THE QUATERNARY GEOLOGY
OF THE
LAKE JOHANNA REGION
WEST-CENTRAL MINNESOTA

A THESIS
SUBMITTED TO THE FACULTY OF
THE GRADUATE SCHOOL OF
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BY
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ABSTRACT

The Lake Johanna Region, encompassing an area of 625 square miles in west-central Minnesota, includes major portions of Swift, Pope, Kandiyohi and Stearns counties. The area has experienced a complex glacial history; all of the surficial deposits are ascribed to depositional events of the Wisconsin stage of the Pleistocene Epoch. If deposits of older glaciations exist in the area, they have eluded recognition. Bedrock is not exposed because of the thick mantle of glacial sediments.

The landscape of the Lake Johanna Region is composed of three major elements: a rolling ground moraine of low relief to the south, that is separated from an extensive outwash plain to the north by a long, linear, hummocky, stagnation moraine complex that runs diagonally in a northwest-southeasterly trend through the area.

Numerous hypotheses have been presented during the past century in an attempt to interpret the depositional history of the drift in the Lake Johanna Region. All previous workers have based their interpretations on the spatial distribution of the various drift units throughout the entire state of Minnesota. This study provides detailed stratigraphic and lithologic descriptions of

all drift units in the Lake Johanna Region.

Two different tills and outwash ranging from thick bedded, boulder gravels to laminated silts, constitute most of the surface and subsurface drift of the area. Numerous exposures show a variety of drift types in superposition including: outwash over till, till over outwash, till over till, and silt over all other sediment types. These stratigraphic relationships, coupled with topography, provide the key to an interpretation of the geologic history. The two tills, both calcareous, are distinguishable on the basis of rock fragment content and texture. Generally, the lower till is a buff, calcareous, sandy, shale-poor till (less than 5 percent contained shale fragments) having a textural compositon of 58 percent sand, 30 percent silt and 12 percent clay (average of 10 samples), whereas the upper till is a buff, calcareous, silty, shale-rich unit (more than 5 percent contained shale fragments) with a textural composition of 51 percent sand, 30 percent silt and 19 percent clay (average of 36 samples).

Regionally, on the basis of composition and texture, the lower till of the Lake Johanna Region is correlated with the till exposed in the Wadena drumlin field to the north. The upper till is correlated with the drift that is the surface deposit over a large area in the Minnesota River Valley to the south. The lower till was deposited by the Wadena lobe, which made its way from its source in the Winnipeg lowland down through north-central Minnesota to its final terminus south of the Lake Johanna Region. The upper till was deposited by the Des Moines lobe, which originated further west and followed the Red and Minnesota River Valley lowlands to its terminus in central Iowa. This divergence in paths accounts for the difference in lithologies of the two types of till.

Ice stagnation played an important role in molding the major geomorphic features of the Lake Johanna Region. Controlling factors included: the amount of debris carried by the ice, the position of the debris in the ice, the volume of meltwater produced, the rate of melting and differential erosion and deposition. The major stagnant ice features include an extensive kame complex, perched lake plains, ice walled outwash plains, the Blue Mounds Ridge System (a perched drainageway), and an extensive esker system. Flanking the linear ice stagnation complex are ground moraines, outwash plains, and proglacial lake-beds. The origin of all these features is intimately related to the activity of two ice lobes and their final disintegration.

The Wisconsin history of the Lake Johanna Region consists of five phases. During the first phase, Wadena lobe ice completely inundated the Lake Johanna Region, depositing a buff to yellow, sandy, calcareous, shale-poor till. No material from the lithologically distinctive upper Cretaceous Pierre Formation was incorporated into this ice, because it flowed along a course east of the Pierre outcrop belt.

In phase two, the Wadena lobe wasted back across the region to a point northeast of the study area, leaving massive blocks of dead ice in pronounced topographic lows which were probably the remains of a pre-Wisconsin drainage system. Meltwater from these large areas of ice swept great volumes of outwash material to the north and south of the ice masses until mantling by this debris slowed the ablation process. The main sheet of ice to the north continued to melt, back through Minnesota, leaving a complex mixture of outwash material and ablation till.

In phase three, the Lake Johanna Region, including the buried dead ice, was covered by an advance of the Des Moines lobe. Because the Des Moines lobe crossed the eastern edge of the Cretaceous Pierre Formation, it deposited, in the study area, a ground moraine comprised of buff to yellow, calcareous, clayey, shale-rich till.

During phase four, both the thin Des Moines lobe and the buried Wadena lobe ice gradually wasted. Water from this melting ice ponded to produce numerous small proglacial lakes along the northeastern margin of the stagnant ice. Large volumes of water poured through an ice-walled gorge south of Starbuck (the Blue Mounds Sluiceway) along a drainage line produced by a crevasse system or a sag in the continental ice sheet along this linear topographic low. This water eventually drained into Glacial Lake Benson which occupied a low-lying area in the southwestern portion of the Lake Johanna Region.

In the last episode of the Quaternary history, the Des Moines lobe had completely wasted, except for a large block of ice that occupied the Lake Minnewaska basin. Meltwater from this ice initially flowed north, but as lower outlet levels were found, the waters flowed south and west into the Lake Emily system. The Wadena dead ice complex was also in its final stages of melting, which caused it to lower a complicated melange of stagnant ice features onto an older stable till surface. Extensive river systems draining this complex again swept copious volumes of debris onto the Bonanza Valley outwash plains. Lake Benson continued to expand until it finally breached an ice-cored morainic dam near Redwood Falls, and then it was quickly drained. As all ice melted, the drainage channels were deprived of their discharge; they have since been gradually filling with paludal deposits.

INTRODUCTION

The Lake Johanna Region, west-central Minnesota, contains glacial sediments and landforms that have been variously interpreted within the context of the Pleistocene history of glaciation in Minnesota. This controversy has focused on the origin of the long, linear, hummocky complex of hills that runs diagonally in a northeast-southwest direction across the area, and on the deployment of ice lobes in this part of Minnesota.

This study utilizes detailed stratigraphic descriptions, lithologic comparisons of the various drift units and the spatial distribution of the major geomorphic features to re-interpret the sequence of events that resulted in the formation of this portion of the Alexandria moraine complex. Heretofore, such detail has been generally neglected, despite the numerous implications that have been made over the past centuries concerning the stratigraphy and lithologies of the various drift units.

Location

The Lake Johanna Region, as defined herein, includes portions of Pope, Swift, Kandiyohi and Stearns counties, Minnesota (Figure 1). This region is about 120 miles west-northwest of Minneapolis and 15 miles south of

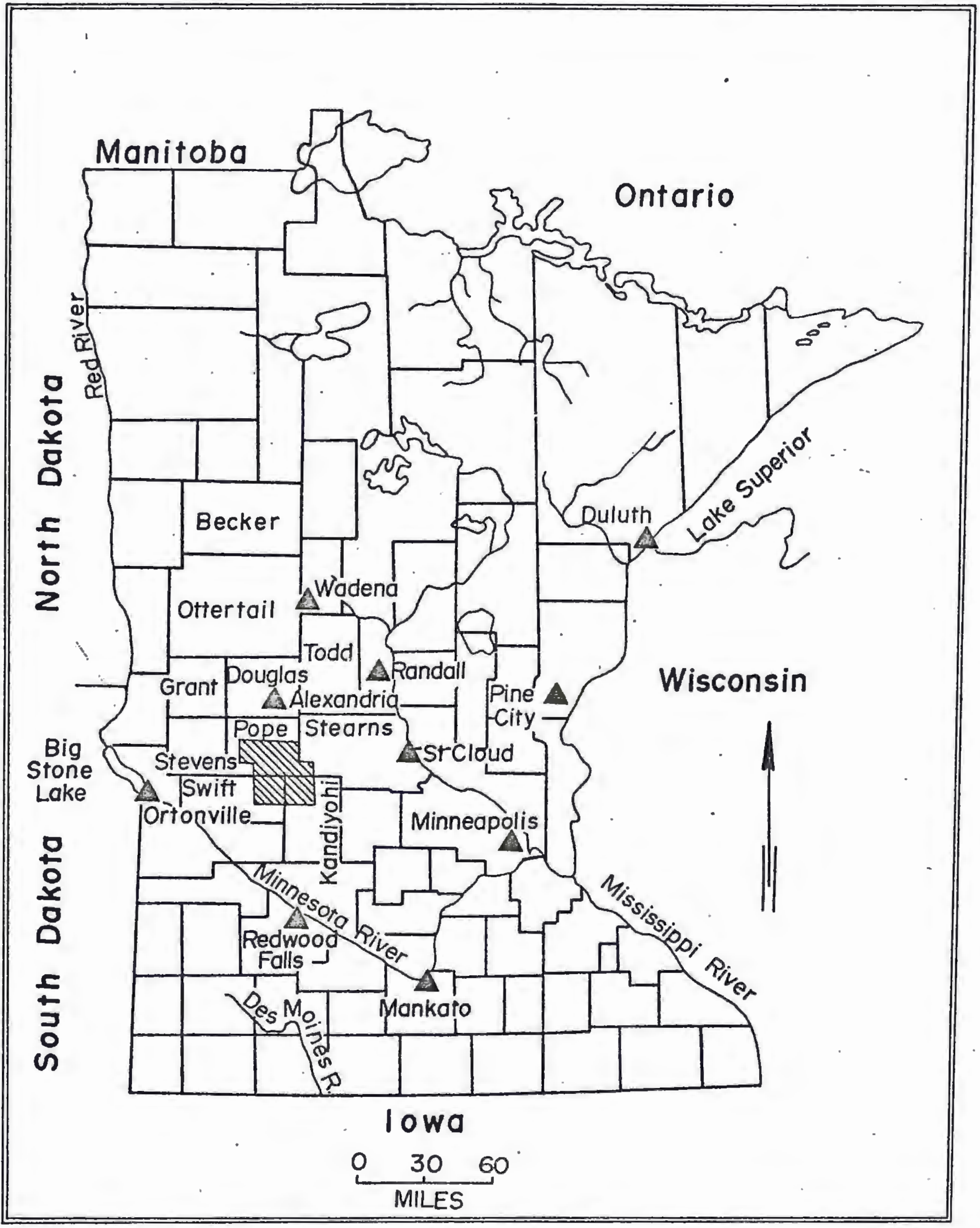

FIGURE # 1 – Index Map of Minnesota showing the location of the Lake Johanna Region

Alexandria. It encompasses an area of approximately 625 square miles.

Field Work

Field Studies were carried out during two months in the summer of 1971. This time was also supplemented by numerous visits to the area during the spring and fall. Surficial deposits were examined in roadcuts, gullies, river banks and borrow pits. The geology was mapped on the 1:24,000 topographic maps for the region issued in 1967 by the U. S. Geological Survey. These topographic maps included the Starbuck, Lake Minnewaska, Terrace, Sedan, Swift Falls, Lake Simon, Lake Johanna, Belgrade, DeGraff, DeGraff S. E., Sunburg and Mount Tom Quadrangles.

Previous Studies

Warren Upham (1888) was the first to describe the Pleistocene geology of central Minnesota. In his work on Pope County, he roughly delineated the main stratigraphic units, and gave excellent, detailed descriptions of the distribution and probable origins of the major geomorphic features. Upham concluded that the complex of drift hills located in the Lake Johanna Region resulted from deposition at the margin of a continental ice sheet that had moved into Minnesota from the north. He believed that two south-moving glacial lobes had entered the state simultaneously, and that eventually the two lobes joined in central Minnesota and more or less flowed as one. The Minnesota lobe moved initially from the Winnipeg lowland south and southeasterly along a course now occupied by the valleys of the Red, Minnesota and Des Moines Rivers. It left a distinctive calcareous blue-grey drift that is readily oxidized to yellow. The lobe from the east followed the Superior lowland into Minnesota and deposited a sandy, reddish drift (Upham, 1888). According to Upham, the belt of rugged topography in western Minnesota, now called the Alexandria moraine complex (Wright, 1962), part of which crosses the Lake Johanna Region, was constructed during various stages in the retreat of these contemporaneous lobes following the last glaciation of Minnesota. Upham envisioned two separate stands of continental ice in the Lake Johanna Region (Figure 2). One he called the sixth, or Waconia stage and the other the seventh, or Dovre stage of a continuous sequence of recessional moraines formed at the margin of the wasting ice sheet. The Waconia moraine supposedly runs from Scandinavian Lake northwest to Glenwood and then curves westerly along the north shore of Lake Minnewaska (Plate 1 and Figure 1). The Dovre moraine runs northwesterly through what is called the Blue Mounds (Figure 19 and Plate 1) and then continues northeasterly through Douglas county (Figure 1) (Upham, 1888).

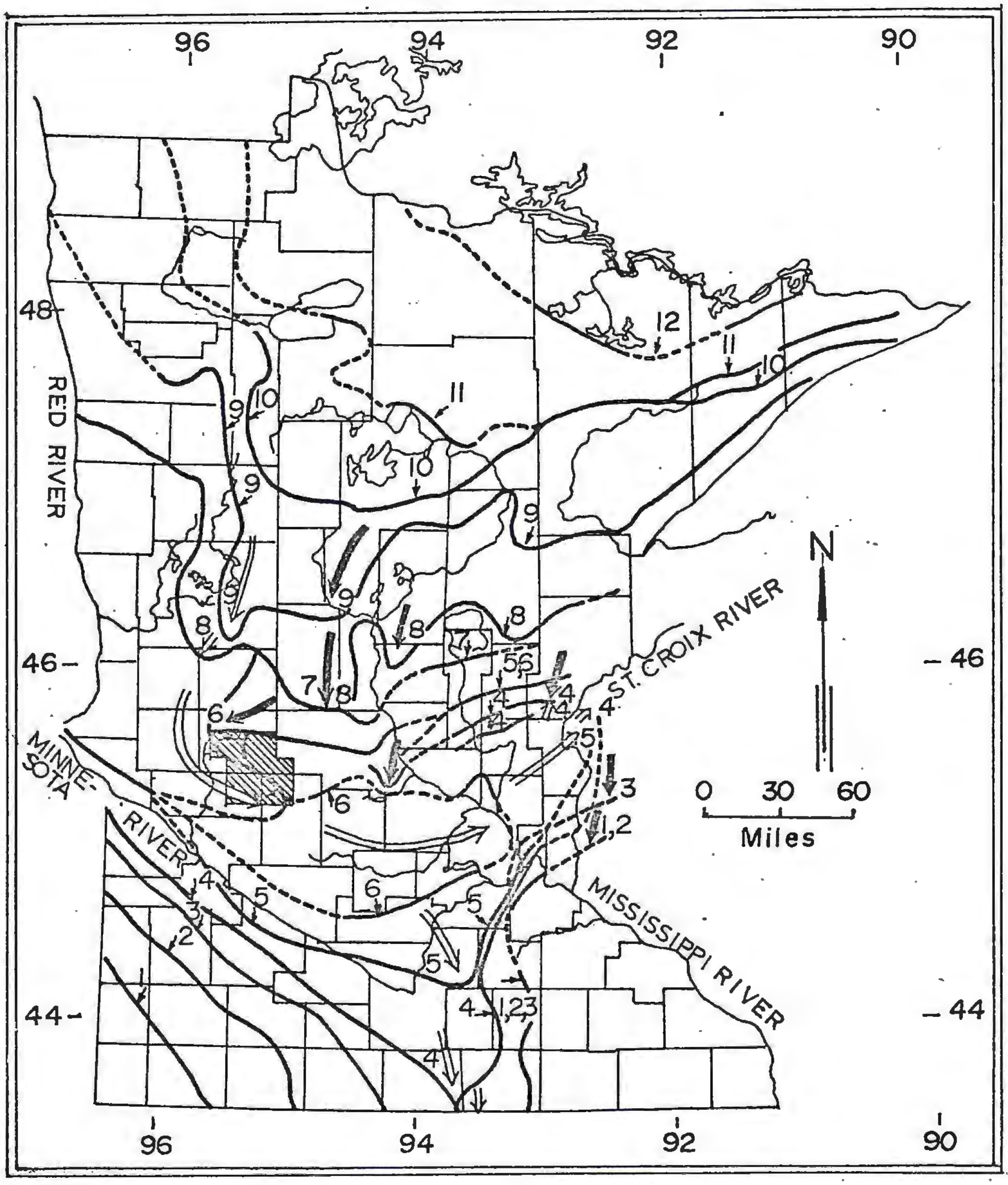

FIGURE 2: Sequence of retreatal moraines of Wisconsin stage in Minnesota according to Upham. Large black arrows show flow direction of eastern ice mass at different moraine stages; large open arrows refer to western ice. Compiled and simplified from Upham (1881; 1896), (In Wright, 1962) and from separate county maps in Winchell and Upham (1888). The moraines were also known by the following names: 1st, Altamont; 2nd, Gary; 3rd, Antelope; 4th, Kiester; 5th, Elysian; 6th, Waconia; 7th, Dovre; 8th, Fergus Falls; 9th, Leaf Hills; 10th, Itasca; 11th, Mesabi; 12th, Vermillion. (In Wright, 1962)

Upham's work implies that with fluctuations in the margins of the two contemporaneous ice lobes, the two drift types became interbedded. Stratigraphically, depending on the relative activity of these two lobes, the red drift of the east would either be above or below the grey-yellow drift of the west.

Leverett and Sardeson (1919) outlined the major drift units of Minnesota and placed them in a generalized framework of Pleistocene stratigraphy. They attributed the morainic system in Pope, Stearns and Kandiyohi counties to glacial deposition on the east side of the south-easterly moving "Keewatin" ice sheet. This ice traveled in a south-easterly direction along the Red River-Minnesota River lowland. The main lobe, called the Des Moines lobe, eventually reached southward into central Iowa. An off-shoot, the Grantsburg sublobe, flowed northeastward from south-central Minnesota into the Minneapolis lowland. Leverett did not find any evidence of the red drift of the earlier Patrician ice sheet in the Lake Johanna Region. This lobe supposedly had its origin on the highlands north of Lake Superior and is stratigraphically beneath the Keewatin grey drift in cental and eastern Minnesota. Thus, Leverett implied that the grey drift in the Lake Johanna Region overlies older unexposed drift that may possibly be pre-Wisconsin in age.

A report by Allison (1932) presented generalized topographic and lithologic descriptions of the surficial deposits in both Stearns and Pope counties. He delineated three major geomorphic features in the Lake Johanna Region: (1) a high plain of outwash sand and gravel extending in a southeasterly direction from Glenwood towards Brooten; (2) a hilly morainic belt consisting of both a sandy and clayey drift that runs through the middle of the region; (3) an outwash plain of sand and gravel associated with the Chippewa River Valley. He made no attempt at a geologic interpretation of these features.

In a later report, Leverett and Sardeson (1932) presented a map of the glacial deposits throughout the state that revised their earlier interpretation of the sequence of the events of the Wisconsin Stage of glaciation in Minnesota. They believed that this glacial stage in Minnesota consisted of two substages: the Middle Wisconsin and the Late Wisconsin. The red drift in the eastern half of the state they attributed to the Middle Wisconsin Patrician ice sheet (Figure 3), while the grey (yellow

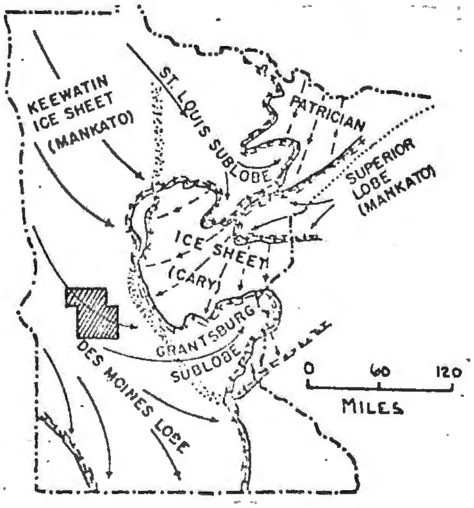

FIGURE 3: Maximum extent of Middle Wisconsin (= Cary) and Late Wisconsin (= Mankato) glaciations in Minnesota according to Leverett (1932; 1939). Arrows show inferred directions of flow. (In Wright, 1962)

where weathered) drift in the western portion of the state they assigned to the Des Moines lobe of the Keewatin ice sheet of Late Wisconsin age.. The Superior lobe of the Labradoran ice sheet was also designated as Late Wisconsin. The Des Moines lobe in their account is essentially the Minnesota lobe of Upham, with the Grantsburg and St. Louis sublobes as appendages. The major Late Wisconsin ice movement followed the Red River-Minnesota River lowland in a southeasterly direction, whereas the Middle Wisconsin lobes originated north of the Lake Superior Region and traveled in a southwesterly direction across the state. Leverett and Sardeson (1932) concluded that the arcuate Alexandria moraine complex formed as a single great recessional moraine (the Altamont-Gary moraine) along the eastern side of the Des Moines lobe. They report little stratigraphic work in the Lake Johanna Region but imply by their work that the Late Wisconsin grey drift in this area should stratigraphically overlie an older drift unit of the Keewatin ice sheet that was designated as belonging to either an extremely late substage of the Illinoian stage or to a pre-Wisconsin, but post-Illinoian stage called the Iowan. This "Iowan" till is the till in the Wadena drumlin field (Figure 4), and according to Leverett (1932) has the composition of typical Keewatin drift. The Iowan ice sheet, like the Des Moines lobe, supposedly followed the Red River-Minnesota River lowland in a southeasterly direction into Minnesota but then was deflected to the northeast into the Wadena area. Leverett and Sardeson found no evidence of Patrician drift in the Lake Johanna Region and concluded that the boundary of the drift formed by this ice sheet lies to the east of the area (Figure 3).

Wright (1962) proposed a drastic revision in the deployment of ice through central Minnesota (Figure 4). As a result of fabric studies on the till in the drumlins located in the Wadena area, he concluded that these drumlins represent ice movement from the northeast rather than from the southwest, as suggested by Leverett (1932). He based this judgement on the orientation and the plunge of the long axes of elongated pebbles in the drumlins. Earlier studies by other workers showed that the orientation of pebbles in both ground moraine and drumlins is parallel to the direction of ice movement and also that the direction of plunge of the stones could be considered as excellent indicators for determining the direction of ice flow (Wright, 1962).

Wright's studies in the Wadena area demonstrated a definite northeast-southwest trend of the long axes of elongate pebbles in the drumlin till and a strong northeast direction of plunge. He concluded, on the basis of these results, that the till in the Wadena

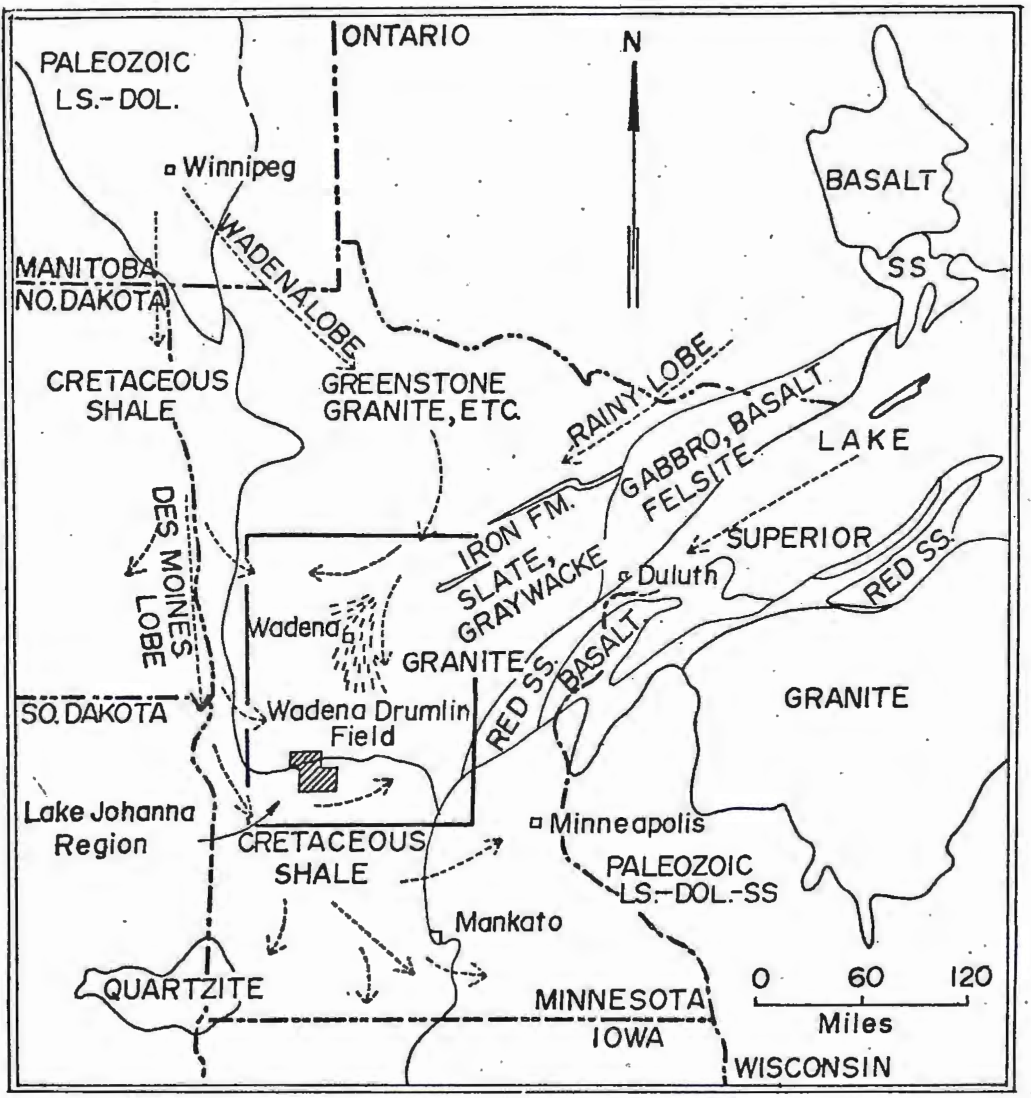

FIGURE 4: Generalized bedrock map of Minnesota and adjacent regions, showing direction of ice movement and rock types important to the identification of the drifts (Wright, 1962).

area was deposited by a sheet of ice that was moving to the southwest rather than to the northeast, as postulated by Leverett (1932). Wright named this ice sheet the Wadena lobe.

Lithologic studies of the till by Wright showed that this ice had moved southeastward into northern Minnesota. Later, he inferred that it was diverted southward by a contemporaneous advance of the Rainy lobe from the east. Wright postulated that this Wadena ice finally terminated on a bedrock upland in and around the Lake Johanna Region. Here the Wadena lobe possibly met the Des Moines lobe that had expanded out of the Red River-Minnesota River lowland. Wright thus believed that the Alexandria moraine was formed near the juncture of the Wadena and Des Moines lobe ice sheets with the core of the moraine consisting mainly of the terminal deposit of the Wadena lobe. The Des Moines lobe drift in the moraine was considered to be a younger cover that blankets the older Wadena deposits. This is in direct contrast to Leverett's theory that the Alexandria moraine was a recessional moraine that was formed along the east side of the Des Moines lobe.

Stratigraphically, according to Wright (1962), the till of the Des Moines lobe should always overlie the drift of the Wadena lobe in the Lake Johanna Region.

The present study was undertaken in order to work out the details of the late glacial history of this area and to attempt to substantiate or revise these previously proposed interpretations.

Acknowledgements

This study was suggested by Dr. C. L. Matsch of the Geology Department of the University of Minnesota, Duluth. The author is grateful to Dr. Matsch for his guidance throughout the project which included several visits to the area, critical inspection of the field occurrences, his many valuable suggestions and a careful critique of the entire manuscript.

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The author is also indebted to the gracious hospitality of Mr. V. Vothauer, Park Ranger of the Glacial Lake State Park near Starbuck, Minnesota, as through his aid, this picturesque setting served as my field camp for the entire field season.

Special thanks also go to Mr. L. M. Ross of the Agricultural Extension Service, University of Minnesota, for his encouragement and helpful advice.

Regional Setting

The Lake Johanna Region lies in the Western Lake section of the Central Lowlands Province which has the general physical characteristics of a young glaciated plain (Fenneman, 1946).

The landscape contains three elements: a rolling ground moraine of low relief to the south, that is separated from an extensive outwash plain to the north by a long, linear, hummocky complex of hills that runs diagonally in a northwest-southeasterly direction throughout the entire area. The linear complex is now interpreted as being a melange of stagnant ice features, including kames, eskers, perched outwash plains and perched drainageways.

The regional slope of the Lake Johanna Region is toward the south and southwest; it comprises the northeast margin of the Minnesota River lowland, a regional bedrock trough that was an important control on glacial ice movements in southwestern Minnesota. The entire area is included in the watershed of the Mississippi River. The area is very poorly drained; the major drainage line is the East Branch of the Chippewa River. The uplands are pocked liberally with sloughs and small lakes. The largest bodies of water are Lakes Minnewaska, Johanna and Andrew, which occupy conspicuous topographic basins that may be the expression of a pre-glacial topography. The maximum relief in the Lake Johanna Region is 375 feet. The lowest point (elevation-1035 feet above sea level) is located along the East Branch of the Chippewa River in the northwestern portion of DeGraff Quadrangle while the highest point (elevation-1410 feet above sea level) is located in the SE1/4, Sec 12, T123N, R37W, Lake Simon Quadrangle.

Bedrock Geology

Bedrock is not exposed in the Lake Johanna Region, because the area is covered by a thick mantle of glacial sediments. Solid granite is reported by water well drillers in both Starbuck and Glenwood at depths ranging from 120 to 300 feet below the surface (Allison, 1932). According to a recent map of the bedrock formations of Minnesota (Sims and others, 1970), the Lake Johanna Region is underlain by a granite-greenstone complex that is Precambrian in age.

Allison (1932) suggested that Cretaceous strata may comprise the lower portion of the high bluffs north of Lake Minnewaska. He noted however, that none of the drill holes south of these bluffs penetrated Cretaceous rocks between the glacial sediments and the granite. In shallow test drilling for hydrologic studies in the Brooten-Belgrade area, Van Voast (1971) encountered no Cretaceous sediments within 200 feet of the surface. If present, the Cretaceous rocks must lie at depths greater than 200 feet.

Pleistocene Geology

The Lake Johanna Region has experienced a complex history of glacial activity during the Pleistocene Epoch. All surficial deposits have been ascribed to glacial depositional events of Wisconsin age. If deposits of older glaciations exist in the region, they have gone unrecognized. Numerous theories have been postulated throughout the past century in an attempt to explain the origin of the drift features found in the Lake Johanna Region. The Alexandria moraine complex is an impressive glacial constructional feature of complicated origin and structure that dominates the present landscape.

PLEISTOCENE STRATIGRAPHY OF THE LAKE JOHANNA REGION

Introduction

Numerous predictions, based on the spatial distribution of various drift types throughout the state of Minnesota, have been made concerning the stratigraphic sequence of drift units in the Lake Johanna Region. Upham (1888) predicted a sequence that would show drift of a northwestern provenance interbedded with drift of a northeastern provenance. Leverett's (1932) interpretation would require the superposition of two tills of the same provenance with the "Iowan-Keewatin" drift being overlain by Keewatin drift of Late Wisconsin age. Wright (1962), on the other hand, predicted that the bulk of the drift in the Lake Johanna Region would be till similar to that in the Wadena region overlain by till of the Des Moines lobe. It should be emphasized that all of these hypotheses were made without the aid of a detailed study of the petrography and the stratigraphic relations of the till units in the area. Field studies reported herein indicate that on the basis of such studies, conducted by the author, two tills of different lithology comprise the greatest volume of sediment in the Lake Johanna Region and furthermore that Wright's hypothesis is supported. Other deposits, in order of importance, are glacial outwash and lake silts.

Methods of Study

The study of the characteristics of the Pleistocene sediments in the Lake Johanna area leading to a stratigraphic interpretation was undertaken both in the field and in the laboratory. The field studies included: (a) general observations concerning the compositon and texture of the sediments; (b) field mapping to show the distribution of the various drift materials; (c) a comparison of the morphology of the different sediment bodies; and (d) sampling of the different drift types. Laboratory analysis of the drift materials consisted of: (a) grain size distribution; and (b) lithologic studies. The lithologic characteristics of the materials were established mainly on the basis of a study of the one to two mm sand size fraction, whereas the results of the grain-size analysis were obtained by standard pipette techniques. See Appendix for a more detailed description of these techniques.

Major Drift Types

Till comprises the greatest volume of sediments and underlies the largest part of the Lake Johanna Region. Outwash deposits ranging from thick bedded boulder gravels to laminated silts make up the remainder of the drift and have a much more restricted distribution. Numerous exposures of Quaternary sediments show a variety of sequences of drift types in superposition. Some of these stratigraphic relationships include: (a) outwash over till, (b) till over till, (c) till over outwash and (d) silt over all of the other sediment types. These relationships provide the key to the glacial history of the region. Although the two till units are both buff and calcareous, they are distinguishable on the basis of rock fragment content and texture.

Tills

Exposures of till are numerous throughout the Lake Johanna Region. Figure 5 is an index map of the area showing the location of all analyzed samples of the various till units. Detailed stratigraphic observations were made at these locations, and a few of the more critical sections are as follows: Sample 14-2 was taken from the south side of a large hill in Glacial Lake State Park, which is located in the SE 1/4, NE 1/4, Sec 23, T124N, R39W, Starbuck Quadrangle (Figure 5). Here a small outcrop of buff, sandy, stony, calcareous, shale-poor till is exposed at the base of a large hill. Lying on top of the till is about 40 feet of sandy, bouldery, cross-bedded and stratified outwash material (Figure 6). Laboratory analysis of this till showed that it contained no Cretaceous shale fragments (see Table 1) and was texturally a sandy loam (see Figure 11). No shale-rich till was found overlying the shale-poor till which suggests that this contact is an erosional unconformity.

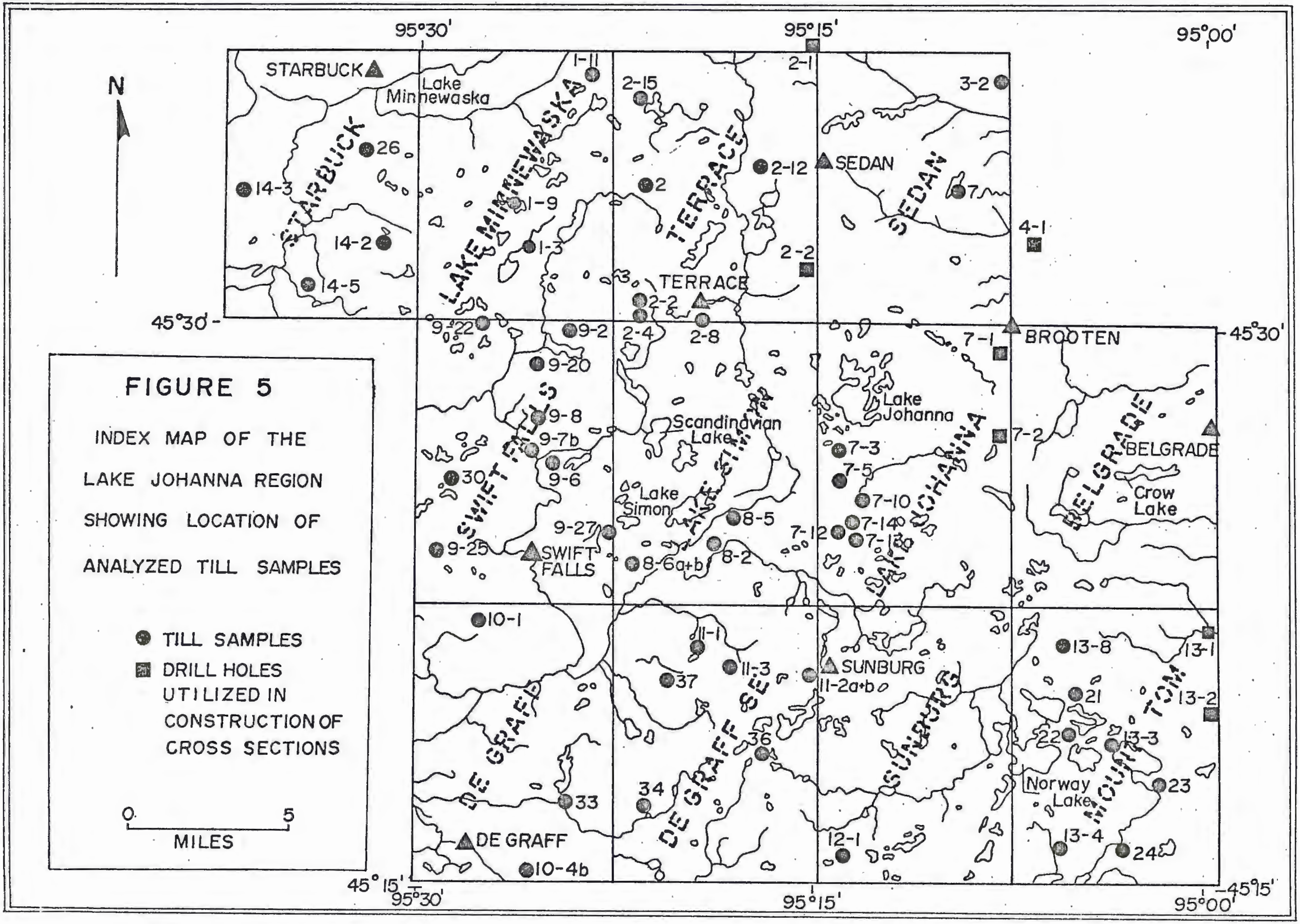


FIGURE 5

INDEX MAP OF THE LAKE JOHANNA REGION SHOWING LOCATION OF ANALYZED TILL SAMPLES

● TILL SAMPLES

▨ DRILL HOLES UTILIZED IN CONSTRUCTION OF CROSS SECTIONS

Location 8-6 is an important multiple till exposure. It is situated on the south side of a large hill a few yards west of Highway 104 in the SE 1/4, NE 1/4, Sec 7, T122N, R37W, Lake Simon Quadrangle (Figure 5). Here a 5 foot section of buff, calcareous, silty till containing abundant Cretaceous shale fragments overlies ten feet of yellow to buff, sandy, bouldery till that is relatively shale-free (Figure 7). No boulder line or soil profile marks the contact between these tills. This suggests that either the time lag between the two phases of ice movement was too short for these features to develop, or the contact is an erosional unconformity. Laboratory analysis of these tills showed that the upper till contained 37 percent shale fragments in the coarse sand fraction, as compared to only 1 percent shale fragments in the lower unit (see Table 1). Texturally the upper till is a loam, whereas the lower till is a sandy loam much like the till found at location 14-2 (see Figure 11).

Location 8-6 was one of the few exposures where the sandy shale-free till was found directly beneath a section of silty shale-rich till, although it was a common occurrence to find small isolated exposures, such as at location 14-2, where the drift was of the sandy shale-free type. Nearly always, such exposures were found where man or natural erosion had carved deep cuts into the overlying shale-rich till.

Sample 7-13 was taken from a large county gravel

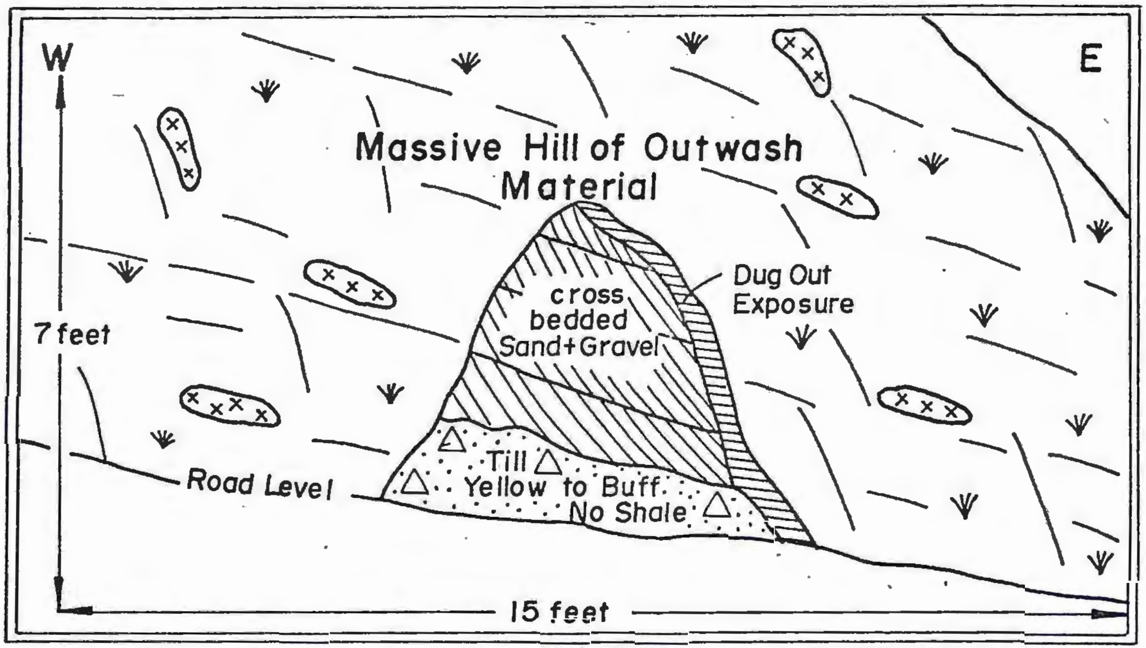


FIGURE # 6 - Diagrammatic cross section of a buried till section in the Glacial Lakes State Park (SE 1/4, NE 1/4, Sec 23, T124N, R39W).

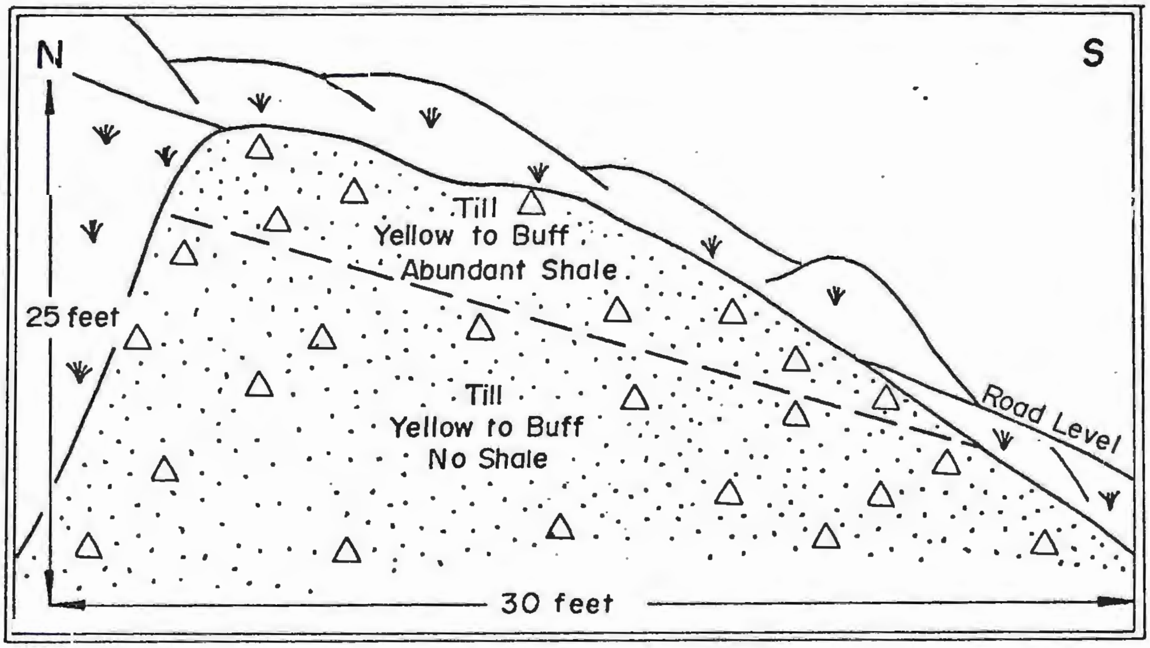


FIGURE # 7 - Diagramatic cross section of a multiple till section S.W. of Lake Simon. (SE 1/4, NE 1/4, Sec 7, T122N, R39W). 7

pit that is 1/2 mile N. E. of Brenner Lake in the NE 1/4, SE 1/4, Sec 5, T122N, R36W, Lake Johanna Quadrangle (Figure 5). Here a 4 foot thick section of yellow to buff, calcareous, sandy, shale-poor till overlies about 15 feet of silt and cross-bedded sands and gravel that contain numerous pebbles, cobbles and boulders of granite, schist and limestone (Figure 8). No evidence of shale particles was found in the outwash material. Numerous slump structures were evident at this outcrop, and it appeared as if the overlying plastic-when-wet till unit had slid over the relatively rigid sand and gravel. This is a common phenomenon, often associated with the till caps. Laboratory analysis of this till showed that it contained 0.5 percent shale fragments (see Table 1) and texturally could be classified as a sandy loam (see Figure 11). Other similar exposures of this "till cap" had extremely variable shale contents that varied from 0.5 up to 47 percent shale (Figure 11). This variability in shale content can be attributed to a dilution effect produced as the advancing ice lobe overrode and incorporated the non-shaley gravels into its sediment load. The shale content of the upper till should then have an inverse relationship to the direction of travel of the lobe of ice (see Figure 13).

Sample 8-5 was taken from a ditch cut on the south side of a small hill in the SE 1/4, SE 1/4, Sec 34, T123N, R37W, Lake Simon Quadrangle (Figure 5). Here a

15 foot section of fine silty material that is largely devoid of pebble and cobble size clasts overlies a 10 foot section of buff, calcareous, clayey, shale-rich till (Figure 9). The entire unit is slumped to the east. An identical unit was recognized about 0.5 miles to the east, but here the slump structure was dipping to the west. To the author, this silt unit could represent the remains of a small proglacial lake. No laminated sediments or wind-faceted pebbles were recognized. Other similar restricted deposits have the same stratigraphic sequence with the silt overlying all other drift units.

In conclusion, it was apparent from field observation that there are two major till types superimposed in the Lake Johanna Region. Four main features characterize the lower till: (1) a high concentration of granitic pebbles (average 61.7 percent); (2) a sandy texture; and (3) a sparsity of Cretaceous shale fragments (average 0.5 percent) (Table 1).

The average textural composition of 9 analyzed samples of this lower till from the Lake Johanna Region is 59.7 percent sand, 29.9 percent silt and 10.7 percent clay.

In contrast, three characteristics of the upper till in the Lake Johanna Region are: (1) a relatively moderate concentration of granitic pebbles (average 43.7 percent); (2) a more silty to clayey texture; and

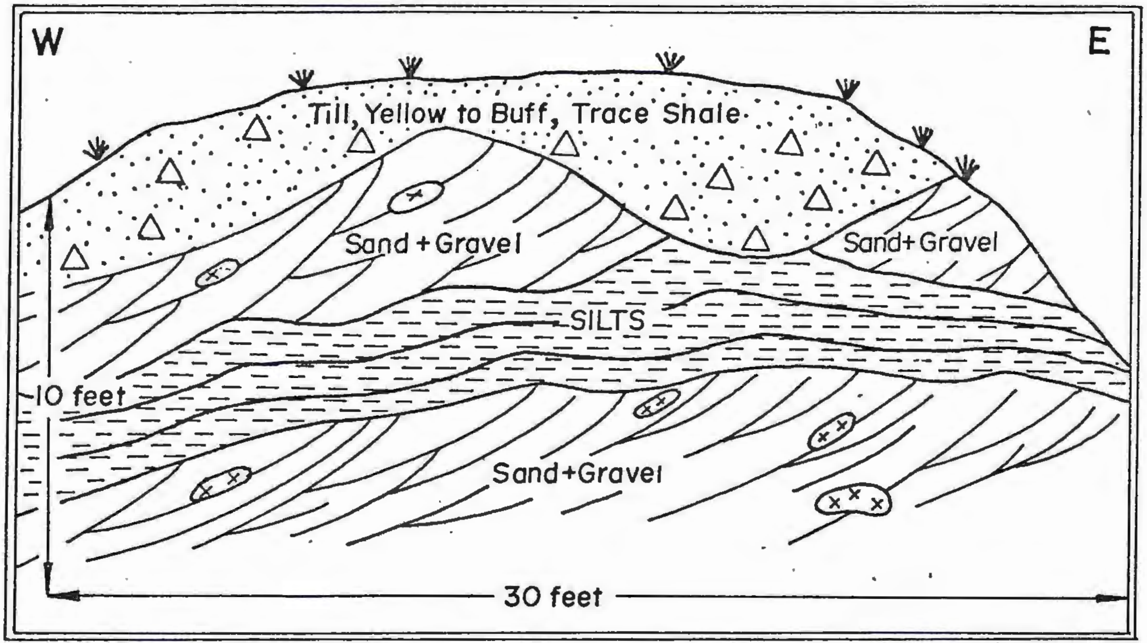


FIGURE #8 – Diagrammatic cross section of a till unit capping a section of outwash material, 1/2 mile N.E. of Brenner Lake. (N.E. 1/4, S.E. 1/4, Sec 5, T122N, R 36W).

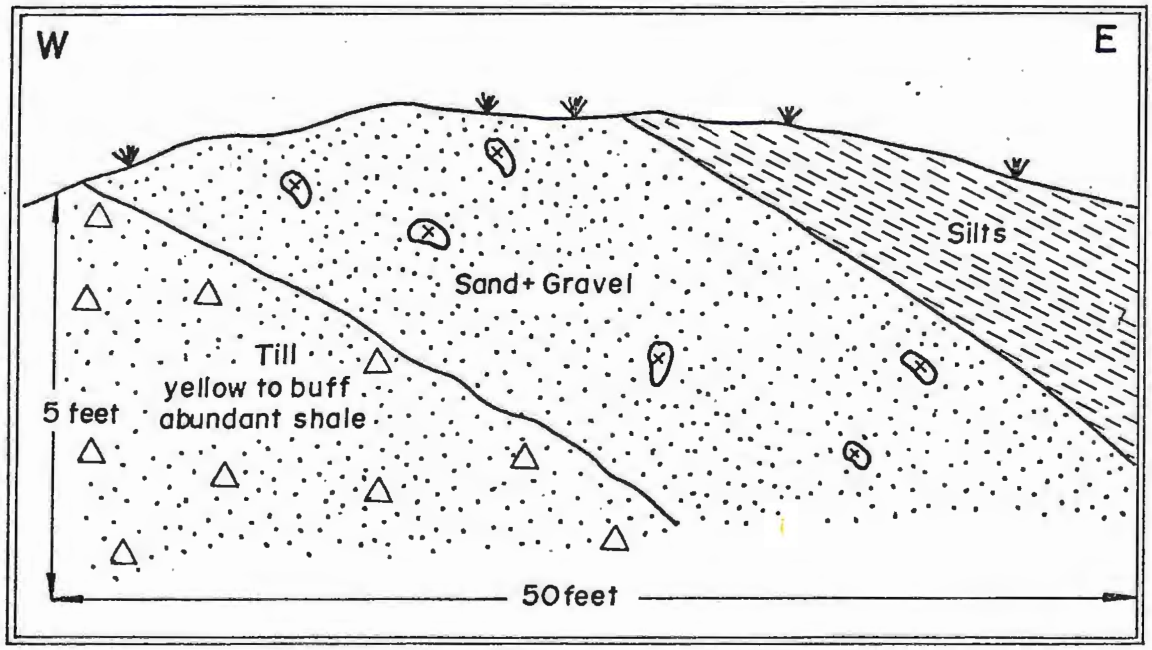


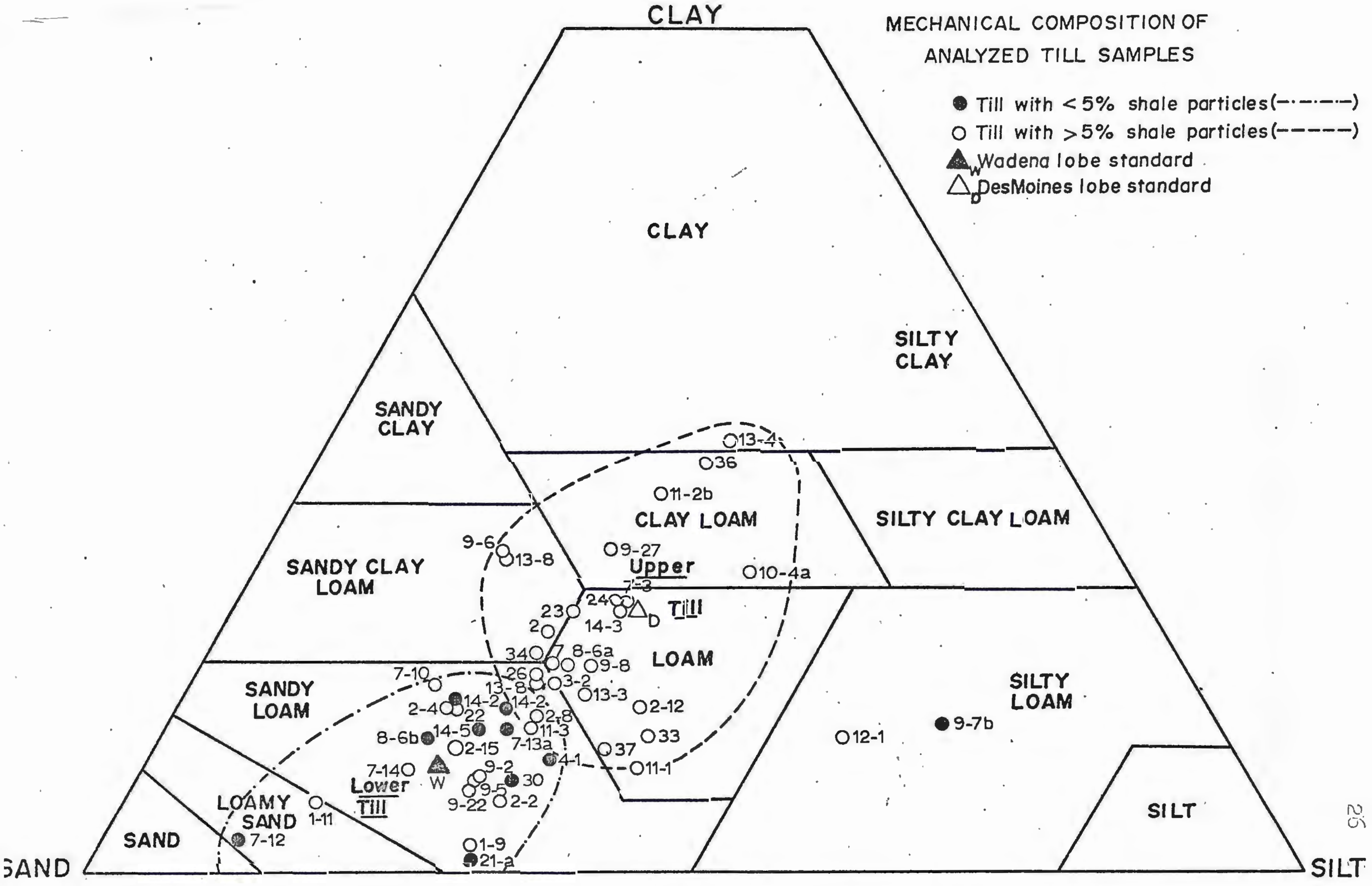
FIGURE #9 – Diagrammatic cross section of a silt unit overlying a section of outwash and till, 1-mile S.E. of Lake Simon (SE 1/4, SE 1/4, Sec 34, T123N, R37W).

FIGURE 10: A four-foot till unit with 28 percent shale fragments capping a sequence of outwash material. (Sample 9-6, NW 1/4, NW 1/4 Sec 26, T123N, R38W)

a high percentage of Cretaceous shale fragments in the coarse sand fraction (average 21.0 percent).

The average textural composition of 37 analyzed samples of this upper till in the Lake Johanna Region is 51.1 percent sand, 29.2 percent silt and 18.7 percent clay.

It should be noted that these differences in characteristics of the two tills could serve as a valuable guide in the field for mapping purposes however, extreme caution must be used as there is some overlap in the data.



MECHANICAL COMPOSITION OF ANALYZED TILL SAMPLES

An interesting diagrammatic separation of the two till units is produced if the results of the mechanical grain size distribution analysis of these two till units are compared with the percentage of shale fragments obtained in the lithologic analysis (Figure 12). Two important trends that are characteristic of the upper till are evident: (1) a high shale content is associated with high clay content and (2) low shale content tends to be associated with sandy texture. The first trend suggests that the clay fraction may be related to the amount of friable shale incorporated into the ice. The second trend may indicate that the decrease in shale might be the result of dilution produced by subglacial erosion of the underlying sandy, shale-free till.

To determine whether regional compositional trends exist in the surface till of the Lake Johanna Region, the percentages of shale fragments obtained in the coarse sand size fraction of the various members of this till were plotted on the index map of the area (Figure 13). There appears to be a systematic decrease in the percentage of shale fragments in the till in a northeasterly direction through the Lake Johanna Region. This trend might well be the effect of progressive contamination as the last ice sheet overrode the older, sandy, shale-free drift.

Outwash

Extensive deposits of outwash cover major portions of the Lake Johanna Region. These deposits, labeled "modified drift" by Upham (1888), generally consist of poorly to well sorted sands and gravels. These deposits contain rock fragments similar to the two tills in the area. They are, hence, buff to yellow, calcareous and contain pebbles, cobbles and boulders of granite, carbonate, Keweenawan types and Cretaceous shale. By means of detailed pebble counts it is possible to distinguish between outwash material that is completely devoid of Cretaceous shale fragments, indicating that it was derived from the lower till, and material rich in shale particles, which indicated that it was derived from the upper till. Stratigraphically, it is often found that the outwash material with sparce Cretaceous shale fragments is capped by a cover of shale-rich till (Figure 8), whereas outwash material rich in these shale fragments is usually deposited on older drift units (Figure 9). The probable intermixing of outwash material from different lobes has resulted in a wide range of outwash lithologies. Both normal and festoon type cross-bedding are present in the outwash material, and they were used to determine directions of current flow where exposed.

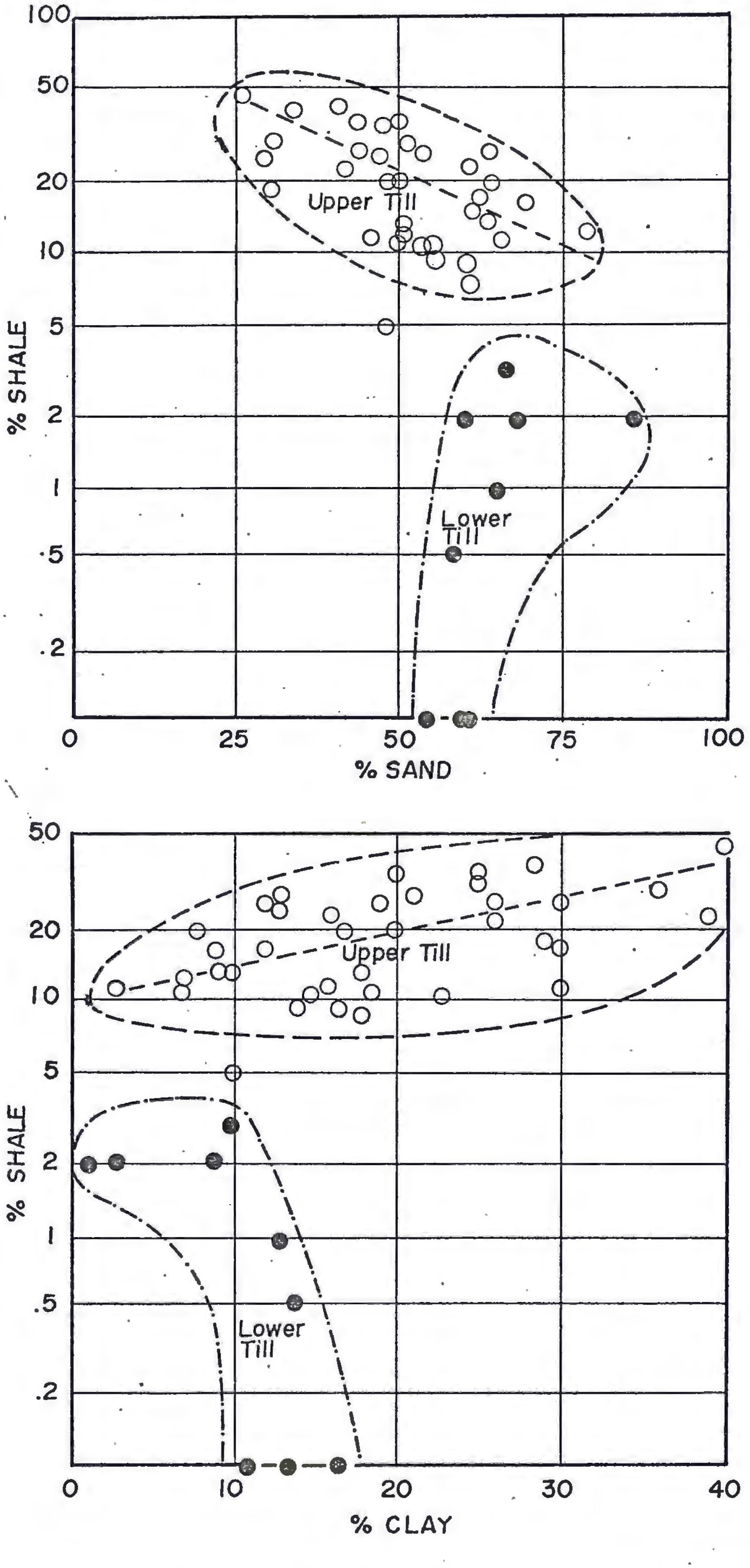


FIGURE # 12 — Relation of percent shale particles to both sand and clay fractions.

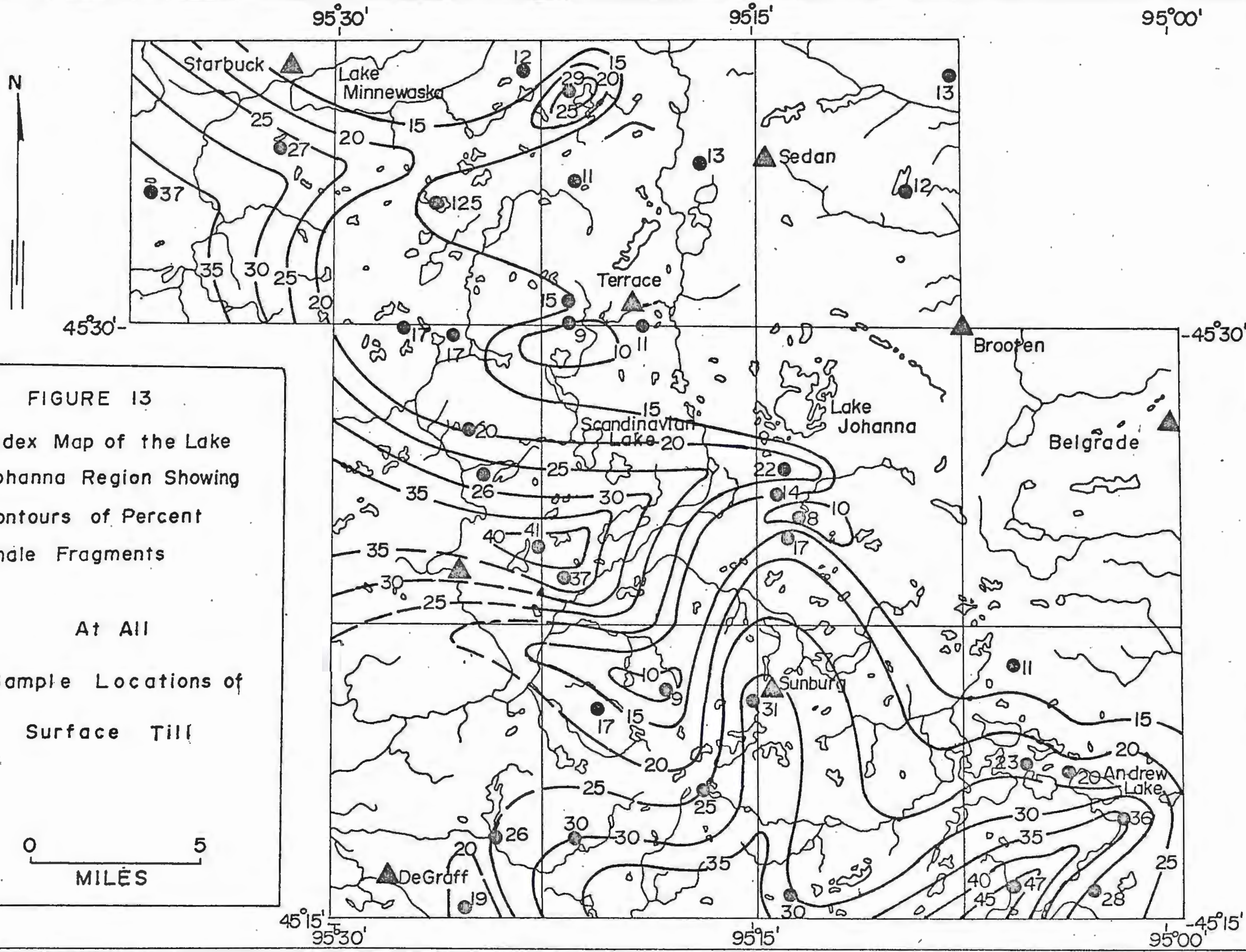


FIGURE 13

Index Map of the Lake Johanna Region Showing Contours of Percent Shale Fragments

At All Sample Locations of Surface Till

Silt

Sizeable deposits of silt are found in restricted areas of the Lake Johanna Region. These deposits are composed of yellow to buff, calcareous, fine, silty, material that is almost completely devoid of clasts in the pebble-cobble size. No wind-faceted stones were found associated with this material. These deposits are interpreted to be lacustrine in origin. Results of size distribution analysis of this silty material show that it has an average composition of 11 percent sand, 56 percent silt and 33 percent clay. Stratigraphically, the lake silts overlie all other drift types (Figure 9). The majority of these sediments lie at near constant elevations however, post-deposition erosion and collapse has modified the original surface of deposition in certain locations.

Summary of Evidence Supporting Multiple Drifts

The Lake Johanna Region is covered by a complex sequence of interbedded glacial sediments. The major drift types are till and outwash. Figure 14 is a series of sections across the Lake Johanna Region showing all stratigraphic units known and inferred to be present in the area. These cross sections were constructed utilizing observable stratigraphic relation-

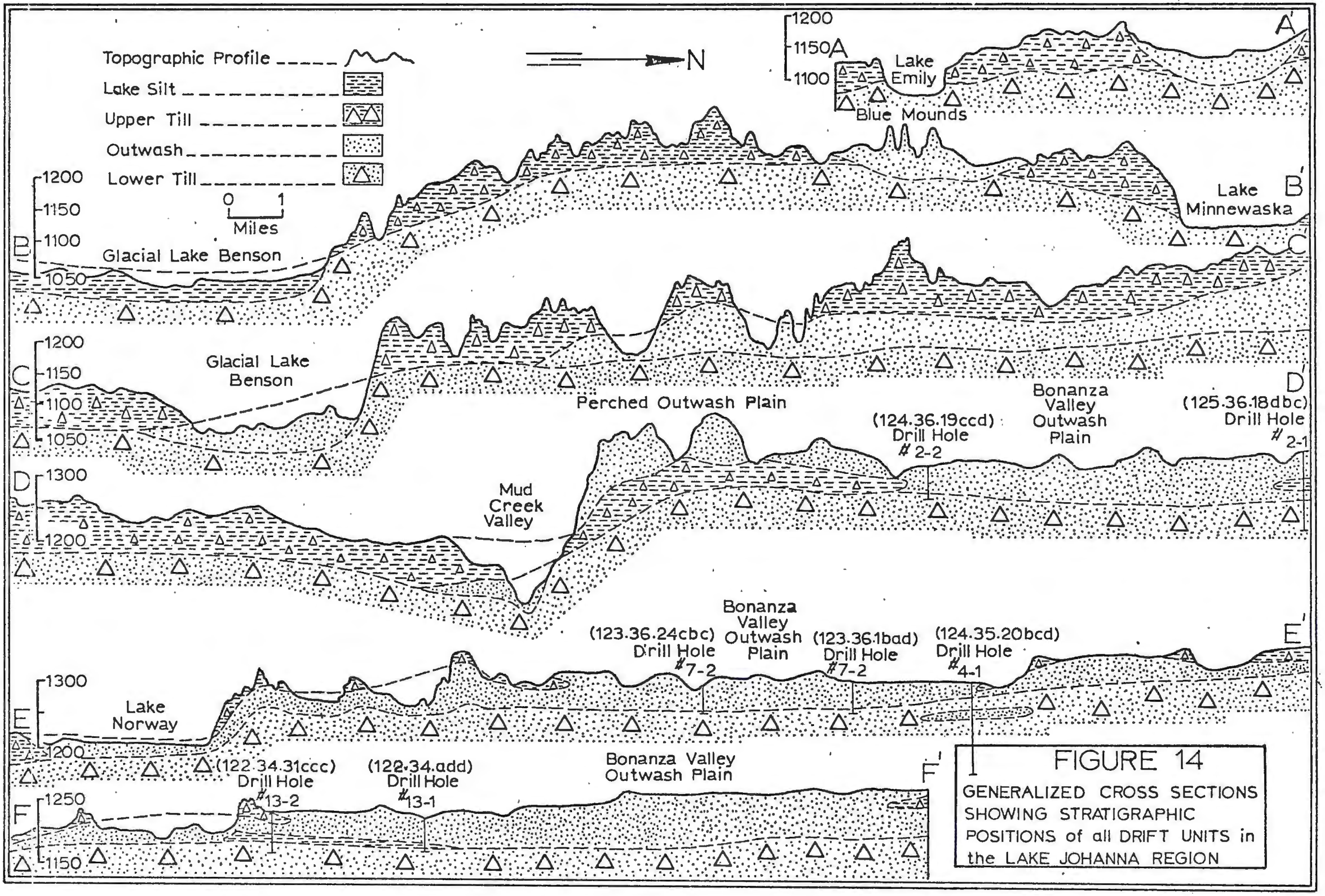


FIGURE 14

GENERALIZED CROSS SECTIONS SHOWING STRATIGRAPHIC POSITIONS of all DRIFT UNITS in the LAKE JOHANNA REGION ships and drill hole data presented by W. Van Voast (1971). The drill hole data has been renumbered for this report to make its presentation less cumbersome so that DH # 2-2 represents Van Voast's DH # 124.36. 19 ccd, etc. Two different till units are distributed throughout the region. The lower till, which lies mainly in the subsurface, is a buff, sandy, calcareous, shale-poor sediment. In comparison, the surface till is a buff, clayey, calcareous, shale-rich unit. Extensive deposits of outwash sands, gravels and silt are found stratigraphically both above and below the shale-rich till.

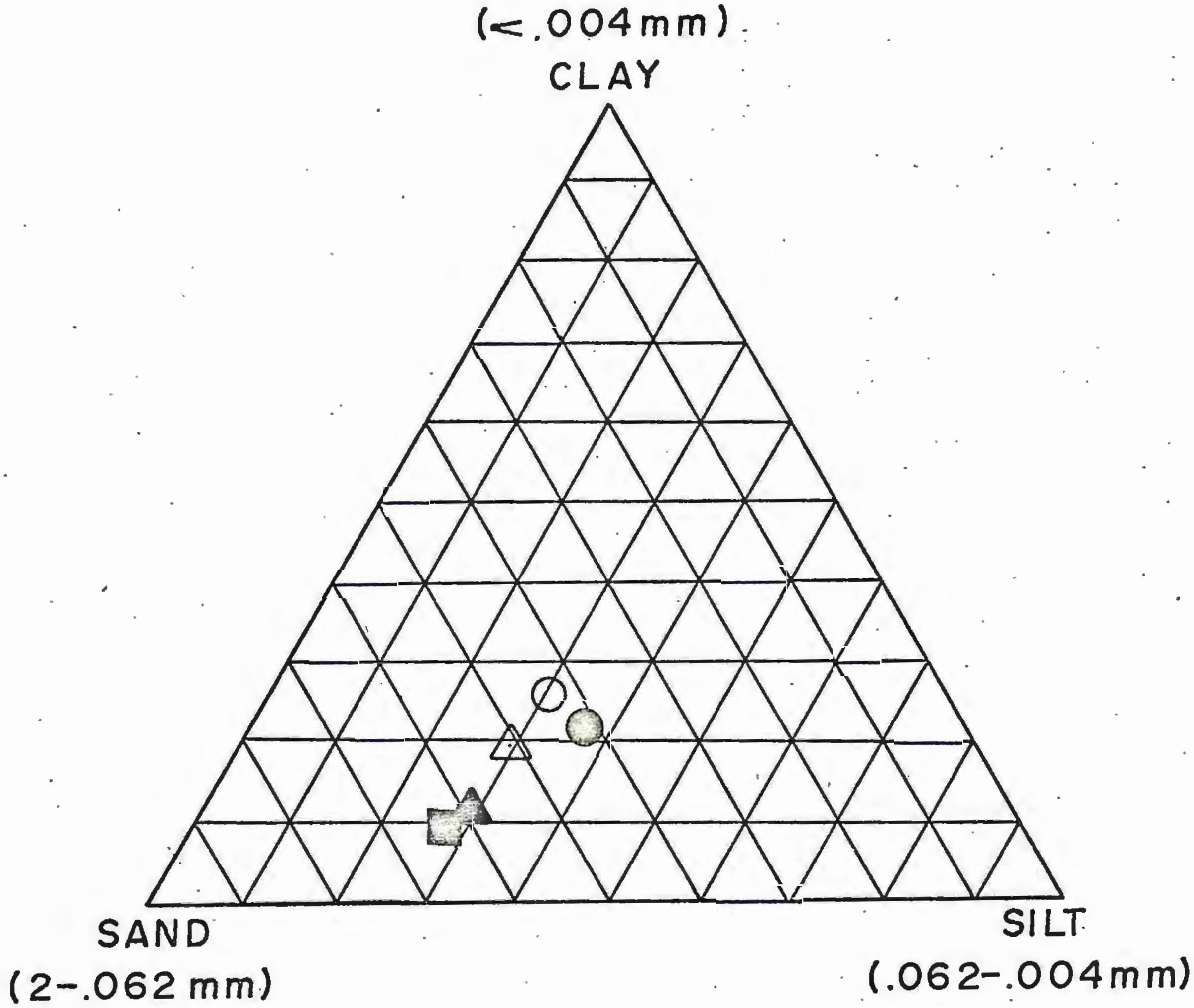
Regional Correlations

Regionally, on the basis of pebble lithologies and grain-size distribution analysis, the two tills of the Lake Johanna Region can be correlated with other tills in western Minnesota.

The lower sandy till of the Lake Johanna Region is similar lithologically to the till exposed to the north in the Wadena drumlin field of Todd county. Wright (1962) described this till as being a buff (yellowish-brown), sandy, calcareous till that contains a high percentage of carbonate pebbles, a variety of granite, metamorphic and mafic igneous rocks, and is shale-free. This till also has, like the lower till of the Lake Johanna Region, a negligible (less than 2 percent) content of rocks such as felsite, red granophyre, basalt, iron formation and red to buff sandstone, considered to have an origin in the Lake Superior Region. Wright (1962) ascribed this till to the depositional activity of the Wadena lobe. Schneider (1961), in his studies of this till, found that the average textural composition was 61.6 percent sand, 25.7 percent silt and 9.5 percent clay (Figure 15).

To the south of the Lake Johanna Region, the sandy lower till is tentatively correlated with the Granite Falls Till described by Matsch (1972). This till is exposed along the shores of Big Stone Lake and is fairly continuous along the valley sides of the Minnesota River to Mankato and beyond. The Granite Falls Till is a yellow to buff, sandy, calcareous unit that is predominately composed of carbonate and granitic rocks with minor amounts of shale (1 to 5 percent) and a few Keweenawan varieties. A younger, shale-rich till is everywhere found on top of it. Mechanical size distribution analysis of the Granite Falls Till shows that it has an average compositon of 41 percent sand, 37 percent silt and 12 percent clay (Figure 15).

The surface till of the Lake Johanna Region can also by correlated with numerous exposures of similar material found throughout a broad region in western Minnesota that was deposited by the Des Moines lobe. Wright (1962) describes this till as a grey (buff



○ New Ulm Till (Matsch, 1970), Ave. of 59 samples

△ Upper Till, Lake Johanna Region, Ave. of 37 samples

■ Wadena Lobe Till (Schneider, 1961) Ave. of 19 samples

● Granite Falls Till (Matsch, 1970) Ave. of 22 samples

▲ Lower Till, Lake Johanna Region, Ave. of 9 samples

FIGURE 15 – Size Distribution Summary of Five Tills in Western Minnesota

where oxidized), calcareous, silty till containing fragments of Cretaceous shale. Matsch (1970) describes numerous exposures of similar till in the Minnesota River lowland as a yellow to olive-brown, calcareous till that contains abundant shale fragments, along with high percentages of carbonate and granitic rock fragments. He named this formation the New Ulm Till (Matsch, 1972). Mechanical size-distribution analysis of the New Ulm Till shows that it has an average composition of 43 percent sand, 30 percent silt and 27 percent clay (Figure 15).

Although the textural differences between the upper and lower tills of the Lake Johanna Region are relatively small, they are consistant with differences in clast compositon and with stratigraphic order in comparison with other known till sheets of regional extent. These three criteria support the assignment of the lower till to the Wadena lobe and the upper till to the Des Moines lobe and thus the conclusions of Wright (1962) concerning the origin and composition of the drift in the Lake Johanna Region have been substantiated whereas, the predictions proposed by both Leverett (1932) and Upham (1888) have been largely negated.

AREAL GEOLOGY AND GEOMORPHOLOGY

Introduction

The surface and subsurface drift of the Lake Johanna Region consists principally of calcareous, buff to yellow till along with a wide assortment of glacial outwash deposits. Two tills are recognized and are distinguishable on the basis of contained percentages of Cretaceous shale fragments, as previously discussed.

Information on drift thicknesses has been gathered from several sources. Upham (1888) cites the location and depths of many wells in Pope county, but all of these wells are too shallow to have reached bedrock. Maximum well depth reported was 37 feet. Considerable data has been taken from Allison's (1932) report on the geology and water sources of Pope, Stearns, Swift and Kandiyohi counties. According to this information granite lies 296 feet below the land surface at the east edge of the town of Glenwood, and at least 225 feet below the land surface 5 miles east of Sedan. Van Voast (1971) presented data from 300 irrigation and domestic wells, 250 power-auger test holes and 3 deep test holes located in the Lake Johanna Region.

Maximum depth drilled was 209 feet with none of the holes reaching bedrock. Due to the thick mantle of glacial drift in the area, it is difficult to determine the role played by a preglacial landscape in the formation of the present topographic profile.

Most of the landforms associated with continental glaciation are found within the Lake Johanna Region. These include ground moraine, crevasse fillings, lacustrine plains, meltwater drainageways, pitted and unpitted outwash plains, eskers and kames. The Alexandria moraine complex, an impressive constructional glacial feature, dominates the topographic profile of the area. The areal geology of the Lake Johanna Region, as mapped by this writer, is shown on Plate 1.

The Alexandria Moraine Complex

The Alexandria moraine complex is a massive arcuate morainic belt that curves northwest and north from southern Stearns county into Becker county, a distance of some 250 miles. This moraine is up to 25 miles wide and is a massive belt of uneven topography which, except for the bedrock highland north of Lake Superior, constitutes some of the higher ground in the state of Minnesota. The Alexandria moraine forms the divide between the Red River-Minnesota River valley and the upper Mississippi River lowland (Wright, 1962). Lithologic and stratigraphic studies on a part of this moraine in the Lake Johanna Region show that it is composed of a mixture of stratified and unstratified drift and in places is a complicated melange of stagnant ice-disintegration features. A complete resume of these features and the processes involved in their formation follows.

Stagnant-Ice Features

The Lake Johanna Region is an excellent locale in which to study the sedimentary features produced in a stagnant-ice environment. The long, linear morainic belt that runs northwesterly through the area (see Plate 1) is marked with many ice-disintegration features. This area includes portions of the Starbuck, Lake Minnewaska, Lake Simon, Lake Johanna, Belgrade and Mount Tom Quadrangles. The Lake Johanna Quadrangle has by far the best examples of the type of topography produced in such a sedimentary regime. The features in the Mount Tom Quadrangle, although characteristic of those produced in a stagnant-ice environment, are more subdued and tend to be elongate to the southeast.

A stagnant ice complex is essentially a slowly rotting or disintegrating thick sheet of ice that for the most part has ceased to move or be replenished by new ice (Flint, 1970). As a result of surface melting, this ice soon becomes veneered by a mixture of outwash and meltout till. Ablation continues until a point is reached where the mantle of debris provides an insulating layer on the ice that shields it from both the sun and warm air currents. This debris cover dramatically slows the rate of ice-disintegration. It can be calculated that if bottom melting due to the geothermal gradient becomes one of the most important sources of heat, it could take thousands of years for a large block of heavily mantled ice to be completely wasted. It is very probable, however, that localized stripping of the debris mantle by slumping, creep, and other forms of mass-wasting results in differential melting.

According to Gravenor and Kupsch (1959), ice-disintegration may give rise to a great variety of landforms. This depends on a large number of factors, including the amount of debris carried by the ice, the position of the debris on, in, or under the ice, the amount of meltwater produced, the rate of melting and the resultant erosion and deposition. The resulting landforms are best preserved only when they represent the last phase of glacial deposition and, thus, are not destroyed by later glacier advances. Gravenor and Kupsch recognize two types of ice-disintegration features: uncontrolled and controlled. Uncontrolled ice-disintegration occurs when the forces that tend to break up an ice sheet are equal in all directions. This produces a field of round, oval, rudely hexagonal or polygonal features that have a general lack of dominant linear trends. In contrast, controlled disintegration occurs along fractures and other lines of weaknesses, and the result is a field of lobate or linear landforms. Both types of disintegration features occur in the Lake Johanna Region. The kames, perched outwash plains and perched lake plains are examples of uncontrolled disintegration features, whereas the perched drainageways, eskers and other linear gravel ridges are examples of controlled features.

Kames

Kames, in general, are conical hills of sand, gravel and till that may have a vertical relief of from 20 to 100 feet. The angle of slope depends on the coarseness of material in the kame. It may reach a maximum of over 30 degrees (Thwaites, 1934). Usually the material in a kame varies from a very bouldery, poorly stratified, poorly sorted gravel to fine, well sorted sand. Slump structures are very common.

In the Lake Johanna Region, the greatest assortment of kames is found in the Mount Tom and Lake Johanna Quadrangles. The largest is approximately sixty feet high. The majority of the larger kames are nearly perfect cones, whereas many of the smaller ones appear to be composite cones that merge into one another (Figure 16). Most of the kames in the Mount Tom Quadrangle are elongate. The kames are composed of poorly sorted, bouldery sand and

FIGURE 16: An elongate or composite kame located in the Mount Tom Quadrangle.

gravel with some till lenses. In most cases the kames are capped by a thin veneer of till which is slumped to one side of the unit.

Flint (1970) states that kames originated in at least two ways. Some are bodies of sediment initially deposited in crevasses and other openings on the surface of the stagnant ice which later melts away, leaving the accumulated sediment in the form of isolated or semi-isolated mounds. Others result from the collapse of deltas and alluvial fans built partially on stagnant ice.

The author believes that the kames in the Lake Johanna Region were produced by a slightly modified version of the first of these two processes. Figure 17 is a diagrammatic presentation of an idealized process and, as shown, there are three major steps. The first is the mantling of the stagnant-ice sheet by a thick cover of englacial debris produced by surface ablation. This sediment dramatically slows down the rate of ice-disintegration. Gradually, localized pockets of melting grow in size, producing fairly large cavities on the surface of the ice into which the surrounding sedimentary veneer slides (phase 2). This slumping immediately produces a new thermal barrier in these cavities, and the melting in these regions is stopped. However, the slump has unroofed new areas,

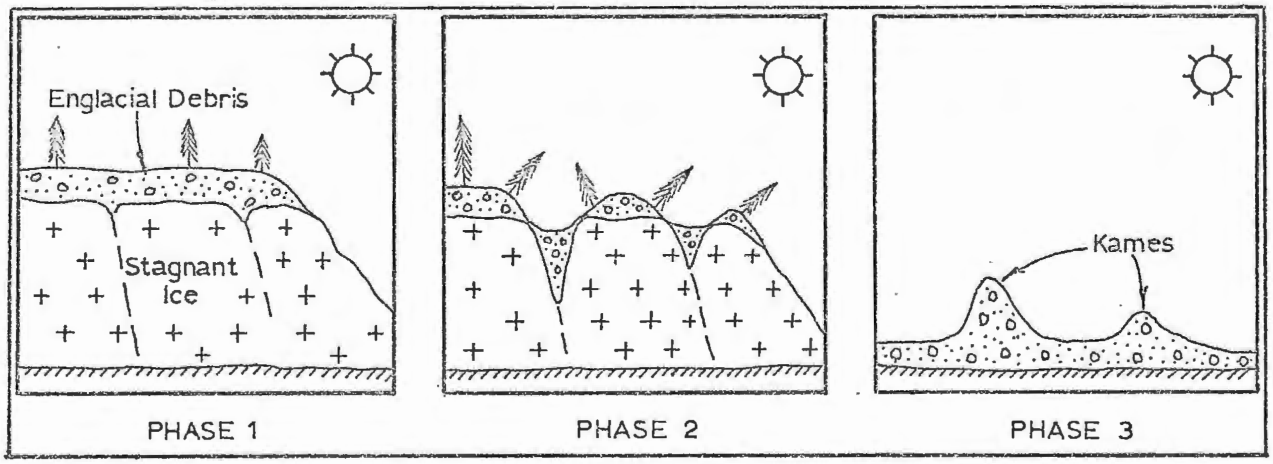


FIGURE 17: Proposed model illustrating sequence of events leading to the formation of kames.

and these become sites for renewed ablation. This process, if uninterrupted, tends to perpetuate itself until the ice sheet is completely wasted. As the process nears completion, the wedges of sediment are lowered onto firm ground and invert to become topographic highs, or cones, whose sides approach the angle of repose for the contained material (phase 3). The surrounding ice-cored areas become lowlands that usually fill with water, producing lakes or swamps. Any renewed ice movement during this process can result in the obliteration or modification of the kames.

The presence of moderately thick (1 to 5 foot) sections of till that cap the tops of numerous kames in the Lake Johanna Region provide a serious enigma to the above process. Lithologically these perched till caps have a composition comparable to Des Moines lobe till as they are moderately clayey and contain a high percentage of Cretaceous shale fragments in the coarse sand fraction. Although the majority of kames in the Lake Johanna Region do have till caps, its absence from some kames is related to slumpage of the plastic-when-wet till off the conical hills into the intervening lowlands. All stages of the development of this de-capping process are observable on the numerous kames of the area.

The formation of a capping veneer of till on a kame would of necessity require two distinct episodes of sedimentation. During the initial episode the proposed "ideal model" is carried through phase one and far into phase two where large quantities of ablation sediment are being accumulated in the cavities and crevasses of a stranded block of stagnant ice. This ice would no doubt be preserved in the remains of a preglacial topographic low. Before this ablation process can be followed to completion, the area is again inundated by a new advance of the continental ice sheet. This advance would completely cover the block of debris-charged stagnant ice which is preserved from destruction by its presence in the topographic low. Ablation of the covered stagnant ice would be completely halted. With a climatic change, the surface ice gradually melts and the block of stagnant ice is unroofed. Once again ablation of this stagnant ice commences however, since this ice block was near the final stages of melting before burial, complete wasting of this ice is quickly achieved. The kames are finally lowered onto firm ground but now they have a characteristic cap of shale-rich till.

Perched Outwash Plains

Another distinctive terrain associated with ice-disintegration is located in the northern portions of the Lake Simon and Lake Johanna Quadrangles (see Plate 1). This geomorphic unit consists of numerous isolated, broad, flat-topped hills that have steep sides reaching a maximum angle of repose of 25°. The hills stand from 25 to 75 feet above the surrounding undulating lowlands. The highest attains a surface elevation of 1390 feet. The largest of the flat-topped hills is approximately one square mile in total area. The flat surfaces display a regional gradient to the north (Figure 18).

FIGURE 18: The southern margin of a perched outwash plain located in Sec 21, T123N, R36W, of the Lake Johanna Quadrangle.

The flat-topped hills are composed entirely of horizontally stratified and cross-bedded sands and gravel containing numerous small boulders, whereas the intervening lowland material consists of a complex mixture of till and gravel. No silt or clay was observed in any of these elevated plains.

Upham (1888) was the first to describe these prominent landforms. He attributed their origin to deposition of outwash in basins that were formed in the melting ice near its margin. The regional slopes of the hills of outwash in the vicinity of Lake Johanna indicated to Upham that the waters had flowed northward, while barriers of ice to the east and west prevented deposition on the adjoining lower land.

The author agrees, in part, with Upham that these features may be the result of northeasterly flowing meltwaters filling in a system of closely-spaced ice-walled basins with outwash material, eventually producing a continuous graded alluvial surface. Each of these basins, however, was for a time a separate entity, being totally isolated from the others by walls of ice which resulted in thinner outwash deposition in the intervening area. This could be compared to the process of completely filling in a plastic egg carton with sand. Eventually both the basins and walls were completely covered with the outwash material producing a uniformly sloping outwash plain however, with the complete melting of the ice, the thicker basin fills were left standing as flat-topped hills, while the areas that were previously topographic ice divides now became extreme lows. These lowlands were sites that received the sediments resulting from localized slumping. This produced the observed complex mixture of till and gravel.

There has also been some question as to whether or not this topography could be caused by post-glacial river dissection of an alluvial plain (these plains are 50 to 70 feet higher than the Bonanza Valley to the north), but the author has discarded this hypothesis, because there is no evidence of an integrated drainage system in the lowlands between the plains. It is also unlikely that such permeable sediments could be dissected to any significant degree.

Schneider (1961) recognized similar forms in his studies of the Randall Region, north-central Minnesota, and it was his conclusion that these plains represent intra-morainic outwash. Due to the absence of concordant crests in the plains of the Randall area (1285, 1350, 1375 and 1420 feet), he suggested that these plains have no special significance and so considered them to be merely randomly arranged depositional features.

Perched Lake Plains

The silty sediment of a perched lake bed is preserved in the southern portion of the Lake Simon Quadrangle in Sections 2, 3 and 35, T122 and 123N, R37W. It covers a total area of approximately two square miles. The lake sediments attain a surface elevation of about 1125 feet. The absence of a continuous planar surface of constant elevation in this unit is evidence of collapse. Silt and clay make up the majority of the sediment in this collapsed lake. The average composition of samples collected of this material is 11 percent sand, 56 percent silt and 33 percent clay. Very little material in the pebble-cobble size range was observed.

The mode of formation of perched lake plains has been well documented (Flint, 1970; Gravenor and Kupsch, 1959). They are the result of silting in of a fairly small lake that sits in a depression on the ice. As this ice basin melts, the lens of lake sediment collapses. Eventually, the ice is completely wasted, and the lake sediments, because of topographic inversion, sit slightly perched above the surrounding moraine. If collapse is not severe, the former lake bottoms retain their flat surfaces.

Perched Drainageways

An unusual stagnant ice feature that is locally called the "Blue Mounds" is situated five miles south of the town of Starbuck in the southeast and southwest corners of the Starbuck and Lake Minnewaska Quandrangles, respectively. This feature is a seven-mile long complex of hummocky mounds and short discontinuous ridges (Figure 19). This ridge complex occupies the center of a long continuous trough system that extends from Lake Emily to Lake Hanson, a distance of some thirteen miles. The material comprising these mounds is mostly cross-bedded sand and gravel containing numerous large boulders, that become progressively finer-grained in a southeasterly direction. No till lenses were observed. The total relief of these mounds ranges from 50 to 100 feet (Figure 20).

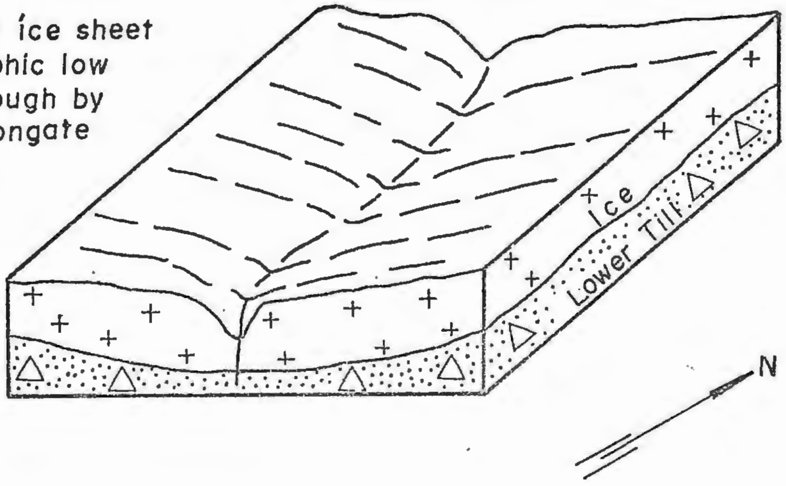
Several theories have been postulated to explain the origin of Blue Mounds. Winchell (1884) attributed its formation to deposition from meltwaters flowing eastward within a trough-like hollow, whose valley sides on the north and south were confluent portions of the ice sheet (In Upham, 1888).

FIGURE 20: Aerial photograph of the Blue Mounds ridge system.

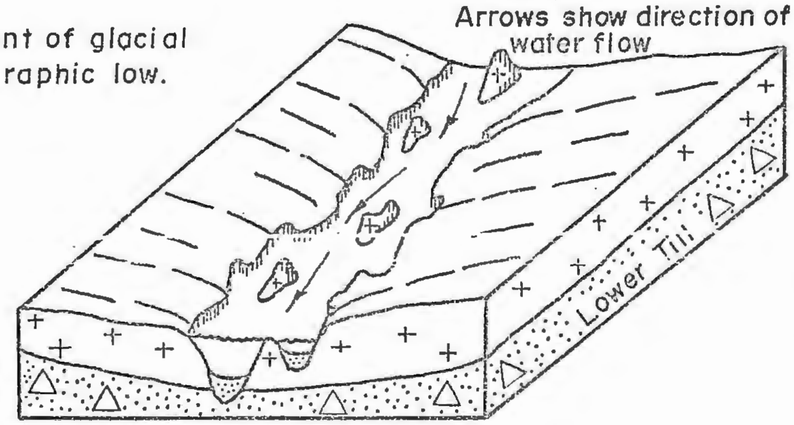
Upham (1888), on the other hand, discounted this theory with the argument that the shortness and the disconnected or irregularily interlocked arrangement of the ridges, along with their variable widths and broken slopes, is not consistent with a normal river regime. He proposed that this unit is a small portion of the terminal or peripheral moraine formed on the northern border of the ice lobe (now known as the Des Moines lobe) which extended from the Red River valley southeastward.

The author, after completing a careful study of the lithology of the Blue Mounds, suggests that Winchell was very near the correct solution. This feature probably represents a restricted river system that flowed on a bed of ice through an ice-walled gorge. As shown in Figure 21, with gradual sediment deposition, the drainage system became clogged with outwash debris and, with a warming trend in the climate, the confining ice walls began to melt. This resulted in a collapse of the once continuous river material, and hence, by the process of topographic inversion the rugged set of hills was produced. From the cross-bedding in the sands, it is evident that the flow of water through the gorge was from the northwest to the southeast. It is possible that the factor that controlled the localization of this gorge was a preglacial topographic low that caused a sag in the overlying Des Moines lobe ice sheet, or an

PHASE # 1 - Sagging of ice sheet over possible topographic low or development of trough by enlargement of an elongate crevasse.



PHASE # 2 - Development of glacial drainage way in topographic low.



PHASE # 3 - Eventual filling in of drainage way followed by complete melting of ice with subsequent inversion of topography.

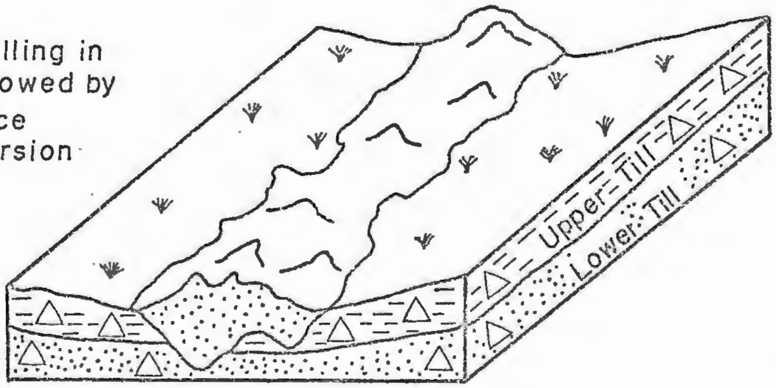


FIGURE # 21 - Proposed model illustrating sequence of events leading to the formation of Blue Mounds.

extensive crevasse system.

Another hypothesis that the author believes has much merit is that the Blue Mounds constitute the remains of an interlobate moraine. An interlobate moraine is formed when two different lobes of the continental ice sheet meet. This mechanism can be closely approximated to the formation of a medial moraine in a valley glacier regime. The juncture between the contemporaneous Des Moines and Wadena lobes may have been either passive or highly active with one lobe overriding the other. Considering the wide distribution of Des Moines lobe till north of the Blue Mounds, this juncture was probably active. The line of confluence between the two lobes may, however, have been later uncovered, and then the two sheets of ice could have shed debris into this area along with considerable volumes of water, which would produce the poorly-sorted, washed sediments. No till would be preserved in this sedimentary regime. Again, the flow of water would be to the southeast.

A final theory is that the Blue Mounds represent the remains of a tremendous esker or tunnel valley system. The very size of the Blue Mounds topographic feature (1 mile wide by 7 miles in length) makes this hypothesis questionable however; eskers have been documented to attain widths of up to 9000 feet and lengths of over 200 miles (Flint, 1970). The sinuosity of the Blue Mounds system coupled with its critical location in the central portion of a topographic trough also lends credibility to the esker theory.

The sharp truncation of the Blue Mounds system at its most northwesterly end may have been the result of post-depositional stream erosion.

Eskers

Eskers are long, narrow, sinuous ridges composed chiefly of stratified material. They range in height from 3 up to 600 feet and in length from less than 300 feet up to more than 250 miles, if gaps which occur in every long esker are included (Flint, 1970). Sides are generally steep, approaching the angle of repose for the sediments in the esker. Crests are smooth or broadly hummocky. Most eskers occur in regions of low relief and generally outline their trends parallel to the direction of flow of the latest of former glaciers. Some eskers are only slightly sinuous, whereas others have great curves that resemble meanders. Often, eskers are compound, having tributaries and braided stream channels.

In the Lake Johanna Region, there is one outstanding area of eskers. This is in Sections 21, 22, 23 and 28, T123N, R36W, of the Lake Johanna Quadrangle. This esker system, as shown in Figure 22, is approximately 3 1/2 miles long and ranges from a height of 80 feet in Section 28 to a height of 20 feet in Section 23,

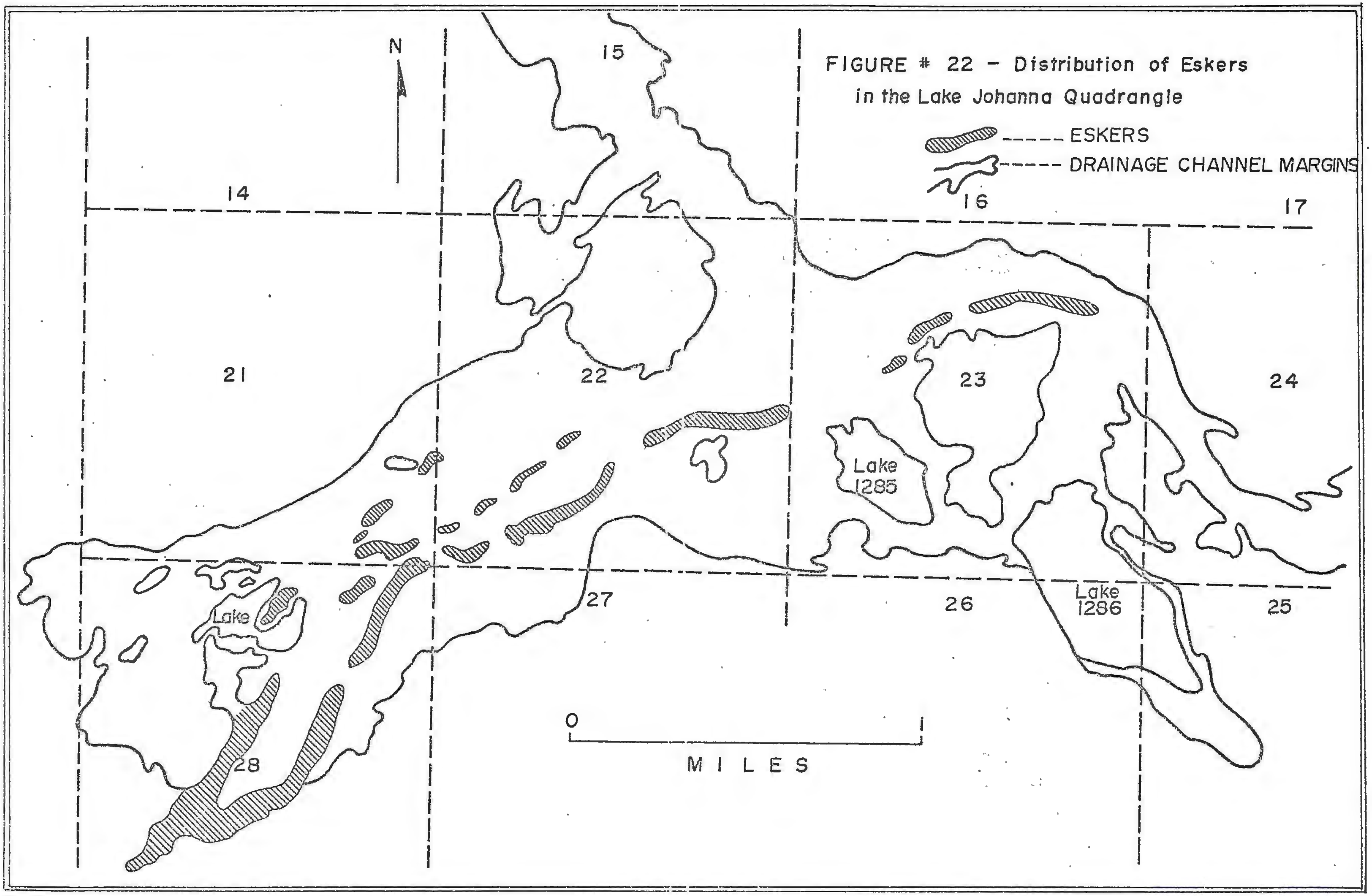


FIGURE # 22 - Distribution of Eskers in the Lake Johanna Quadrangle giving its surface an average slope of 17 feet per mile. The average width of the eskers ranges from 100 to 400 feet. As shown, this esker set consists of numerous intersecting channels that run along the botton of a much larger channel that is from 1/2 to 3/4 miles wide (Figure 23).

FIGURE 23: Aerial photograph of a portion of the Lake Johanna Quadrangle Esker System (Sec 21, 22, 23, 26, 27, 28, T123N, R36W)

The material in these eskers consists of poorly sorted sands and gravel with numerous interspersed boulders. Bedding is generally very irregular and often absent. Stones vary from rounded to subangular.

Eskers are formed in several different ways. The most commonly accepted theory is that they were formed in tunnels, or perhaps open channels, at the base of the glacier during so late a phase in deglaciation that the ice was thin and stagnant (Flint, 1971). It is highly unlikely that these tunnels could form and stay open in a moving, active-ice environment. Eskers drained water produced by surface melting, and this water worked its way through crevasses and other openings to the base of the ice. The lowest possible channelways were sought, which is why the eskers generally occupy conspicuous valleys. These valleys may represent topographic control exerted by the partial remains of a preglacial drainage system. The sinuosity of the esker system would then reflect the maturity of this preglacial drainage system. Wright (1965) disagrees with this last concept in that he believes that the wide valleys ("tunnel-valleys") may represent the maximum size that the tunneled rivers had attained. According to Wright these large tunnels were probably kept open by the extensive erosive and hydrostatic pressures that were exerted on the walls of ice by the enclosed river. With the eventual decrease in velocity of the river, there was no longer enough pressure to hold the ice walls back, and so they crushed inward until only a small stream channel that was rapidly choked with sediment remained in the once massive, eroding river bed. With the melting of all the ice, this small channel is left as a topographic high in an extensive lowland.

Another valid, though less spectacular theory, was proposed by De Geer (1899, in Flint, 1971). He observed that certain eskers in Sweden consist of short segments, each segment beginning upstream with coarse gravel and grading downstream into fine sediments. The coarse upstream part is narrow, but the downstream portion broadens into a distinct delta. He thus concluded that each esker section represents the deposit made during one year, chiefly in the summer ablation season. The short narrow part of the esker was made in a short subglacial tunnel leading to the terminus, beyond which the stream was free to spread beyond the confining walls of the tunnel to build a delta.

The author believes the first theory mentioned best explains the development of the eskers in the Lake Johanna Region. Although segmented, these eskers show no evidence of spreading to form cyclical deltas, and they are more or less continuous through the entire 3 1/2 mile length. The author also postulates that the alignment of lakes extending to the northwest of Crow Lake may represent the eastern edge of the stagnant ice complex. Once free of the ice, the once-tunneled river became an extensive meandering system that debouched a copious volume of sediment onto the outwash plains to the east.

Other Glacial Landforms

Flanking the central morainic complex are various landforms, including ground moraines, outwash plains, glacial drainageways and proglacial lake plains that do not owe their origin directly to the process of ice-stagnation. These features are associated with the retreatal stages of the continental glaciers and, hence, are due to normal ablation processes rather than massive ice stagnation.

Ground Moraine

Ground moraine, as defined by Flint (1955), is moraine having low relief devoid of transverse linear elements. It forms undulating plains marked by gently sloping swells, sags and depressions with an apparently random pattern. Local relief usually amounts to less than 20 feet. The chief material comprising ground moraine is till, mainly lodgement till, but in some areas ablation till as well.

Ground moraine is exposed in the extreme southern and southwestern portion of the Lake Johanna Region and is classified on Plate 1 simply as till. In the De Graff, De Graff SE, Sunburg and Mount Tom Quadrangles the ground moraine has very low topographic relief and is restricted entirely to low, rolling mounds. Here the moraine is composed entirely of shale-rich till and is extremely fine-textured, having a clay content of up to 39 percent. Farther to the north, this ground moraine blankets older till of the Alexandria moraine complex, and because of the later collapse of the complex, the landforms are very choppy. The ground moraine also becomes much sandier. A few isolated patches of ground moraine composed of shale-rich till are found in the northeast portion of the Lake Johanna Region (see Plate 1), indicating that the Des Moines lobe extended northeast of the study area.

According to Flint (1971), ground moraines can be composed of either lodgement or ablation till. Lodgement till is deposited from the base of a glacier. Pressure melting of the flowing ice frees drift particles and allows them to be plastered, one by one or in aggregates as layers, under pressure onto the subglacial floor and there lodged in the accumulating drift. No size sorting is involved, but stones tend to lodge with their long axis parallel to flow. The till is thus compact with a definite fissile structure. Under this mechanism, given enough time, great thicknesses of till could be built up.

Ablation till, in contrast, is deposited from drift in transport upon or within the terminal area of a melting glacier (Flint, 1971). As the ice melts inward, this drift slides, flows, is dumped, or subsides onto the ground. The resulting till is loose, noncompact and there is no preferred orientation of the long axis of the pebbles. Unlike lodgement till, ablation till consists only of the load of debris carried by the ice at the time of ablation, and, hence, is likely to be thin.

This author believes that the sandy, shale-free, lower till in the Lake Johanna Region may be ablation till deposited by the Wadena Ice Sheet, whereas the clayey surface till may, in contrast, be lodgement till of the Des Moines lobe. The lower till is characteristically noncompact, fairly sandy and nonhomogeneous while the upper till is fairly homogeneous, and extremely compact. More work is needed to verify these observations.

Bonanza Valley Outwash Plain

Extensive deposits of outwash material cover an area of approximately 250 square miles in the northeast portion of the Lake Johanna Region. These deposits form a graded surface that covers major portions of the Terrace, Sedan, Lake Johanna, Belgrade and Mount Tom Quadrangles (Plate 1).

The outwash consists of thick deposits of stratified and cross-bedded gravel and sand. Minor amounts of silt and clay are present, but they are largely restricted to the southwest edge of the outwash plain (Van Voast, 1971). Test drilling in this plain (Van Voast, 1971) has shown that, locally, this outwash material reaches a thickness of 100 feet.

Generally, these outwash sediments underlie a low featureless plain (Figure 24) that is broken only by the abandoned channels of two meandering meltwater river systems. The plain has a regional gradient towards the southeast. The average slope is approximately five feet per mile and grades from a maximum elevation of 1350 feet above sea level north of the village of Sedan to a minimum elevation of 1230 feet in the northeast corner of the Mount Tom Quadrangle. The plain also has, imprinted upon this major regional gradient, a minor localized slope along its southwest edge that grades to the northeast away from the centralized linear stagnant ice complex. The channels of the two abandoned rivers follow this localized slope in a northeasterly direction into the plains.

Leverett (1932) postulated that this outwash plain was produced when the southeasterly advancing Des Moines lobe blocked a pre-existing southward drainage system, causing ponding along the northeastern flank of the ice, which resulted in the subsequent deposition of silt and clay interbedded with outwash sand and gravel in the old drainage system. In the early stages, most of the

FIGURE 24: A typical portion of the Bonanza Valley outwash plain (Belgrade Quadrangle).

incoming waters flowed southward along the ice face, but as deposition continued and sufficient outwash and lake deposits had accumulated this outlet was blocked. This caused drainage in the northern area to be reversed, and hence, the meltwaters flowed northward.

Since the two major river systems that cross these plains originate from the southwest and are then eventually deflected to the east-southeast, the author believes that much of the outwash material was derived from the stagnant ice in the Alexandra moraine complex.

Possibly, rivers from the north also contributed outwash material, but due to the lack of obvious drainage lines in this direction, the author concludes that the amounts added were of little importance. It is also possible that a portion of the 100-foot plus accumulation of outwash material needed to fill this pre-existing channel system was derived from the Blue Mounds sluiceway. Although only scanty remnants of an integrated drainage system connecting the Blue Mounds to these plains can be found along the northern margin of the stagnant ice complex, it is very possible that collapse and local slumping has largely obliterated such evidence.

Glacial Drainageways

Numerous "dry" channels representing the remains of extensive meltwater drainage systems are widely spread throughout the Lake Johanna Region (Plate 1). These channels provided the major exits for waters accumulating from the melting of the ice sheets. All sediment deposition associated with the filling in of these drainage lines consists of stratified, well sorted sands and gravels. Gravel-pit developers have fully recognized these characteristics and are constantly utilizing this material.

Two major abandoned stream systems are clearly recognizable in the Lake Johanna Region:

(1) those rivers that once drained northeast into the extensive Bonanza Valley outwash plains to the north of the central morainic complex; and (2) those that drained southwest into the Glacial Lake Benson and Lake Emily basins. Comparing the forms of the rivers in these two systems it appears that the rivers draining northeastward were in a much more well developed system than those flowing to the southwest. The northeastward-grading channels display meander patterns.

The Lake Emily-Lake Minnewaska drainage system is a notable exception to the above generalization about stream province, as it may have derived its waters from a massive block of stagnant ice that had occupied the Lake Minnewaska basin. Excellent exposures of a massive, well-stratified, almost varve-like accumulation of silt, sand and clay are found in the Starbuck gravel pit, which is located in the SE 1/4, Sec 23, T12~~5~~4N, R39W, Starbuck Quadrangle. This pit is on the southern flanks of an extremely high scarp of outwash material that runs along the north shore of Lake Minnewaska. This perhaps suggests that the outwash is associated with meltwaters that drained northward away from the ice-clogged lake basin in an extensive braided river system. Eventually, after melt-out of the stagnant ice block, water was diverted to the west along this topographic trough, producing the present system of drainage lines.

Presently, the Chippewa River which is associated with the Glacial Lake Benson-Lake Emily stream system, is the only active drainage system in the Lake Johanna Region. This river normally has a maximum width of approximately five feet and, fills the the 3/4-mile-wide channel in which it flows only at peak flood stages. This grossly underfit river is dramatic evidence, attesting to the great volume of water liberated during the ablation process of the central stagnant ice complex.

Lake Plains

A large proglacial lake occupied a major portion of the De Graff Quadrangle in the southwestern portion of the Lake Johanna Region (Plate 1). This glacial lake is known as Glacial Lake Benson (Matsch and Wright, 1966), and it covers a total area of 35 square miles in the study area, and has a total area of about 1500 square miles. The highest shoreline of Glacial Lake Benson was approximately 1050 feet above sea level. The floor has a regional gradient towards the southwest. Generally, this lake plain is flat and relatively undisturbed, although it has been slightly dissected by post-glacial erosion by the east branch of the Chippewa River. The material comprising this unit is clay and silt; however, it does get notably coarser in the northeastern extremities because of deltaic sedimentation.

The origin of Glacial Lake Benson is intimately related to the wasting process of the Des Moines lobe from the Minnesota River lowland (Matsch and Wright, 1966). As the ice melted to a position at the Big Stone moraine north of Ortonville, Minnesota, a fairly large lake basin was uncovered. This basin stretched from Ortonville nearly to Redwood Falls, a distance of approximately 75 miles. The outlet of this basin was over an ice-cored moraine near Redwood Falls. A broad, shallow bay of this lake reached eastward beyond Benson into the Lake Johanna Region. Here meltwaters liberated from the stagnant ice complex were also ponded in this shallow basin. The sands and gravels in the eastern portion of this lake may represent deltaic deposits that were produced as high energy channels funneled their sediment-laden waters into this low area of deposition. Perhaps the Blue Mounds sluiceway contributed a major portion of these waters.

QUATERNARY HISTORY OF THE LAKE JOHANNA REGION

Introduction

An interpretation of the glacial history of the Lake Johanna Region is shown in Figures 25 to 27, and is discussed below. Each phase portrays the formation of the major geomorphic and stratigraphic units that were recognized in the study area. Moraines, meltwater channels, outwash plains, perched drainageways, proglacial lakes, perched outwash plains and numerous other features were used to establish successive positions of the various ice sheets and also the nature of the ice retreat during each episode. Only the events of the Wisconsin Stage of the Pleistocene Epoch are discussed; no evidence is known to exist in the area to attest to its earlier Pleistocene history.

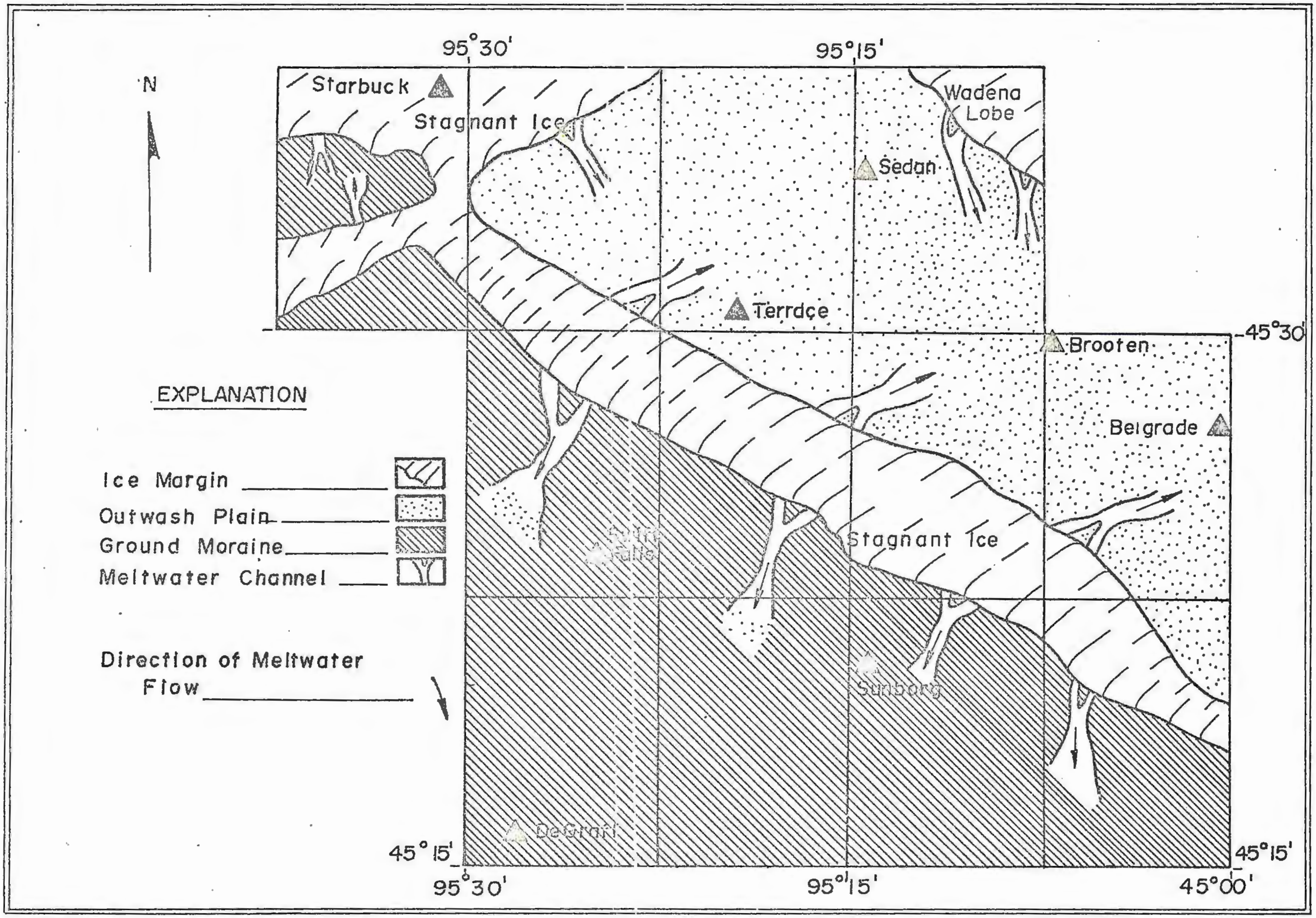
Phase One

In the first phase the Wadena lobe flowed from its source in the Winnipeg lowland into central Minnesota in a south-southeasterly direction to its final terminus south of the Lake Johanna Region. This ice sheet, as far as the author can determine, completely covered the study area. Because its path crossed central Minnesota, this lobe incorporated into its sediment load material from Minnesota's granite-greenstone basement complexes; the load was already highly charged with Paleozoic carbonate rocks from central Manitoba. Little or no material from the Upper Cretaceous Pierre Formation, which is a distinctive greenish-grey shale, was incorporated into this ice, because the main flow was east of the Pierre outcrop belt. The Wadena ice sheet thus deposited a buff to yellow, sandy, calcareous, shale-poor till as ground moraine throughout the Lake Johanna Region.

Phase Two

The edge of active Wadena lobe ice now retreated back across the region to a position to the northeast of the study area (Figure 25). The glacier left in its retreat a massive block of dead ice in an elongate northwest-southeasterly trending topographic low. This low trend was possibly the remains of a pre-Wisconsin drainage system. With partial melting of this ice block, extensive deposits of outwash material were swept to the north and south of the centralized ice mass. Subsequent mantling of the ice with melt-out debris eventually stalled the ablation process.

In the north, the margin of the Wadena lobe continued its retreat back through Minnesota, leaving a complex mixture of outwash material and ablation till.



FIGURE#25: PHASE 2 OF GLACIAL HISTORY

According to a radio-carbon date on wood from silts above the Wadena lobe drift, a tentative date of greater than 40,000 years has been set for the deposition of the Wadena lobe material (Wright and Ruhe, 1965). It is noted by Wright, however, that on the basis of the topographic expression and the shallow weathering profile, the Wadena lobe till should be younger than the radio-carbon date suggests, so additional dating is required.

Phase Three

The Lake Johanna Region, including the buried stagnant ice complex, was then inundated by an advance of the Des Moines lobe. Like the Wadena lobe, this ice sheet originated in the Winnipeg lowlands area, but instead of traversing the central portion of the state of Minnesota, it was funneled down through the Red River-Minnesota Valley lowland to its final terminus in central Iowa. The Des Moines lobe material in the Bemis moraine in Iowa has a well controlled date of 14,000 years (Wright and Ruhe, 1965). The Des Moines lobe crossed the eastern edge of the shaly Cretaceous Pierre Formation and hence deposited in the Lake Johanna Region a ground moraine that is a buff to yellow, calcareous, clayey, shale-rich till. Ice movement in the Lake Johanna Region was probably in a southeasterly direction cutting across the valley axis at a low angle towards the east. This trend changed regionally to the east-northeast as the Grantsburg sublobe protruded from the main lobe into the Minneapolis lowland to its final terminus near Pine City, Minnesota. This phase of the Des Moines lobe has a radio-carbon date of 12,700 to 11,800 years (Wright and Ruhe, 1965).

Phase Four

With wasting of the Des Moines lobe which was probably thin, the Bonanza Valley system was freed of ice and the buried Wadena ice again began to melt (Figure 26). Renewed differential melting in the complex produced a ponding of waters in numerous small proglacial lakes located along the northeast margin of the stagnant ice. Southerly drainage of ponded waters liberated from the quickly melting Des Moines lobe in the northwestern portion of the area poured through an ice-encased gorge south of Starbuck (The Blue Mounds Sluiceway) along a drainage line produced by a crevasse system or a sag in the now thin continental ice sheet overlying the long, linear topographic low shown in Figure 25. These waters probably contributed outwash material to the Bonanza Valley system and to the restricted proglacial lakes, but due to their small size, these lakes were quickly filled in. Most of this water drained off the ice in a southerly direction into Glacial Lake Benson, which occupied a relatively low-lying area already freed

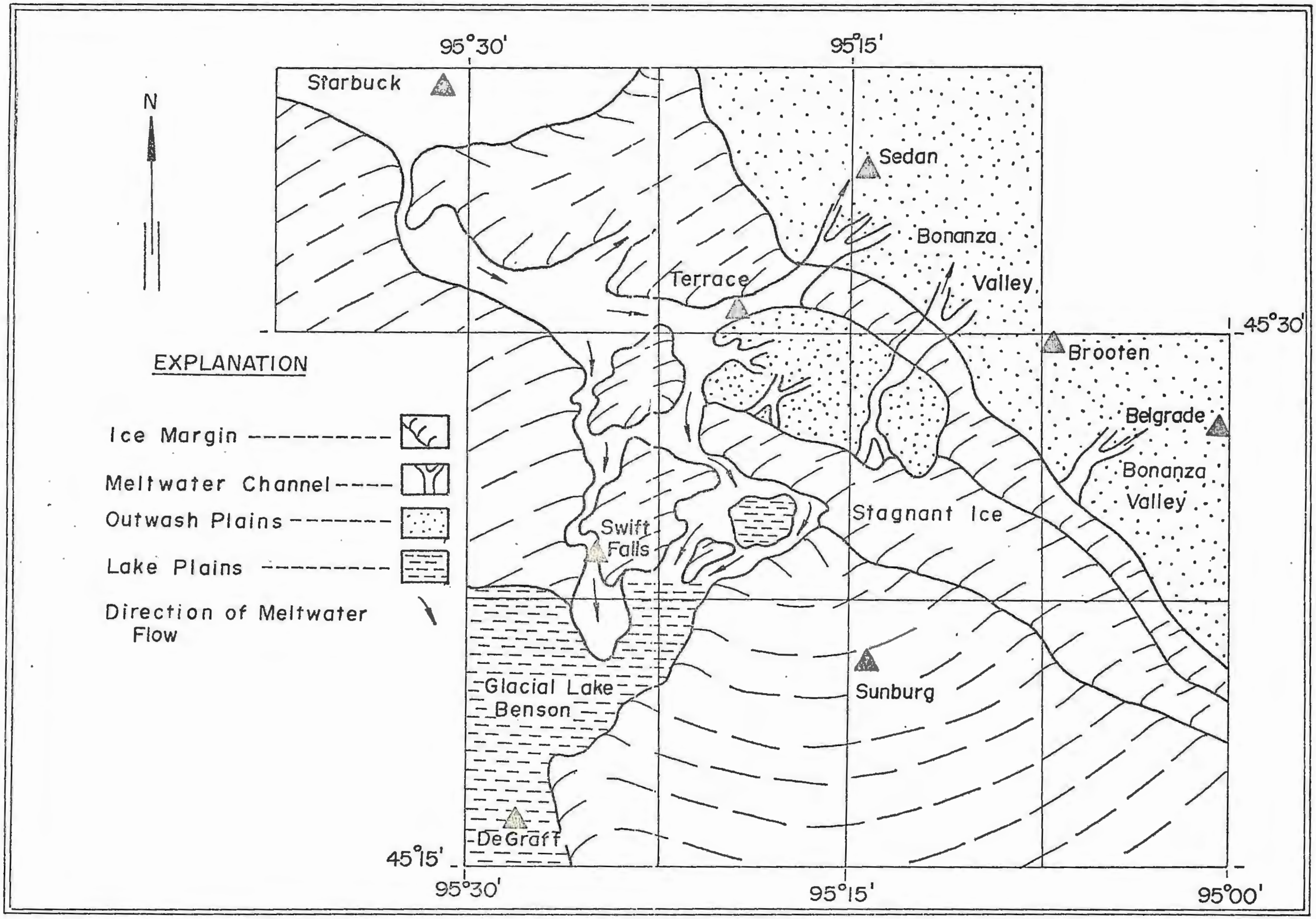


FIGURE # 26 – Phase 4 of Glacial History of ice. Meltwaters from the Des Moines lobe ice located in the southwestern portion of the area flowed both north into the Bonanza Valley system and southwest into Glacial Lake Benson. Erosion by these waters no doubt removed considerable volumes of Des Moines lobe till from the floor of Bonanza Valley. Major portions of the Lake Johanna Region were still covered with stagnant ice.

Phase Five

In the last episode of the Quaternary history of the Lake Johanna Region, the Des Moines ice sheet had completely wasted, except for a large block that occupied the Lake Minnewaska basin (Figure 27). Initially, meltwaters derived from this ice block drained northward away from the ice-clogged lake basin in an extensive braided river system, but as melt-out continued, a major lower outlet was formed to the west of Starbuck, allowing the ponded waters to flow westward away from this region. A small river branch also drained southward from Lake Minnewaska through a restricted channel into the great central topographic low. Melting and collapse of the sediment-choked Blue Mounds crevasse system had dammed the eastern extension of this lowlying area, which deflected drainage lines westward into the Lake Emily system. The ice that had previously surrounded the proglacial lakes north of the

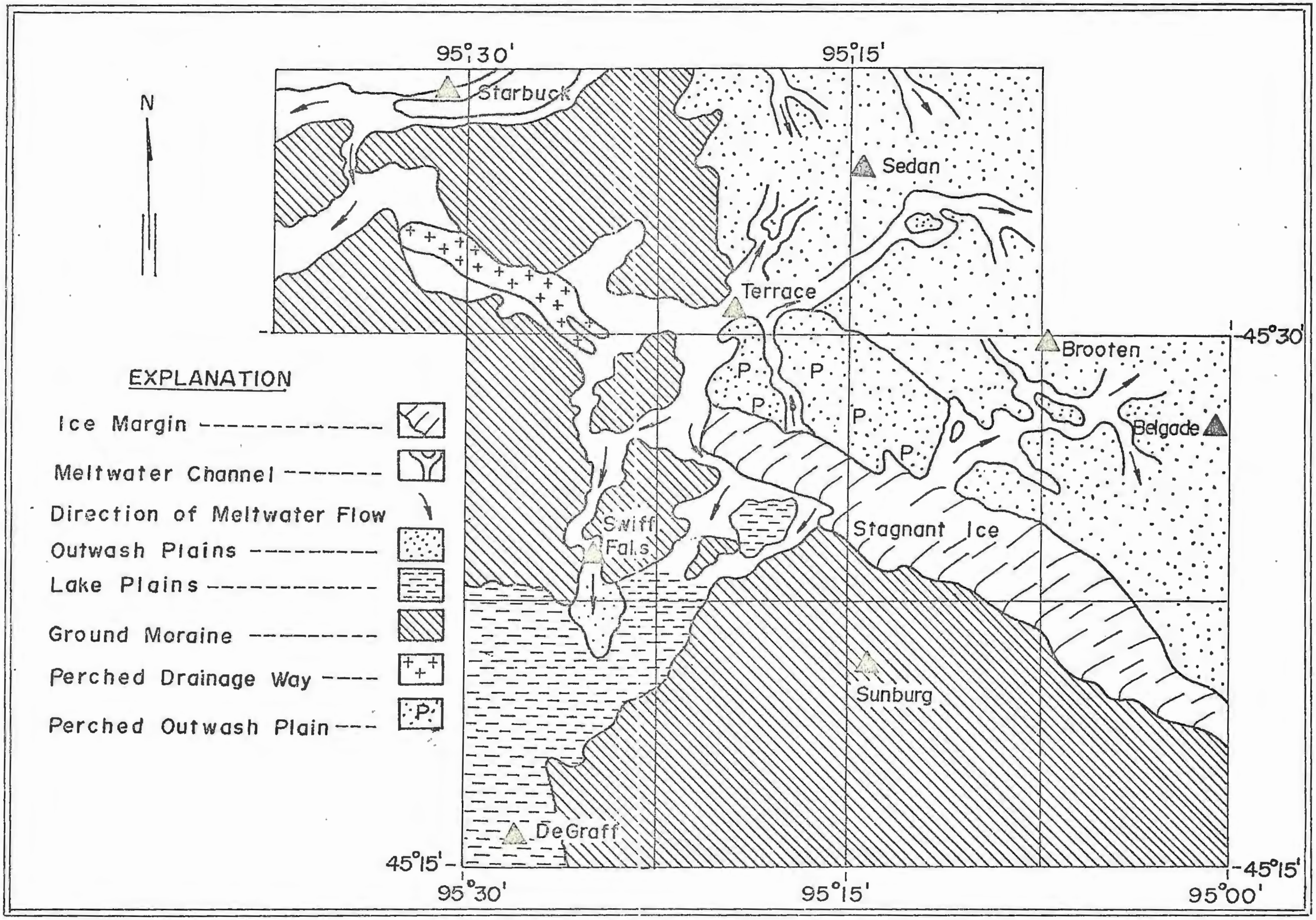


FIGURE # 27 – Phase 5 of Glacial History

Wadena lobe stagnant ice complex had also melted out, and this isolated the numerous flat-topped perched outwash plains. The Wadena ice complex was also in its final stages of melting, and so the melange of features now associated with this complex were slowly being deposited upon an older stable till surface. Extensive river systems draining the complex debouched copious volumes of debris out onto the Bonanza Valley outwash plains, with eskers forming rapidly in the decaying ice tunnels. To the south of the complex, meltwaters were still being ponded in Glacial Lake Benson. High water levels and the subsequent extensive shore line erosion accentuated the topography of the hills to the north and east of the lake, producing the bluffs that are now so prominent.

With the passage of time, all of the dead ice wasted away. This deprived the meltwater channels of their discharge, and so they became filled with paludal deposits. The waters of Glacial Lake Benson breached their morainic dam near Redwood Falls and then quickly drained away, leaving a vast stretch of mud flats, which is now the best farmland in the entire Lake Johanna Region. Because the topographic lows now occupied by Lake Minnewaska and Lake Emily were never filled in with sediments, they still persist, being continually fed by groundwater seepage.

Conclusions

In conclusion, the author believes that, although the Lake Johanna Region lies within the context of the massive Alexandria moraine complex, the linear series of drift hills running diagonally through the area does not represent a moraine that was deposited at the terminus or margin of an ice sheet. They do, however, have an origin that is intimately associated with the localization of drainage lines along a pronounced sag, or crevasse system, in the continental ice sheet. This system may have been the expression of a major pre-Wisconsin topographic low. Ice stagnation in the southeastern portion of this topographic low produced an extensive melange of stagnant ice features, while a complicated history of successive drainage lines in the western region developed a system of interconnected lakes and rivers along with tremendous quantities of well sorted outwash sediments.

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APPENDIX

STATISTICAL DATA

LABORATORY METHODS

The procedure for determining the grain size distribution of the material in a till sample is as follows: to a 50-gram sample about 30 mls. of a solution of 10 gms. of calgon per litre of water is added, and then the mixture is allowed to stand overnight. The silt and clay solution is then carefully washed through a 230 mesh (0.063 mm seive), and the sand residue remaining is placed in an oven at approximately 100 degrees centrigrade and heated to absolute dryness. The mixture of clay, silt and calgonated water is then thoroughly mixed and poured into a one-litre graduated cylinder. Once dry, the sand is put into the set of seives in a sonic sifter and run for approximately five minutes, separating again the sand from the silt and clay. The silt and clay collected is now added to the solution already standing in the cylinder, and then this fine-grained material is analyzed by standard pipette methods. The remaining dry sand fraction is now weighed to the nearest 0.001 gram, and this weight is added to that calculated for the silt and clay. Recalculating these to 100 percent gives the percentage breakdown for the till sample.

This method was found to have excellent reproduceability values, having discrepancies on succesive runs on the same sample of only one to two percent. Considering the nature of a typical till, these discrepancies can be considered as being extremely respectable.

The lithology of the sand sample collected and weighed in the previous procedure was then studied, and the pebbles counted with the aid of a binocular microscope. Two ranges of size were categorized in detail - that greater in maximum diameter than 2 mm. (10 mesh), and that between 1 (18 mesh) and 2 mms. (10 mesh). The number of grains counted ranged from greater than 100 up to occasionally 350, varying on the nature and amount of coarse material in the till sample. The major lithologic materials observed were classified as belonging to one of these ten categories:

(a) North Shore Volcanic group, including felsite, red granophyre, basalt, gabbro and diabase,

(b) sandstone, both red and white,

(c) granite and quartz,

(d) metamorphics,

(e) iron formation,

(f) Cretaceous shale,

(g) carbonates,

(h) chert,
(i) quartzites and
(j) others.

Again, as with the size distribution analysis, this method had quite an excellent level of reproduceability on successive runs of the same sample.

TABLE 1

Stone Counts of Till in the Lake Johanna Region (1 to 2 mm. size fraction). North Shore, or Keweenawan-type, rocks include felsite, red granophyre, basalt, gabbro and diabase.

LOCALITY	GRANITIC ROCKS	CARBONATES	CRETACEOUS SHALE	NORTH SHORE	SANDSTONE RED & WHITE	IRON FM.	OTHER ROCKS
13-4	22	27	47	1	0	2	1
9-27	29	27	41	1	0	tr	2.5
8-6A	23	28	37	3	2	1	6
14-3	36	20	37	1	1	3	2
23	32	26	36	3	1	2	0
11-2B	30	28	31	4	0	3	4
34	33	30	30	2	0	3	2
12-1	40	24	30	0	0	6	0
2-15	38	27	29	2	tr	2	2
24	34	29	28	4	1	4	0
26	44	23	27	3	0	2	1
9-6	43	22	26	3	1	3	2
33	45	22	26	4	tr	2	1

TABLE 1 (Continued)

LOCALITY	GRANITIC ROCKS	CARBONATES	CRETACEOUS SHALE	NORTH SHORE	SANDSTONE RED & WHITE	IRON FM.	OTHER ROCKS
36	40	26	25	tr	0	5	4
22	42	29	23	3	tr	2	1
7-3	40	26	22	1	0	5	6
9-8	38	35	20	3	2	tr	2
13-3	41	31	20	3	2	2	1
9-22	46	28	20	3	1	tr	2
10-4A	42	28.5	18.5	3	1	2	5
37	43	29	17	2	0	5	4
9-2	49	30	17	1	1.5	1.5	0
7-14	54	11	17	8	2	5	3
2-2	48	27	15	5	1	2	2
7-5	42	31	14	3	3	7	2
2-12	53	25	13	3	1	2	3
3-2	68	14	13	1	tr	3	1
1-9	46	29	12.5	2	1	5	4.5

TABLE 1 (Continued)

LOCALITY	GRANITIC ROCKS	CARBONATES	CRETACEOUS SHALE	NORTH SHORE	SANDSTONE RED & WHITE	IRON FM.	OTHER ROCKS
4	50	22	12	5	tr	4	7
1-11	51	28	12	5	1	2	1
2-8	50	27	11	2	0	8	2
2	51	27	11	3	tr	2.5	4.5
10-3	53	21	11	4	2	3	6
2-4	54.5	27.5	9	3	1	3	2
11-3	59	25	9	2	2	2	1
7-10	55	25	8	5	0	4	3
11-1	53	29	5	7	2	2	2
21-4	59	27	2	4	1	3	4
7-12	65.5	22	2	5	tr	2	3.5
30	67	16	2	8	0	6	1
8-6B	60	30	1	4	2	2	1
9-7B	50	41	tr	2	1	2	3.5

TABLE 1 (Continued)

LOCALITY	GRANITIC ROCKS	CARBONATES	CRETACEOUS SHALE	NORTH SHORE	SANDSTONE RED & WHITE	IRON FM.	OTHER ROCKS
7-13A	64	23	tr	7	1	4	tr
14-5	60	27	0	6	tr	3	4
14-2	62	29	0	5	0	1	3
4-1	67	21	0	2	1	5	4

TABLE 11

Mechanical Composition of Tills in the Lake Johanna Region

SAMPLE NO.	SAND	SILT	CLAY	SAMPLE NO.	SAND	SILT	CLAY
13-4	26.0	33.0	41.0	2-2	62.0	31.0	7.0
9-27	41.0	31.0	28.5	7-5	63.0	28.0	9.0
8-6A	50.0	30.0	20.0	2-12	46.0	38.0	16.0
14-3	43.0	32.0	25.0	3-2	52.0	30.0	18.0
23	47.0	28.0	25.0	1-9	66.7	30.3	2.9
11-2B	34.1	29.7	36.3	4	----	----	----
34	52.0	27.0	21.0	1-11	77.0	16.0	7.0
12-1	31.0	56.0	13.0	2-8	55.0	30.0	15.0
2-15	63.0	25.0	12.0	2	50.0	27.0	23.0
24	43.0	31.0	26.0	13-8	53.3	28.2	18.4
26	53.0	28.0	19.0	2-4	61.3	22.2	16.5
9-6	50.0	19.4	30.8	11-3	56.0	30.0	14.0

TABLE 11 (Continued)

SAMPLE NO.	SAND	SILT	CLAY
33	47.0	40.0	13.0
36	29.0	32.0	39.0
22	61.0	23.0	16.0
7-3	42.0	32.0	26.0
9-8	48.0	32.0	20.0
13-3	50.0	33.0	17.0
9-22	64.0	28.0	8.0
10-4A	30.6	40.6	28.8
37	51.0	37.0	12.0
9-2	62.3	28.7	9.3
7-14	68.0	22.0	10.0
7-10	62.0	20.0	18.0
11-1	49.4	40.6	10.0
21-A	67.3	31.4	1.3
7-12	85.5	11.4	3.2
30	60.0	31.0	9.0
8-6B	65.0	22.0	13.0
9-7B	22.5	63.4	14.2
7-13A	58.0	28.0	14.0
14-5	60.2	26.0	13.8
14-2	61.0	22.5	16.8
4-1	55.0	34.0	11.0