0	0	0	0	0	0	3	0
8/12/81-4	29	18	12	6	0	23	0	0	6	0	0	6	0	0	0	0	0	0	0	0	0
8/12/81-4e	40	8	6	8	2	21	0	2	0	0	0	11	0	0	0	0	0	0	0	0	2
8/17/81-6	56	8	4	4	12	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/17/81-7	39	10	11	5	0	15	6	2	2	0	0	7	0	0	0	0	0	0	0	0	3
8/17/81-8	45	14	0	14	4	14	4	0	0	0	0	4	0	0	0	0	0	0	0	0	0
8/17/81-9	33	29	4	11	0	15	0	4	0	0	0	4	0	0	0	0	0	0	0	0	0
8/26/81-1	42	9	5	0	0	43	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8/26/81-5	42	28	2	2	2	19	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0
8/26/81-6	28	57	0	0	0	11	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0
8/26/81-7	44	25	2	2	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/26/81-13	48	25	5	2	2	17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8/27/81-5	52	14	14	3	0	15	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
8/27/81-6	58	11	11	0	0	16	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
8/28/81-3	57	5	5	4	0	27	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
9/7/81-1	43	23	5	6	1	18	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
9/7/81-2	39	47	7	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9/7/81-3	51	26	0	3	3	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9/7/81-5	48	21	5	11	1	11	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
1-2mm coarse sand																					
8/11/81-9	20	4	2	18	12	16	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/12/81-4	28	6	0	26	6	11	15	0	0	0	0	2	0	6	0	0	0	0	0	0	0
8/12/81-4e	18	11	0	18	3	16	19	0	0	15	0	0	0	0	0	0	0	0	0	0	0
8/17/81-7	18	7	4	11	15	13	28	0	0	4	0	0	0	0	0	0	0	0	0	0	0
8/17/81-8	25	17	0	16	7	19	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/17/81-16	18	6	1	33	5	10	18	1	1	0	0	7	0	0	0	0	0	0	0	0	0
8/23/81-3	17	12	0	35	8	16	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8/27/81-5	28	4	1	28	13	12	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0
8/27/81-6	27	14	1	17	9	11	15	0	0	1	0	1	0	4	0	0	0	0	0	0	0
8/28/81-3	15	12	0	20	9	9	26	0	0	0	0	3	0	6	0	0	0	0	0	0	0