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LANDFORM ASSEMBLAGES AND GLACIAL HISTORY OF A PORTION OF THE ITASCA MORAINE, NORTH-CENTRAL MINNESOTA

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ABSTRACT

Landform assemblages within the Itasca Moraine of north-central Minnesota suggest a new interpretation for the glacial history that involves the advance of the Wadena and Koochiching lobes during Late Wisconsinan glaciation. The Itasca Moraine initially formed as a stagnation complex during the recession of the Wadena lobe. Later, the Itasca Moraine marked the southern margin of the Koochiching lobe. The abundance of shale fragments in Koochiching-lobe deposits distinguishes them from Wadena-lobe deposits. The complex glacial topography of the Itasca Moraine includes landform assemblages containing proglacial, supraglacial, and subglacial deposits. Advance of the Koochiching lobe was previously thought to have been a result of the Wadena-lobe retreat, which opened a conduit allowing the Koochiching lobe to advance from the west. Results presented in this paper and in St. George (1994) suggest that the Wadena lobe never actually retreated from its position at the Itasca Moraine prior to the initial advance of the Koochiching lobe, but that the ice-flow center gradually switched from the north-northeast to the north, and eventually to the west-northwest. If a retreat of the Wadena lobe had occurred prior to the initial advance of the Koochiching lobe, a distinct stratigraphic contact would separate the shale-bearing deposits of the Koochiching lobe from the non-shale-bearing deposits of the Wadena lobe. The stratigraphic record shows that this contact is gradational, suggesting that the Koochiching lobe also contributed, to a certain degree, to the later-stage formation of the Itasca Moraine and associated landforms. This change in ice-flow direction would be contemporaneous with the retreat of the Rainy lobe, which opened an area into which the ice could flow and advance towards the southeast.

INTRODUCTION

Interpretations relating to the gradational shift in ice-flow direction of the Wadena lobe are made here as a result of the detailed study conducted in the Itasca moraine region of north-central Minnesota (Figs. 1 and 2). The initial study was related to a groundwater-recharge investigation (St. George, 1994) within the Itasca Moraine; it focused on the variations in spatial distribution of groundwater recharge among different landform assemblages. As a result of this study, a detailed Quaternary landform map was constructed (Fig. 3). This landform map prompted the reevaluation of ideas regarding the formation of the glacial deposits associated with the Itasca Moraine and directed attention to relations between deposits of the Wadena and Koochiching lobes (Fig. 4). Geological mapping also allowed assessment of the deposits immediately to the north of the Itasca Moraine, over which there has been debate by Martin and others (1989, 1991) and Meyer (1993) regarding the timing and extent of the advance of Koochiching-lobe ice.

The Itasca Moraine is a laterally extensive accumulation of glacial sediment that was interpreted by Wright (1972) and Wright and Ruhe (1965) to have been deposited by ice flowing from the north and northeast during Late Wisconsinan glaciation (Figs. 1 and 4).

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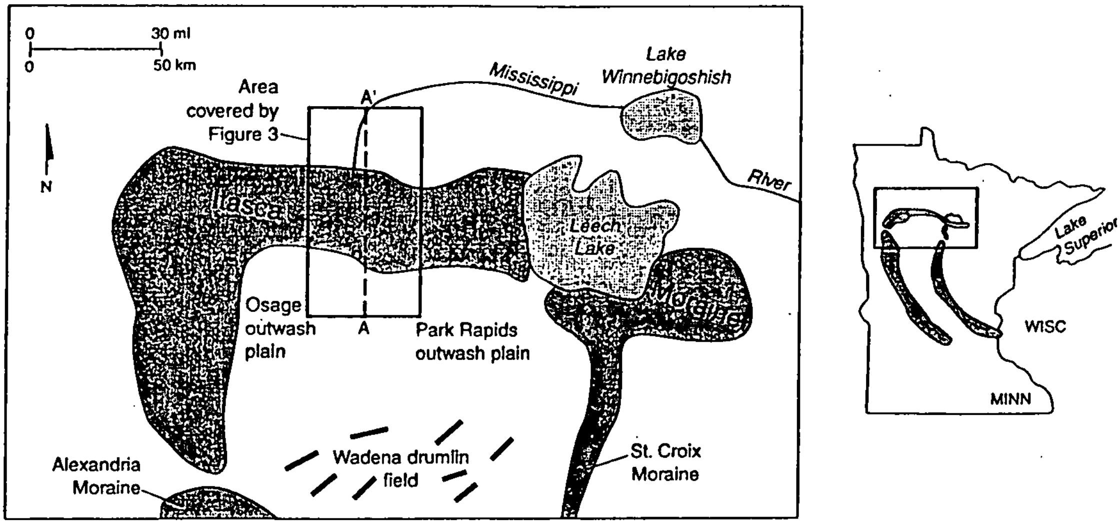


Figure 1. Location of the Itasca Moraine and associated landforms of north-central Minnesota. Portions of the previously formed Alexandria and St. Croix Moraines are also shown. Location of landform-assemblage map (Figure 3) is indicated. Dashed line (A-A') represents one possible location for generalized cross section (Figure 2).

Wright and Ruhe (1965) and Wright (1972) defined the Wadena lobe as ice originating in the Winnipeg lowland to the northwest. This ice mass then flowed toward the southeast into northeastern Minnesota, where it was diverted to the southwest by the advancing Rainy lobe. Therefore, the Wadena lobe entered central Minnesota from the northeast forming the Wadena drumlin field and the Alexandria Moraine. The Wadena lobe later retreated and stabilized forming the Itasca Moraine in north-central Minnesota. Recent investigations by Goldstein (1986, 1989, and this volume) and Meyer (1986) have shown that the Wadena lobe originated in the northeast. Meyer (1997) and Meyer and Knaeble, 1996) discontinued use of the term Wadena lobe. Mooers and Lehr (1997) have also discontinued use of Wadena-lobe terminology. There is, however, still considerable debate on abandonment of established terminology, and for the purposes of this investigation, usage of the term Wadena lobe is retained because an alternative has not been widely accepted.

Retreat of the Wadena lobe was followed by an advance of an eastern offshoot of the Des Moines lobe, which Leverett (1932) called the St. Louis sublobe after exposures in east-central Minnesota. Wright (1972) and Wright and Ruhe (1965) extended the use of St. Louis sublobe to eastward and southeastward-flowing ice north of the Itasca Moraine. Martin and others (1989, 1991) and Meyer (1993) now restrict usage of St. Louis sublobe to that portion of the ice south of the Mesabi Range; the term Koochiching lobe is used for northwest-derived ice that extended to the north of the Itasca Moraine. Several named phases of the Wadena and Koochiching lobe have been previously described (Wright, 1972; Wright and Ruhe, 1965; Martin and others, 1991) and are widely accepted. A historic synopsis will not be presented in this paper; refer to cited references for detailed phase descriptions.

The area studied encompasses approximately 1700 km² within the Anchor Hill, Big Basswood Lake, Heart Lake, Lake Hattie, Lake Itasca, LaSalle Lake, Osage, Park Rapids, Park Rapids NW, Schoolcraft Lake, Skunk Lake, and Two Inlets 7.5-minute quadrangles (Fig. 3). The rather strong topographic relief of the Itasca Moraine offered an ideal setting for the groundwater-recharge investigation conducted by St. George (1994) and resulted in the landform-assemblage definitions presented here.

BACKGROUND

The Itasca Moraine is roughly 150 km long and nearly 30 km wide and rises 100-200 m above adjacent areas to the north and south (Figs. 1 and 2). The Itasca Moraine is highest along its central axis; this high crest divides the Itasca Moraine into two regions of contrasting morphology and sedimentology. The proximal (up-glacier or northern) portion of the Itasca Moraine is a hummocky ice-stagnation complex represented by ablation till and isolated glaciolacustrine and glaciofluvial deposits (St. George, 1994). The distal (down-glacier or southern) portion of the Itasca Moraine is also characterized by ice-stagnation topography, but the suite of landforms is strikingly different (St. George, 1994). The southern

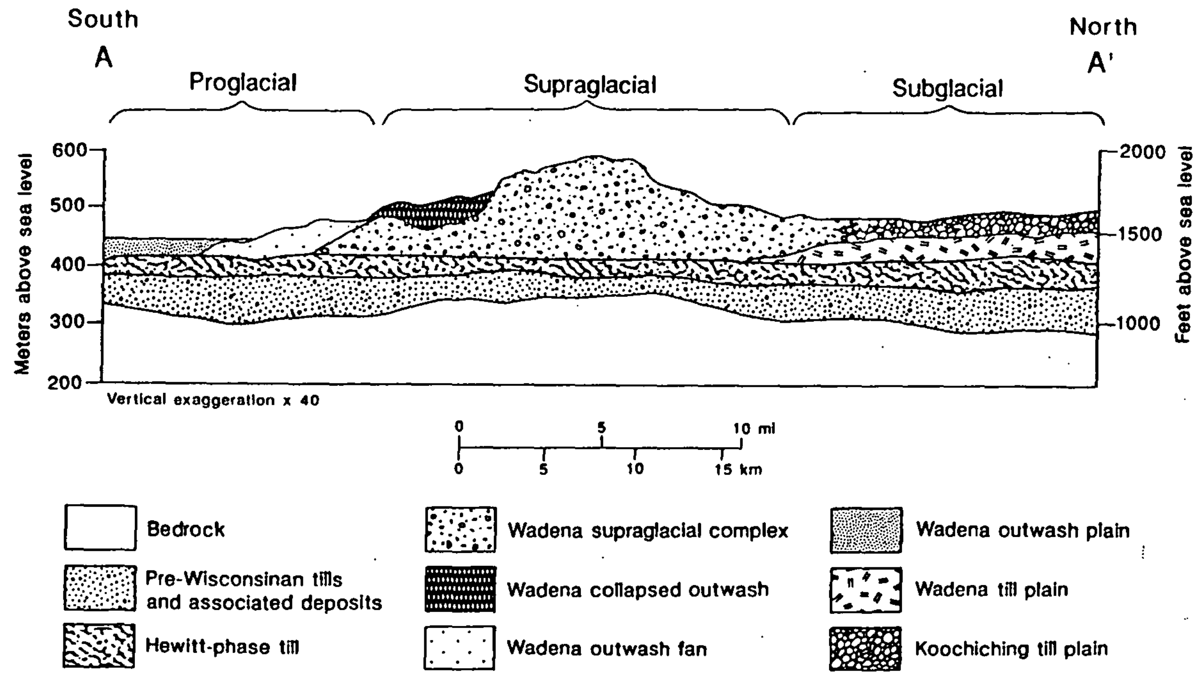


Figure 2. Generalized north-south cross section through the Itasca Moraine showing landform assemblages and their inferred relations (Fig. 1). Although the Wadena till plain and Koochiching till plain are shown as separate units with a distinct contact on this figure, there is a gradational contact between these two units. Bedrock elevation and sediment thickness were derived from well and geologic logs (St. George, 1994). Lacustrine, outwash channel and perched lake landform-assemblages are not shown in this figure due to limitations of scale. Vertical exaggeration is 40x.

portion of the Itasca Moraine contains an integrated drainage network composed of large meltwater channels and chains of ice-walled lake plains connected by rivers (St. George, 1994; Mooers and Norton, 1997). The southern portion of the Itasca Moraine is also crossed by numerous tunnel valleys, now expressed as chains of lakes, that reflect the englacial and subglacial drainage system that developed during and prior to Itasca Moraine formation (Wright, 1993).

The Park Rapids outwash plain lies to the south of the Itasca Moraine (Figs. 1 & 2). The outwash forms a gently sloping plain that grades from the distal portion of the Itasca Moraine southward, where the outwash apron breaks into fingers interpreted to result from water flowage between drumlins of the Wadena drumlin field (Goldstein, 1989 and this volume). The Wadena drumlin field was constructed during the earlier Hewitt phase of the Wadena lobe.

North of the Itasca Moraine we recognize 2 distinct tills within the till plain. They are associated with separate ice lobes, and are classified as separate landform assemblages. The eastern assemblage contains Wadena-lobe till, which is a stratigraphically older sandy loam, containing abundant metamorphic and igneous rock types derived from the Canadian Shield as well as abundant limestone, dolomite, and chert derived from Paleozoic carbonate rocks. Gowan (1993, and this volume) presented convincing evidence that the source area for the Wadena-lobe ice lay in the Hudson Bay region to the northeast, where Paleozoic carbonate rocks occur extensively. However, it has also been suggested that the carbonate in the sediments associated with the Wadena lobe may have had a source in the underlying carbonate-rich till, that was derived from the Winnipeg area to the northwest (Goldstein 1989, and this volume).

The western assemblage contains Koochiching-lobe till, which is younger, contains a suite of rock types similar to the Wadena-lobe till, but is slightly finer-textured, and contains abundant Cretaceous shale. This fine-textured till is compositionally and texturally similar to that of the later Koochiching-lobe tills of northwest-source (Meyer, 1993). The stratigraphic boundary between the two till units is gradational. The upward change in clast types suggests a reorientation of ice flow from a north-northeast source (Wadena lobe) to northwest source (Koochiching lobe) during the formation of the Itasca Moraine.

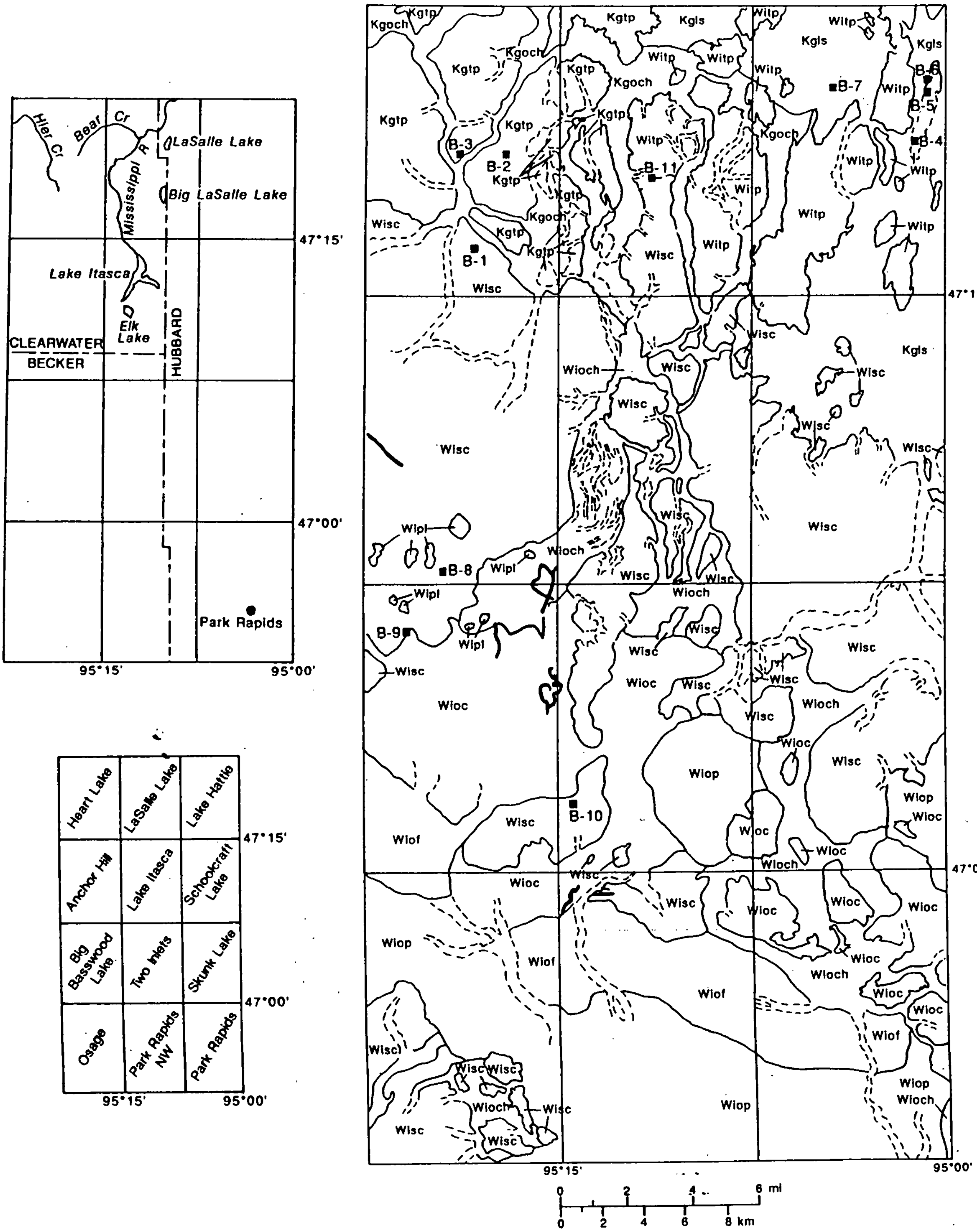


Figure 3. Quaternary landforms of the Itasca moraine area. Inset shows names of U.S. Geological Survey 7.5 minute series (topographic) quadrangles covered in this study and geographic features mentioned in text. For location of Figure 3 see Figure 1.

EXPLANATION FOR FIGURE 3

KOOCHICHING LOBE

Kgtp - Koochiching Till Plain
Low relief undulating plains comprising light olive brown sandy loam to silty loam till. The till contains abundant shale clasts and has a high carbonate content.

Kgls - Lacustrine Sediments
Low relief, broad flat plains comprising sand and sandy loam deposited by lacustrine processes. All the sediments are very leached. The sediments have a low carbonate content and shale clasts are largely absent.

Kgoch - Outwash Channels
Broad flat areas or deep channel-like valleys bounded by steep sides. These channels crosscut other landform-assemblages. Channel deposits are well-sorted sands and gravels that include some shale clasts.

WADENA LOBE

Wiop - Outwash Plain
This landform assemblage contains two geographically separate level plains (the Osage outwash plain in the southwest and the Park Rapids outwash plain in the southeast). Both have gently sloping surfaces and a few closed depressions. These outwash plains contain compositionally and texturally identical sands.

Wiof - Outwash Fan
Narrow, low relief apron of moderately well sorted sand and gravel that slopes gently to the south and contains numerous small depressions. This unit is situated between the collapsed outwash of the stagnant ice field to the north and the broad flat outwash plains of the proglacial environment to the south.

Wipl - Perched Lakes
Isolated ice-walled lake plains (flat-topped hills) composed of silt that grades laterally and vertically into fine sand. The gradation reflects the proximity to the margin of an ice-walled lake. This landform-assemblage occurs within the western and southern parts of the supraglacial complex, and is not areally extensive.

Witp - Wadena Till Plain
Undulating plains marked by gently sloping swells, sags and depressions. This area is dissected by numerous stream valleys. The till is mainly a sandy loam and is light olive brown in color. Sediments have a high carbonate content and shale clasts are absent.

Wioc- Collapsed Outwash
Hummocky topography with relatively low relief and numerous closed depressions. Composed of weakly stratified loamy sand with gravel that is not always well sorted.

Wisc - Supraglacial Complex
Knolls, hummocks and closed depressions characterized by high relief and sharp, irregular surfaces. Comprises sandy loam (55%), poorly to moderately sorted sand and gravel (40%) and silts (5%). Tills are light olive brown and rich in carbonate. Cretaceous shale clasts are absent. Compositionally and texturally similar to the Wadena lobe till plain.

Wioch - Outwash Channels
Broad flat areas or deep channel-like valleys bounded by steep sides that crosscut other landform-assemblages. Channel deposits are well-sorted sands and gravels.

Scarps - interpreted as channel boundaries

Eskers

B-2 Soil Boring Location

LANDFORM ASSEMBLAGE APPROACH

A landform-assemblage approach was used to evaluate the origin, structure, sedimentological complexity, and glacial history of the Itasca Moraine (St. George, 1994). Glacial terrains are composed of landforms such as hummocks, eskers, kettles, ice-contact forms, and outwash features. Each landform has developed due to a particular set of processes operating within the glacial system, and has similar relief, stratigraphy, and sedimentology. A landform assemblage is not limited by size; it can range from an extensive glacial outwash plain to long narrow channels, to small or large hummocky knobs, or large tracts of hummocks with similar topographic expression. A landform assemblage may be structurally and sedimentologically complex but the complexity is similar throughout the landform assemblage. Once the areal extent of a landform assemblage has been determined, the physical characteristics can be described from field observations, sample collection and laboratory analysis, and from compilation of stratigraphic data from borings.

Mapping of the landform assemblages was initially based on their topographic expression interpreted from maps and aerial photographs, and was compiled on 7.5-minute topographic quadrangles. Landform-assemblage types ranged from broad flat sand plains to complex glacial-morainic deposits, ice-stagnation features, till plains, and glaciolacustrine plains (Fig. 3). The landform assemblages were grouped into categories based on the glaciogenic environment in which they form.

Recognition of landform assemblages implies a genetic relationship among the assemblages and materials involved in their development (Flint, 1971; Sugden and John, 1976: Eyles, 1983; Eyles and Menzies, 1983). Based on identification of the landform assemblages and terrain type, the geometry and character of subsurface stratigraphies can be generalized for large areas. Eyles and Menzies (1983) describe three principal depositional environments: subglacial, supraglacial, and proglacial. Each depositional environment is associated with characteristic topographic expression, stratigraphy, and sedimentology. The landform assemblage associated with subglacial deposition and erosion generally results in undulating plains of low relief. Landform assemblages associated with supraglacial environments are generally characterized by blankets of debris on the ice surface that are left behind as the ice retreats. Retreating ice margins produce large tracts of hummocky supraglacial topography that frequently form arcuate belts (moraine complexes) several tens of kilometers wide (Eyles and Menzies, 1983). Landform assemblages associated with proglacial environments result from transport of sediments from the active ice surface, and their deposition by glaciofluvial or glaciolacustrine processes beyond the active ice margin.

Field Reconnaissance

The landform assemblage map (Fig. 3) was used to select areas for detailed study and to identify areas for collection of sediment samples. Field checking involved the classification of deposits associated with each landform assemblage on the basis of description of physical and chemical properties such as color, texture, structure, indicator grain lithology (shale, metamorphic, carbonate, etc.), relative density (i.e. compaction), caliche, mottling, gleying and reaction to dilute hydrochloric acid to determine presence of carbonate in all size fractions. Where possible, stratigraphic and sedimentological characteristics, and inferred depositional environments were noted. Field textures were confirmed by laboratory grain-size analysis using the method described by Folk, (1980) resulting in the percent of gravel, sand, silt, and clay. The resulting percentages of sand, silt and clay from each sample was applied to the US Department of Agriculture textural classification.

Because many portions of the study area are remote, most sediment descriptions are based on exposures in road cuts or borrow pits, or on samples obtained with a hand auger. Care was taken to distribute observations and sampling sites throughout the various landform assemblages and over a wide elevational range. A total of 498 sites were visited and described. The stratigraphy at 12 sites was assessed using core obtained with a Giddings probe.

DESCRIPTION OF UNITS

Landform assemblages were delineated primarily on the basis of topographic expression. Classification was further refined on the basis of sediment characteristics and inferred depositional mechanisms and interpreted glaciogenic origin. A total of eight separate landform assemblages were identified (Fig. 3). These eight landform assemblages are: till plain (Wadena lobe), till plain (Koochiching lobe), supraglacial complex, collapsed outwash, outwash plain, outwash fan, outwash channel, and lacustrine sediment. A generalized north-south cross section showing relations between these landform assemblages and their respective depositional environments is shown in Figure 2. The following is a detailed description for each of the landform assemblages, organized on the basis of glaciogenic environment.

Landform Assemblages of Subglacial Origin

Till Plain (Wadena Lobe) (Witp)

The Wadena lobe till plain, located on the northern margin of the Itasca Moraine, is characterized by low relief; undulating plains are marked by gently sloping swells, sags, and depressions with an apparently random pattern. The area has been dissected by streams and contains several remnant tunnel valleys such as those occupied by Lower LaSalle and Big LaSalle Lakes (see inset, Fig. 3). Grain size was analyzed for 11 samples collected from the Wadena-lobe till plain, and an additional 33 sites were visited and described. Three soil borings (B-4, B-5 and B-6, Fig. 3) were made to further assess the sedimentology and stratigraphy. Within the Wadena-lobe till plain approximately 90 percent of the sediment is subglacially deposited till, and 10 percent of the sediment is sand of glaciofluvial or glaciolacustrine origin. The tills are sandy loam (mean of 11 samples: 62 percent sand, 34 percent silt, 4 percent clay) and are light olive brown (2.5Y 5/4) in color. Pebbles within the tills are dominantly igneous, metamorphic, and carbonate. The till is calcareous, slightly compact and contains abundant secondary carbonate.

Till Plain (Koochiching Lobe) (Kgtp)

The till plain of the Koochiching lobe is located to the northwest of the Itasca Moraine (Fig. 3); it is also characterized by undulating plains with low relief, although it is slightly less dissected than the Wadena-lobe till plain. Two channels, now occupied by Hier Creek and Bear Creek (Fig. 3), are entrenched within the till plain and interpreted as tunnel valleys. Sediments of the Koochiching-lobe till plain are classified on the basis of grain-size analysis on 13 samples, together with observations at 34 additional sites. Two deep soil-probe borings (B-2 and B-3, Fig. 3) were also made. This till plain is primarily composed of subglacially deposited sediments. The landform assemblage contains 80 percent subglacially deposited till and 20 percent glaciofluvial-glaciolacustrine sediments. The subglacially deposited till is composed of 51 percent sand, 43 percent silt, and 6 percent clay; it is light olive brown (2.5Y 5/4) in color. The till contains a considerable amount of Cretaceous shale clasts as well as abundant carbonate clasts; shale is the predominant clast type. In some locations, handfuls of shale can be picked or scooped from the till and outwash deposits. This till is more compact than the till of the Wadena-lobe till plain, but like sediments of the Wadena-lobe till plain, it also contains secondary carbonate.

Lacustrine sediments within the Koochiching-lobe till plain have a loam to loamy sand texture. The lacustrine sediments were only inspected to a depth of approximately 0.5 m because they occur within topographically lower portions of the till plain where exposures are rare. The lacustrine sediments are dark olive brown (2.5Y 4/4) in color and are noncalcareous.

Landform Assemblages of Supraglacial Origin

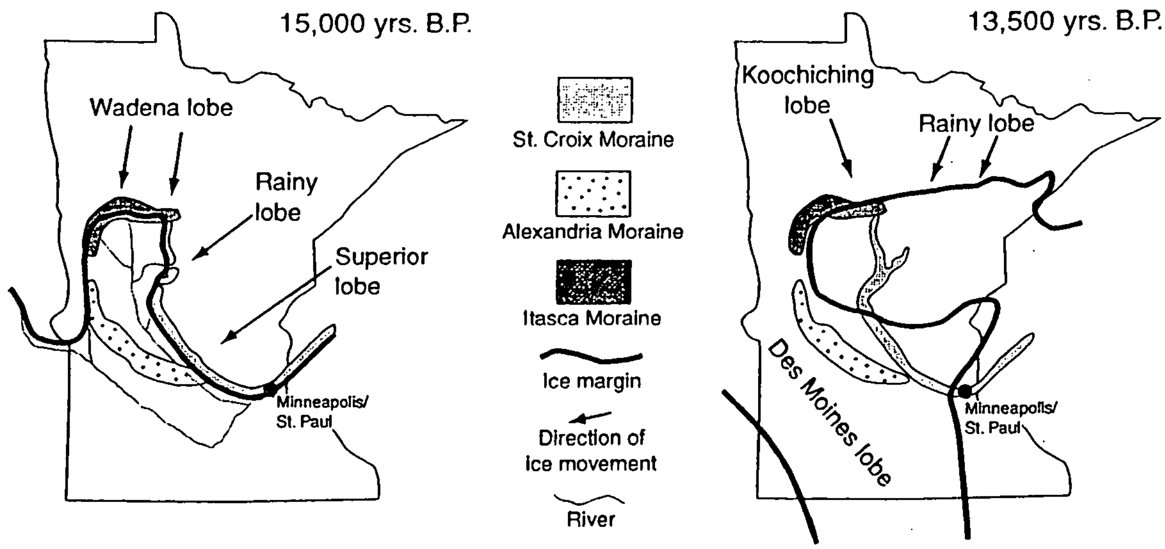
Supraglacial Complex (Wisc)

The ice-stagnation topography of the supraglacial complex is characterized by high relief and sharp irregular surfaces. The supraglacial complex contains knolls, hummocks, and closed depressions of various shapes and sizes. This type of topography has been described as hummocky ablation drift, which is an apparently random assemblage of hummocks, ridges, basins, and small plateaus without pronounced parallelism of these elements and with variations in slope angles and steepness (Flint, 1971). In the Itasca Moraine the supraglacial complex is cut by several large north-south trending channels interpreted as tunnel valleys (Wright, 1993), such as the one now occupied by Lake Itasca (see inset, Fig. 3). The supraglacial complex is structurally complicated, and stratigraphic continuity is very limited.

Deposits associated with the supraglacial complex are primarily composed of three sediment types. The most common sediment type within the landform assemblage (55 percent of the samples collected and analyzed for grain size) is a sandy loam till. Poorly to moderately sorted sand and gravel make up 40 percent of the assemblage, and lacustrine silt-loam accounts for about 5 percent of the samples collected and analyzed. These percentages are based on grain-size data for 85 samples (18 of which are from a study by Schulte, 1993). An additional 113 field observations, which include five shallow borings (B-1, B-8, B-9, B-10, and B-11, Fig. 3) were also made. The sandy loam till is light-olive brown (2.5Y 5/4) and rich in carbonate. The main clast types within the gravel fraction are igneous, metamorphic, and carbonate. Cretaceous shale clasts were not observed. This till is compositionally and texturally similar to that of the Wadena-lobe till plain, from which it is distinguished on the basis of its geomorphic expression and depositional environment. The sand and gravel component of these deposits is a result of fluvial deposition during moraine formation.

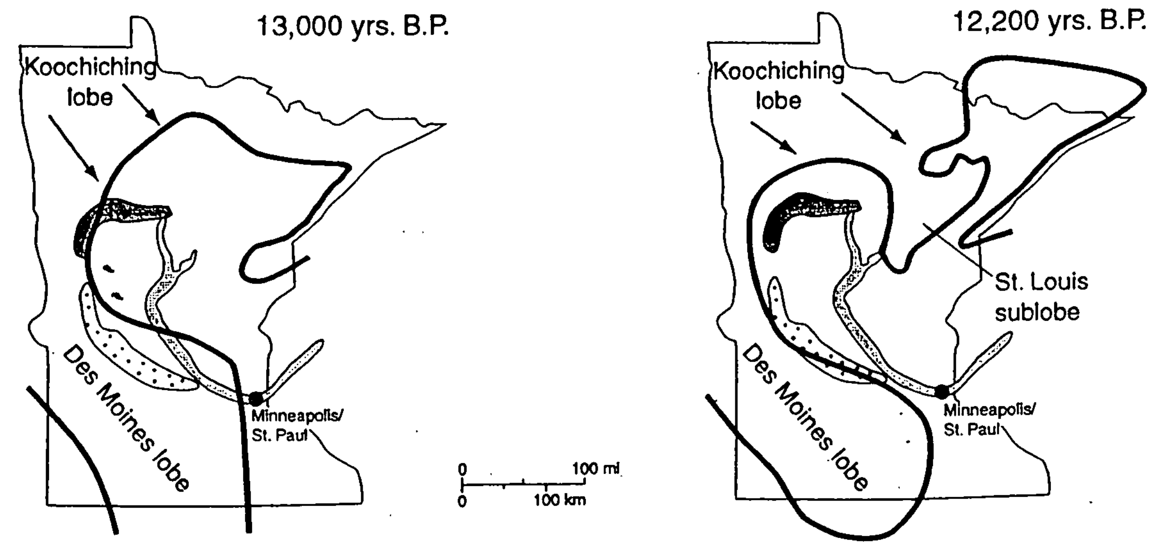
Collapsed Outwash (Wioc)

Areas of collapsed outwash are characterized by hummocky topography with frequent, relatively low relief, undulations and numerous closed depressions. This topography can best be described as low-relief mounds and shallow basins with gentle sideslopes. The material is weakly stratified; the stratification generally parallels the upper surface. The collapsed-outwash landform assemblage primarily occurs in the southern portion of the Itasca Moraine. Sediments within this assemblage



A. Advance of the Wadena lobe from the north was contemporaneous with advance of the Rainy and Superior lobes from the northeast approximately 15,500 years ago.

B. Wadena lobe remained at or near its terminal position as the Rainy and Superior lobes retreated to the northeast. Ice flow direction for ice terminating at the Itasca Moraine became more southeast-directed. At this point the northwest-sourced Des Moines lobe reached its maximum limit across south and central Minnesota.



C. Northward retreat (vs. stagnation) of Wadena-lobe ice as ice- flow direction became dominated by northwest-sourced, southeast-directed Koochiching-lobe ice.

D. Northwest-sourced, southeast-directed Koochiching-lobe ice extends across much of north and north-central Minnesota as the Des Moines lobe retreats.

Figure 4. Sequence of glacial events associated with the development of landform assemblages of the Itasca Moraine (Mooers, written communication, 1998). Dates are included for general reference only.

contain 85 percent sand and 15 percent sandy loam. Thirty-nine samples were collected and analyzed for grain size (23 of which are from Schulte, 1993); field observations were made at 15 additional sites. The sandy loam tills are poorly exposed; where they are exposed they represent portions of the stagnation complex that were not completely blanketed by the outwash that was deposited on top of stagnant ice after a slight recession of the ice margin. The outwash sand and gravel are often poorly sorted, reflecting their close proximity to their source. The collapsed outwash is distinguished from the adjacent outwash plains to the south on the basis of topographic expression.

Landform Assemblages of Proglacial Origin

Outwash Plain (Wiop)

Outwash plains are characterized by level, gently sloping surfaces with a few closed depressions. The outwash-plain sediments are moderately well sorted sands. Grain size analyses were completed for 19 samples (14 of which are from Schulte, 1993). The grain size of the sand shows an overall decrease away from former ice margins. Two geographically separate outwash plains are distinguished; the Osage outwash plain (Schulte, 1993) to the southwest, and the Park Rapids outwash plain (Norton, 1983) in the southeast (Fig. 1). Despite their geographic separation, these outwash plains are considered as a single landform assemblage.

Outwash Fan (Wiof)

An outwash fan is located south of the Itasca Moraine. It is characterized by an apron of low relief, the surface of which slopes gently to the south and contains numerous small depressions or closed basins. It was deposited at the terminus of a large esker, between the collapsed outwash of the supraglacial depositional environment and the outwash plain of the proglacial depositional environment to the south. Sediments in the outwash fan are moderately sorted sand with some gravel. Sixteen samples were collected for grain-size analysis (13 of which are from Schulte, 1993). The outwash fan bears stratigraphic and sedimentologic similarities to outwash plains, but is distinguished by its distinct fan shape and collapsed topography.

Outwash Channel (Wioch and Kgoch)

The outwash channels are defined on topographic maps as broad flat areas typically bounded by steep sides; the channels crosscut other landforms. The outwash channels result from glaciofluvial processes associated with melting ice. The outwash channels range from large or deep channels interpreted as subglacially carved tunnel valleys to flat-bottomed channels. A series of discontinuous valley-like features can be identified running north-south through the moraine, and are now occupied by a chain of lakes. Wright (1993) suggested these were tunnel valleys formed by subglacial meltwater. In many cases these valleys can be traced for up to 30 km from the subglacially deposited till plains through the morainic complex to the head of the outwash plain. Within the till plains, the channels often have broad flat bottoms, indicating they were occupied by subaerial streams. Most of the sediment within the channel deposits is well sorted sand and gravel. Till may be present in the middle or along the edge of the channels. The Wadena outwash channels (Wioch) can be distinguished from the Koochiching outwash channels (Kgoch) by the presence of shale clasts within the Koochiching outwash channels.

Lacustrine Sediment (Kgls)

The proglacial lacustrine sediment forms plains that occupy low portions of the till plain to the northeast of the Itasca Moraine. The sediments are predominantly moderately sorted medium to fine non-calcareous sand. The sand is occasionally interbedded with semi-calcareous silts. At one locality this lacustrine sediment is 2.7 m thick, and is underlain by till of the Wadena-lobe till plain (boring B-7, Fig. 3). Only the lower portion of the lacustrine sediment (below 0.75 m) in boring B-7 is calcareous. The upper portion of the lacustrine sediment (the top 0.75 m) is leached of calcareous material. The proglacial lacustrine sediments were deposited in a lake associated with the melting of the Koochiching lobe in the northeastern portion of the study area. The Koochiching-lobe meltwater ponded over the Wadena till plain between the Itasca Moraine and the retreating Koochiching lobe and deposited sands, silts, and clay.

INTERPRETATIONS

The traditional framework of glacial geology of the Itasca Moraine (Wright, 1957, 1962, 1972, 1993; Wright and Ruhe, 1965) has been modified to varying degrees by Sackreiter (1975), Harris (1975), Anderson (1976), Perkins (1977), Norton (1983), Goldstein (1986, 1989), Mooers (1988), and Gowan (1993). The development of the Late Wisconsinan geomorphic and sedimentologic features of the Itasca Moraine, and the sequence of events presented here (Fig. 4) are based in part on previous investigations as well as on the field studies of St. George (1994).

The advance of the Wadena lobe from the north was contemporaneous (Fig. 4A) with the advance of the Rainy and Superior lobes from the northeast during the Itasca / St. Croix phase (Wright, 1972; Wright and Ruhe, 1965) approximately 15,500 years ago (Clayton and Moran, 1982). Ice of the Wadena lobe may have persisted at the Itasca Moraine for a long time to account for the massive accumulation of drift (Wright, 1972). Evidence suggests (Fig. 4B) that the Rainy lobe retreated eastward from the St. Croix Moraine while the Wadena lobe remained at or near its position at the Itasca Moraine (Norton, 1983; Mooers 1988).

After the Wadena lobe retreated to its position at the Itasca Moraine, development of the moraine occurred in stages as the ice-flow center shifted to a northwest source. The heads of outwash of the Osage and Park Rapids outwash plains mark the maximum southern limit of the Wadena lobe during initial moraine formation. The presence of numerous tunnel valleys, which terminate at the heads of outwash (St. George, 1994; Wright, 1993) suggest that an integrated englacial and subglacial drainage system developed in the near marginal zone of the Wadena lobe. The southern extent of the Wadena- and Koochiching- lobe till plains marks the northern margin of the ice-stagnation complex.

The high central axis of the supraglacial complex apparently represents the area of maximum accumulation of debris on the glacier surface. As debris accumulated during retreat and stagnation, the active ice margin shifted northward. During this stage of formation, outwash draining from the ice surface was deposited over stagnant ice, and subsequent melting of the ice led to the formation of the collapsed-outwash landform assemblage. Evidence suggests that at this time there was a corresponding change in the nature of the englacial and subglacial drainage system. Several of the prominent tunnel valleys can be traced southward to the central axis of the moraine. At or slightly down-glacier from the moraine axis, these meltwater conduits flowed to the surface. Meltwater and sediment then flowed as surface streams over the stagnant ice in the proximal portion of the moraine to the Osage and Park Rapids outwash plains. One example of such a relationship is the tunnel valley now occupied by the western arm of Lake Itasca (Fig. 3). The tunnel valley can be traced from the Koochiching-lobe till plain into the supraglacial complex, along the western arm of Lake Itasca, and into the present basin of Elk Lake (Fig. 3). South of Elk Lake, a network of subaerial meltwater channels characterize the drainage system. It is likely that Elk Lake itself occupies the mouth of the channel.

Mooers (1988) suggested that the change in ice-flow direction from the north (south-flowing) Wadena lobe to the northwest (southeast-flowing) Koochiching lobe in the area of the Itasca Moraine was not punctuated by a retreat of the Wadena lobe. As the ice-flow center shifted and began to carry Cretaceous shale clasts from the west, the Rainy lobe began to retreat. The contemporaneity of these events allowed the Koochiching lobe to begin flowing toward the southeast and across the northern portion of the moraine (Figs. 4C and 4D). This conclusion is consistent with stratigraphic relations documented for the Itasca Moraine region (St. George, 1994). In the northern part of the Itasca moraine region, shale-bearing sediments that are representative of Koochiching-lobe deposits (origin from the northwest) overlie non-shale-bearing sediment that is representative of Wadena-lobe deposits (origin from the north). These two sedimentary packages are not separated by a sharp contact. In fact, there appears to be a gradational change from non-shale-bearing till to shale-bearing till (borings B-2 and B-3 in Fig. 3). If the Wadena lobe had retreated, one would expect the contact between these two tills to be sharper. One might even expect to see lacustrine or outwash deposits on the northern margin of the moraine, separating the two till units; these features were not observed within the Itasca moraine region. Meltwater and outwash from the Koochiching lobe reoccupied channels and tunnel valleys that formed during early phases of moraine development by the Wadena lobe. This relationship is inferred from abundant shale fragments in outwash sand and gravel, suggesting that ice flow from the northwest was occurring contemporaneously with moraine formation. Fragments of shale are also observed at the base of a sediment core taken from Elk Lake (Stark, 1976). In order for shale-bearing sediment to travel this far into the moraine these channels must have remained active while the Koochiching lobe was present north of the moraine. These relations suggest that within the Itasca moraine region, the Wadena lobe did not retreat prior to the advance of the Koochiching lobe, but that there was a shift in the ice-flow direction from south to southeast during the development of the Itasca Moraine (Fig. 4). This change in flow direction was contemporaneous with the retreat of the Rainy lobe, which allowed a conduit to open for further ice advance toward the southeast (Mooers, 1988). This reconstruction is consistent with interpretations presented by Dyke and Prest, 1987.

CONCLUSIONS

Based on the results of the detailed field studies of the Itasca moraine region (St. George, 1994), a modification to the accepted interpretation of the glacial history described by Wright (1972) is postulated. Wright (1972) states that ice of the Wadena lobe and St. Louis sublobe (Koochiching lobe) advanced separately; the Wadena Lobe advanced from the north, and retreated to its position at the Itasca Moraine approximately 20,000 years ago. He interprets the Wadena lobe to have then retreated and the St. Louis sublobe (Koochiching lobe) to have advanced from the northwest.

In this paper we suggest that the two events were not separated by a retreat. This interpretation is based on the gradational contact between the non-shale-bearing Wadena-lobe till and the overlying shale-bearing Koochiching-lobe till. Evidence for drainage channels within the moraine being occupied by meltwater from both ice lobes also supports this interpretation. The data indicate that there was a progressive shift in direction of ice-flow from a north-to-south direction during initial stages of the formation of the Itasca Moraine, to a northwest-to-southeast direction during the final stages of moraine and associated landform development (Fig. 4). Such a change would have caused a shift in the source of the deposits from the north to the northwest, which explains the change in sediment composition to include fragments of Cretaceous shale. This early phase of the Koochiching lobe has been termed the Guthrie phase (H.E.

Wright, Jr., oral communication 1992), based on exposures of shale-bearing Koochiching-lobe till overlying non-shale-bearing Wadena-lobe till near Guthrie, Minnesota.

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