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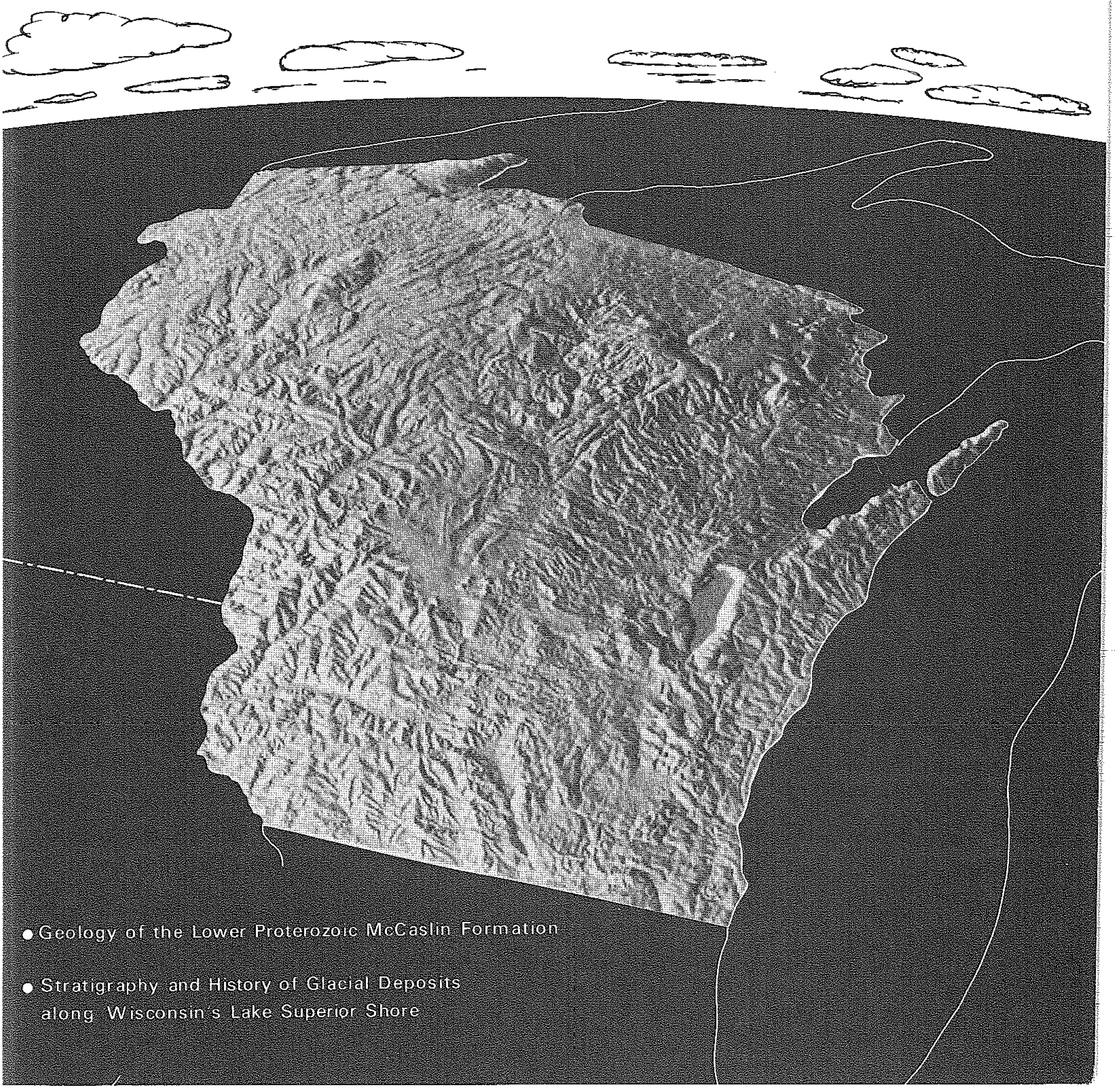

- Geology of the Lower Proterozoic McCaslin Formation
- Stratigraphy and History of Glacial Deposits along Wisconsin's Lake Superior Shore

Cover: An oblique photograph of a plastic raised relief map of Wisconsin by Hans J. Stolle a graduate student in the Geography Department, University of Wisconsin - Madison.

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by

Jean M. Olson

STRATIGRAPHY AND HISTORY OF GLACIAL DEPOSITS ALONG WISCONSIN'S LAKE SUPERIOR SHORELINE-WISCONSIN POINT TO BARK POINT

by

Edward A. Need and Mark D. Johnson

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin--geology in the broadest sense to include rocks and rocks as related to soils, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

The two papers in this issue address a Lower Proterozoic (possibly Baraboo interval) quartzite in northeastern Wisconsin, and Pleistocene stratigraphy along the Lake Superior shoreline. Jean Olson describes the McCaslin Formation which consists predominantly of conglomerate and quartzite, overlies metavolcanic rocks, and is included in units of the Wolf River batholith. Edward Need and Mark Johnson describe stratigraphy and sedimentology of tills and associated units that form the bluffs of Lake Superior. We thank the Journal of Sedimentary Petrology for permission to reproduce figure 10 on page 31 in the Need and Johnson report.

We encourage submission of manuscripts relating to Wisconsin geology. Special consideration will be given papers which deal with timely topics, present new ideas, and have regional or statewide implications.

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THE GEOLOGY OF THE LOWER PROTEROZOIC McCASLIN FORMATION, NORTHEASTERN WISCONSIN

by

Jean M. Olson[1]

ABSTRACT

The McCaslin Formation of northeastern Wisconsin overlies the Waupee Volcanics and has been intruded by the Hager Rhyolite Porphry and High Falls Granite of the Wolf River Batholith. The McCaslin Formation is at least 1,220 m thick, consisting of a thin, basal quartz-pebble metaconglomerate and a thick metamorphosed orthoquartzite. The formation was metamorphosed to the hornblende hornfels facies by the 1,500 Ma old Wolf River Batholith. The McCaslin Formation forms a major syncline plunging 30° to the S. 20° W. The southern branch of the McCaslin range consists of overturned quartzite.

The McCaslin Formation appears to have been deposited as part of a braided alluvial system. The sedimentation was influenced by the lack of land vegetation, intense weathering, and probably aeolian conditions in the source areas. Paleocurrent data show that the direction of sediment transport was mostly from west to east with substantial local variation. Clast lithologies and heavy minerals indicate multiple sediment sources. The tectonic environment was generally stable with slight but steady subsidence.

The McCaslin Formation may correlate with several other quartzites in the region, including the Baraboo, Waterloo, Barron, Flambeau, and Sioux Quartzites. Radiometric ages on related igneous rocks indicate deposition of these formations during the Early Proterozoic between approximately 1,760 and 1,630 Ma.

Minor radioactivity of the McCaslin Formation is due to placered zircon grains. The metaconglomerate is probably too young to contain Elliot Lake-type placered uranium. However, since the McCaslin-Waupee contact is not exposed and has not been studied, an unconformity-type uranium deposit can not be ruled out.

INTRODUCTION

The McCaslin Formation (Mancuso, 1960) is located in northeastern Wisconsin in parts of Forest, Oconto, Marinette, and Langlade Counties (fig. 1). The main topographic features are McCaslin Mountain, Thunder Mountain, and Deer Lookout Tower Hill. Eastward the range splits into two ridges, informally referred to as the northern and southern branches.

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The McCaslin Formation is underlain by the Waupee Volcanics which consists of basalt, andesite, rhyolite, and interflow metasedimentary rocks (Mancuso, 1960; Lahr, 1972). The McCaslin Formation has been intruded by the Wolf River Batholith, which in the McCaslin area consists of the Hager Rhyolite Porhyry and High Falls Granite.

LITHOLOGY

The total thickness of the McCaslin Formation is difficult to evaluate because of extensive glacial cover. The basal contact with the Waupee volcanics is not exposed although the two crop out within 30 m of one another. The thickness of the McCaslin Formation varies from 1,220 m at Thunder Mountain to 610 m across the northern branch (Olson, 1982). The varying thickness may be due to erosion of the McCaslin prior to emplacement of the Hager Rhyolite Porphry.

The main rock types comprising the McCaslin Formation are quartzite and a basal metaconglomerate. The metaconglomerate, best exposed on the northern side of the range, is generally thin and lenticular. It becomes interlayered with cross-bedded quartzite upward in the section and eventually disappears about 300 m from the base. Approximately 73 percent of the pebbles counted were white vein quartz (fig. 2). The remainder included iron-formation, 18 percent; white chert and quartzite, 7 percent; and jasper 2 percent. In general, the pebbles decrease in size from 3 cm at Ada Lake in the west to 0.2 cm at Thunder Mountain in the east. The average size also decreases upwards through 85 m of section at Ada Lake from 3.0 cm to 1.5 cm.

The majority of the quartzite is light maroon in color due to disseminated hematite. Original grain boundaries are visible only on the extreme western end where the quartz has not been significantly recrystallized by contact metamorphism.

Much of the quartzite is cross-bedded (fig. 3). A total of 123 crossbeds was measured in the field. Approximately 25 percent are classified as tabular or planar and 75 percent as trough. The cross-beds range between 2.5 and 61 cm in thickness, both types averaging about 12 cm. The upper part of the section contains very little cross-bedding. This may be due to changes in the depositional environment or it may have been obscured by contact metamorphism of the Wolf River Batholith.

A few silty layers, up to 3 cm thick, are present in the McCaslin Formation, however these comprise only a very small percentage of the total exposure. Asymmetrical ripple marks are present in one outcrop along the southern branch. These trend northeast-southwest with an apparent current direction from the southeast. The ripple index is about 9, indicating subaqueous deposition.

Cyclicity is common in the bedding and cross-bedding of the quartzite of the McCaslin Formation, with an upward decrease in grain size and scale of cross-bedding. In general, light-colored coarse beds with large-scale crossbeds alternate with darker colored, finer-grained beds with small-scale crossbeds.

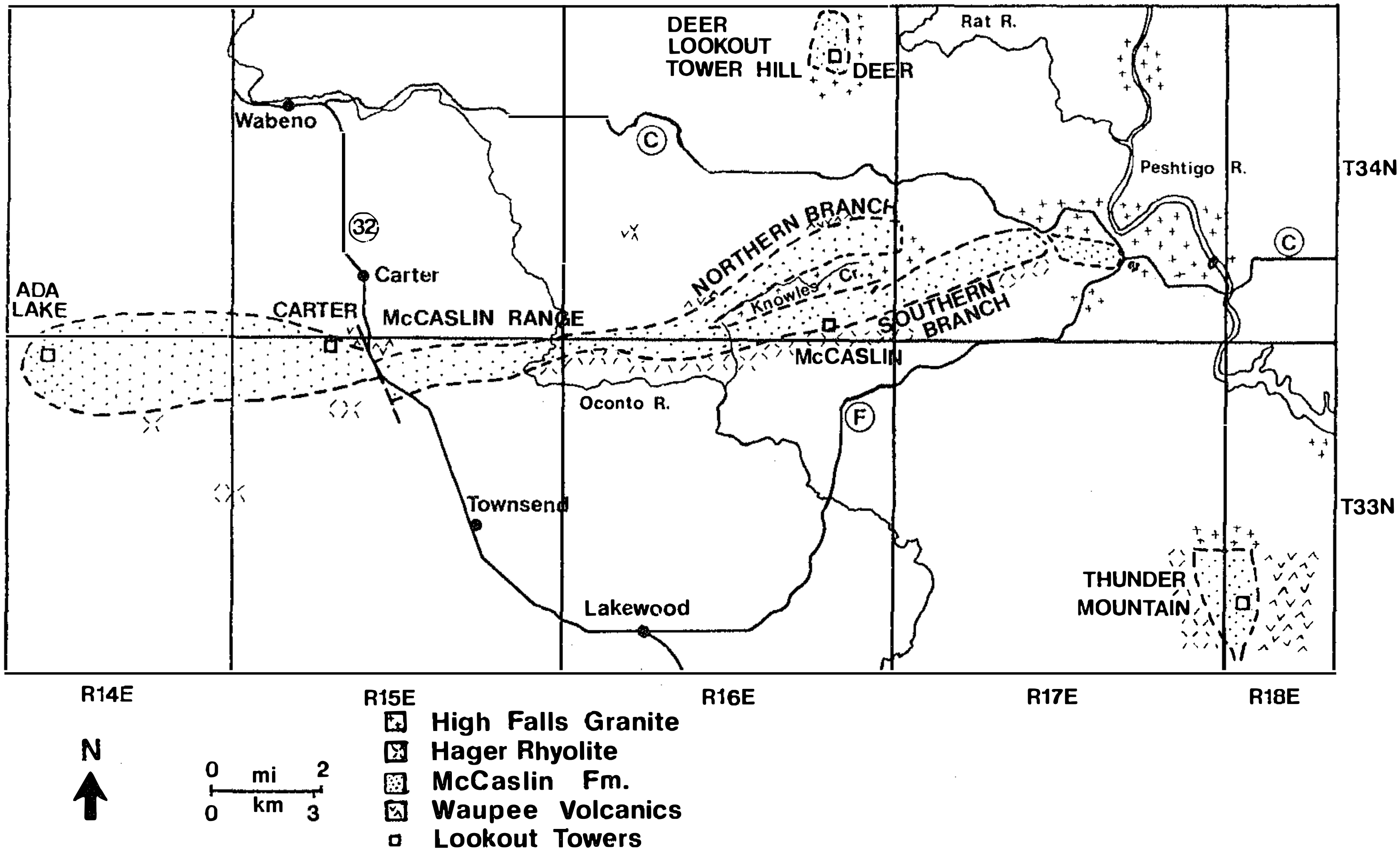

FIGURE 1.--General location map of McCaslin Formation.

FIGURE 2.--Metaconglomerate at Carter Lookout Tower (NE¼ sec. 5, T. 33 N., R. 15 E.). Note predominance of vein quartz pebbles.

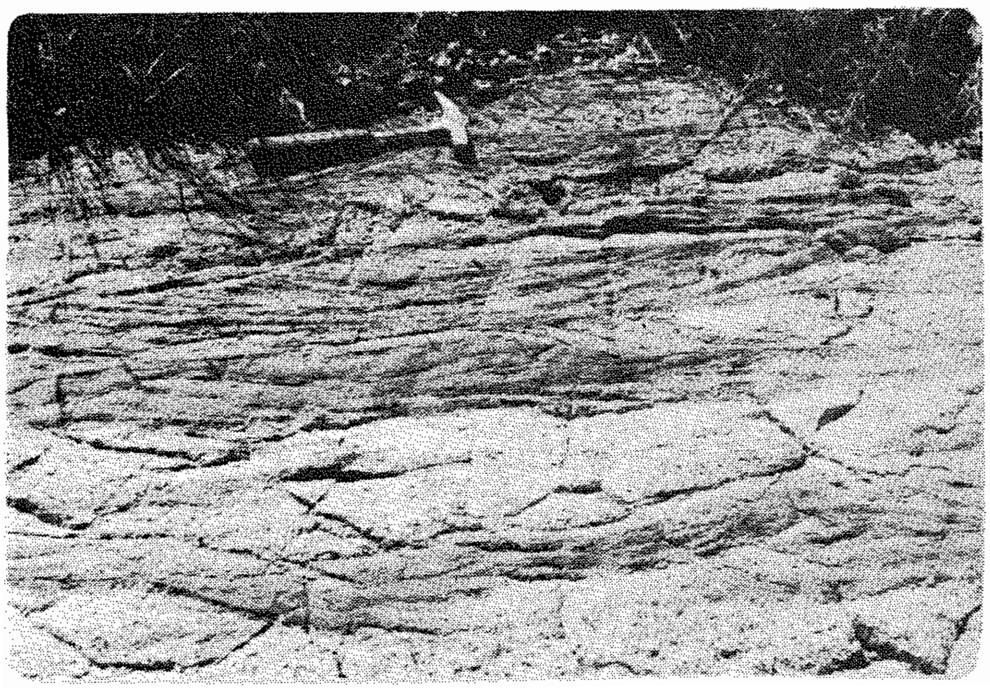

FIGURE 3.--Large scale trough cross-bedding in quartzite at Thunder Mountain (SE¼ sec. 30, T. 33 N., R. 18 E.).

STRUCTURE

The McCaslin Formation generally dips to the south along most of the ridge including the northern branch (fig. 4). However, along the southern branch, the bedding dips to the north and is overturned. Beds at both Thunder Mountain and Deer Lookout Tower Hill dip to the west. A pi diagram of 242 poles of bedding shows the girdle of a syncline plunging 30 degrees to the S. 20° W. (fig. 5). The axis of the syncline lies between Thunder Mountain and McCaslin Mountain.

The overturning of the southern branch is a secondary feature in the syncline (fig. 6). The overturned orientation of the bedding was determined on the basis of overturned trough cross-bedding north of the McCaslin Mountain Lookout Tower. The presence of quartz pebbles in this outcrop suggest it is proximal to the basal metaconglomerate. There may be a fault related to the intrusion of the High Falls Granite between the northern and southern branches. The location of the fault zone is marked by quartzite breccia recemented by white vein quartz as well as a lineament observable on aerial photographs. The zone trends northeast and appears to cut the eastern edge of the northern branch.

A major fault, oriented north-northwest, occurs south of Carter (Mancuso, 1960). It is a right lateral fault. The Waupee-McCaslin contact is offset about 300 m across the fault. The quartzite along the fault has also been recemented by white vein quartz.

Deer Lookout Tower Hill appears to be separated from the McCaslin Range by a major fault which strikes approximately east-northeast, but the direction of displacement is unknown. The fault trace appears as a lineament on aerial photographs and as a linear series of magnetic highs and lows on an airborne magnetic survey.

Another smaller reverse fault is also present at Deer Lookout Tower Hill, trending north-northeast. The Waupee-McCaslin contact is repeated indicating dip slip movement with the western block uplifted relative to the eastern block.

PETROGRAPHY

Seventy samples of the McCaslin were studied in thin section. All thin section chips were stained for alkali feldspar and plagioclase. Twenty-five thin sections were point counted along random traverses perpendicular to bedding.

There are three types of sand-sized rock fragments in the McCaslin Formation. These include recrystallized chert, quartz sandstone, and iron-formation composed of banded hematite and chert. There are three types of quartz present in the sand fraction. These include monocrystalline or common quartz, recrystallized chert, and recrystallized sandstone grains.

Muscovite occurs as laths which may be poikiloblastic enclosing the quartz, especially near faults and granite intrusions due to the shearing and higher metamorphic grade in these areas.

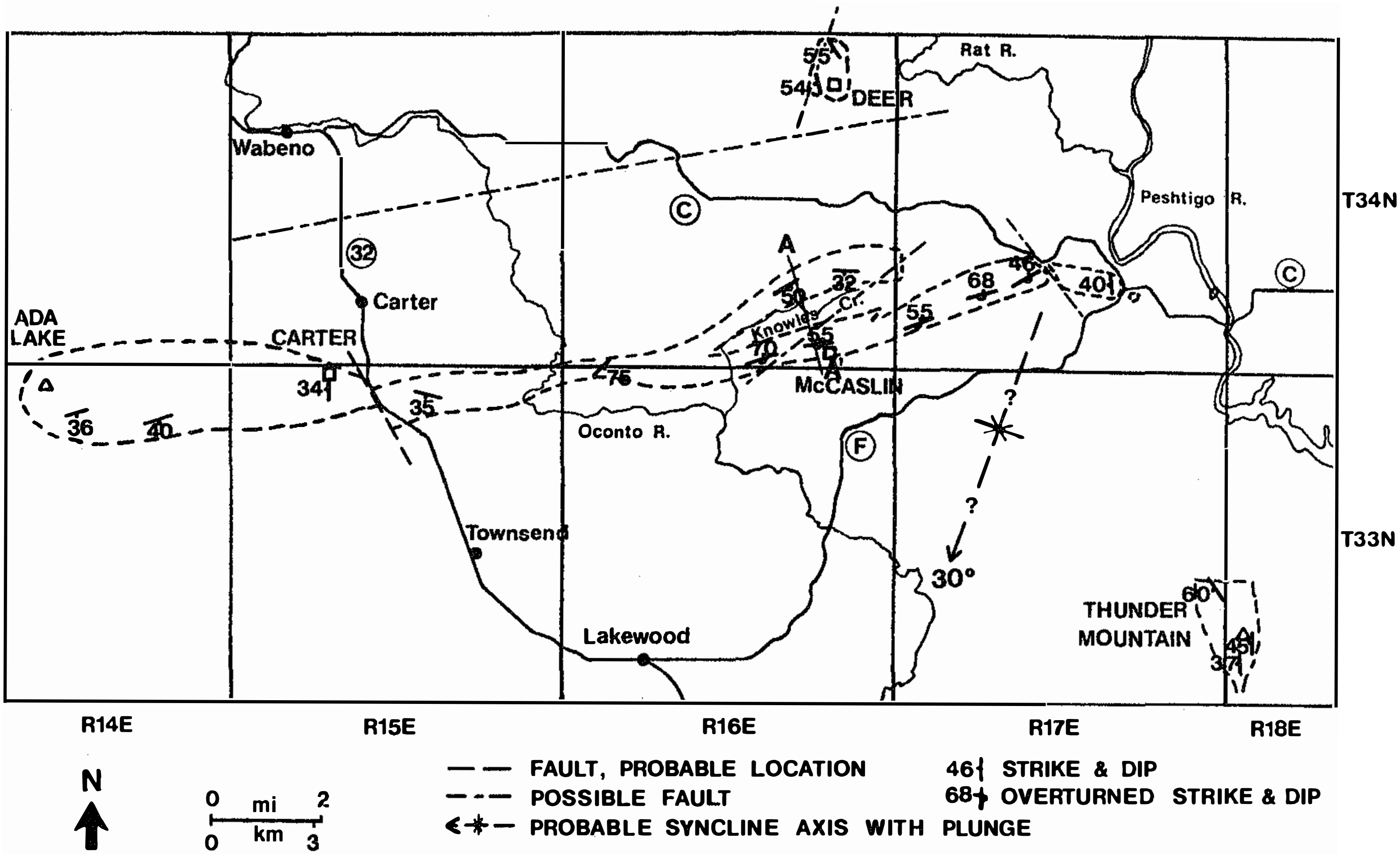

FIGURE 4.--Structure of the McCaslin Formation.

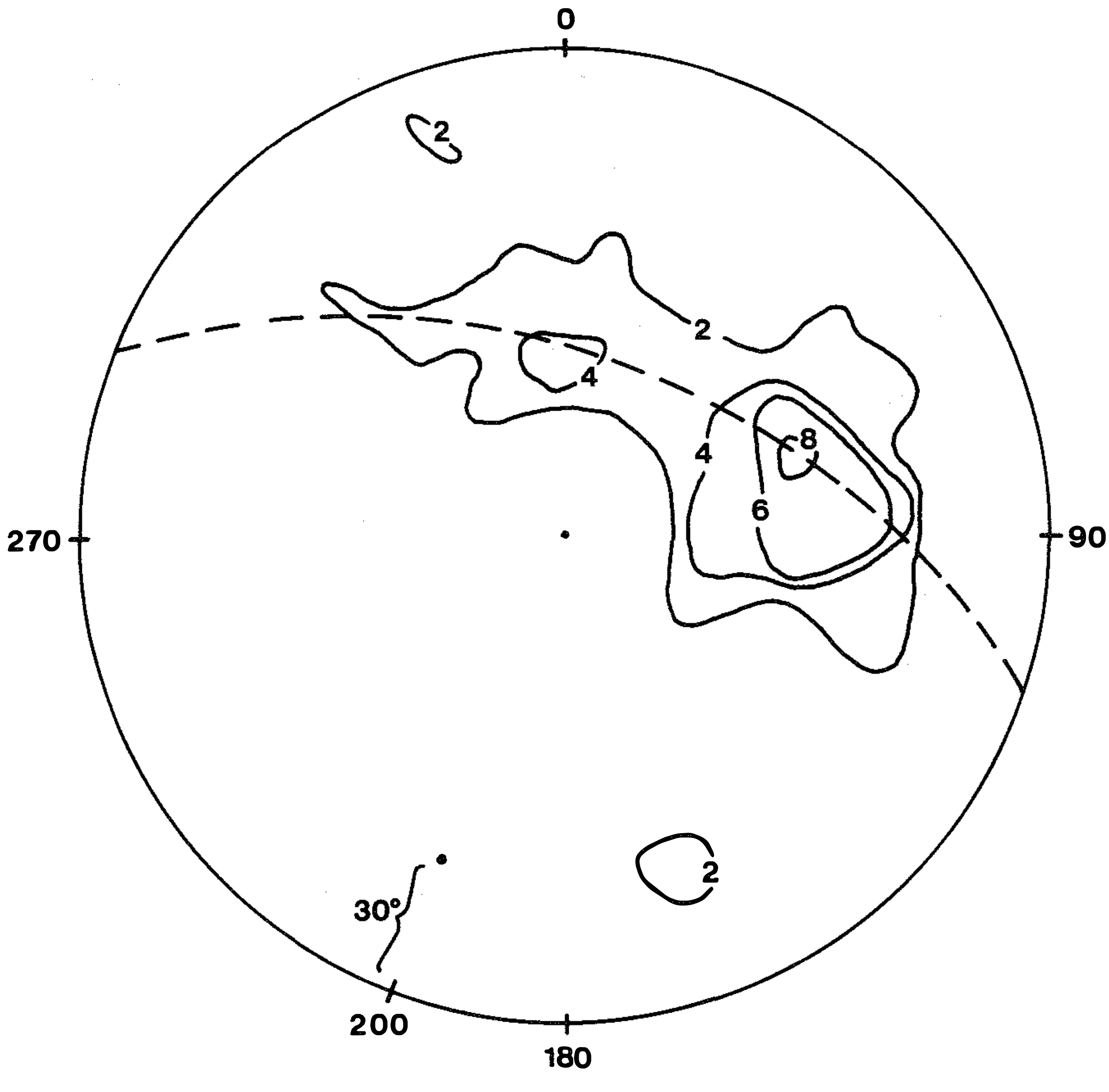

FIGURE 5.--Contour diagram of poles of bedding. 242 total measurements, contour interval 2%. Syncline plunges 30° at azimuth 200°.

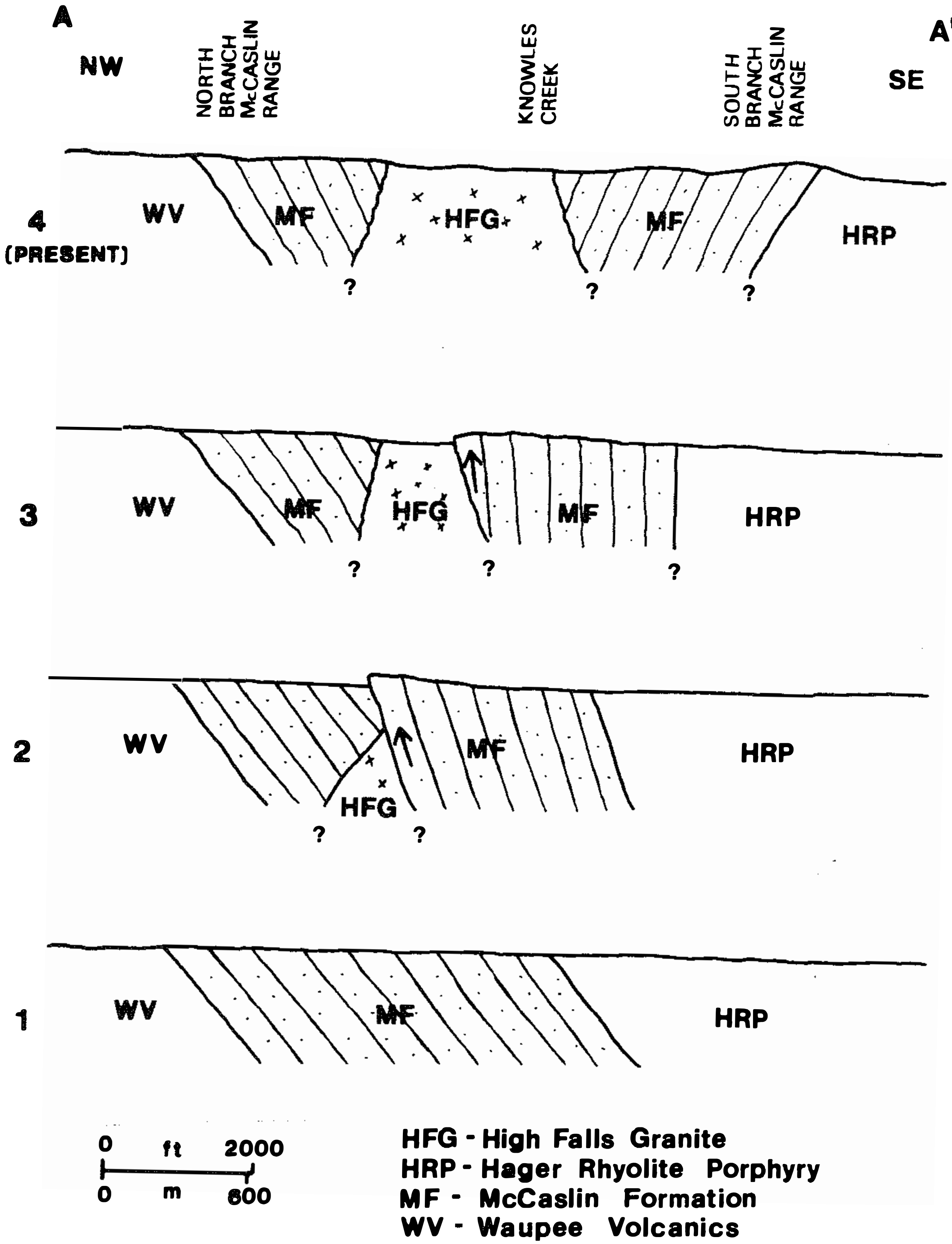

FIGURE 6.--Hypothetical cross sections showing possible overturning of McCaslin and intrusion of High Falls Granite.

Epidote occurs near Ada Lake at the western end where the metamorphic grade is lowest. It is present as irregular, secondary grains in a micaceous matrix.

Feldspar only occurs in an outcrop near the Peshtigo River where a 5 m block of quartzite has been surrounded by High Falls Granite. Albite, microcline, and perthite are present. The microcline and perthite are less altered than the plagioclase, and poikiloblastic around quartz grains. Apparently potassium was supplied to the quartzite by the granite, enabling the formation of the feldspar at the expense of andalusite.

Chloritoid is found in samples from Deer Lookout Tower Hill Thunder Mountain, and the northern branch. It is pleochroic green to blue, twinned, and forms needles and laths.

Andalusite occurs in varying amounts throughout most of the area. It commonly shows signs of alteration to sericite and probably formed from metamorphism of the original interstitial clay.

Andradite appears in samples from Deer Lookout Tower Hill, Thunder Mountain, and the southern branch. It commonly has alteration rims of chlorite.

Sillimanite occurs in quartzite at Deer Lookout Tower Hill and Thunder Mountain. It typically forms needles, generally radiating from grain contacts.

Only two minerals are found as matrix in the quartzite. Sericite or fine-grained, slightly impure muscovite, appears as tiny individual laths less than 30 microns long. Kaolinite, identified by x-ray analysis, is similar in appearance to sericite but has lower birefringence. Minor amounts are present locally as small laths. The kaolinite is probably not primary, possibly forming by alteration of pyrophyllite. The pyrophyllite reported by Motten (1972) and Miller (1980) was not observed in this study.

The only mineral which can be identified as cement is silica. It is observable as quartz overgrowths in samples from the western end of the outcrop area. Elsewhere recrystallization has obscured the original grain boundaries.

Fifteen heavy mineral mounts from the McCaslin Formation were also studied. At least 300 nonmagnetic, non-opaque grains were counted for each. The heavy mineral suite can be divided into detrital and metamorphic groups. Those which show evidence of abrasion such as rounding are detrital; the rest are considered metamorphic.

The most abundant detrital heavy mineral is zircon. Zircons were divided into six categories based on the presence of zoning and degree of roundness. On the whole, unzoned zircons are more numerous, averaging 61 percent. The angular categories include idiomorphic grains, broken grains, and those with euhedral overgrowths and constitute 76 percent of the total. The subrounded groups comprise 21 percent with the rounded categories making up about 3 percent of the total.

Detrital red rutile is uncommon, making up less than 1 percent of the total heavy mineral suite. Tourmaline is rare; it generally shows brown-green pleochroism and occurs as broken crystals. The ZTR Index (Hubert, 1962) of the detrital heavy minerals is 100 percent, indicating a very mature suite. Opaque minerals include magnetite and hematite. Pyrite also occurs but appears to be secondary.

The metamorphic heavy minerals include andalusite, andradite, sillimanite, epidote, and clinozoisite. Yellow rutile is generally associated with hematite in thin section, and probably resulted from the separation of titanium and iron from ilmenite and leucoxene during weathering and metamorphism.

Almost all of the McCaslin thin sections can be classified as quartzite or quartzose metaconglomerate. On a ternary sandstone classification diagram (Pettijohn, Potter, and Siever, 1973), these would plot at the quartz corner. There are no feldspar or rock fragments present in the sand fraction. Assuming the sericite, andalusite, and sillimanite represent original clayey matrix, almost all the samples would be classified as metamorphosed quartz arenites. Only one fine-grained sample, containing more than 15 percent matrix, would be classified as a quartz wacke.

METAMORPHISM

The contact metamorphism is a result of the intrusion of various phases of the Wolf River Batholith. The only two metamorphic facies present in the McCaslin are the hornblende hornfels facies, and the albite-epidote hornfels facies which is essentially low pressure greenschist facies.

Metamorphism resulted from contact with the Hager Rhyolite Porhyry as well as the intrusion of the High Falls Granite. McCaslin outcrops adjacent to the Hager contain sillimanite and andradite, indicating it was very hot, possibly equal in temperature to the High Falls Granite.

The lowest metamorphic grade is found at Ada Lake where epidote, siderite, and andalusite occur. The majority of the quartzite contains some andalusite with chloritoid and andradite present locally. Sillimanite represents the highest grade of metamorphism, and occurs at Deer Lookout Tower Hill, Thunder Mountain, and near the Oconto River. The Sillimanite needles typically formed at the expense of andalusite.

SEDIMENTATION

Rose diagrams of 113 paleocurrent measurements, corrected for structural dip by a two-tilt solution (Ramsay, 1961) are shown in figure 7. After rotation of bedding back to horizontal, the mean dip of inclination of the cross-bedding was 21 degrees, decreasing slightly upward in the formation. Although most of the outcrops have a high variance, the calculated vector means are subparallel to the east. The overall direction of sediment transport is interpreted to have been generally from west to east with substantial local variation.

The overall characteristics of the McCaslin Formation include cyclical, small-scale trough and planar cross-bedding, poor to moderate sorting, thin discontinuous conglomerate, rare asymmetrical ripple marks, and compositional maturity. Silt and clay are scarce and herringbone cross-bedding is totally

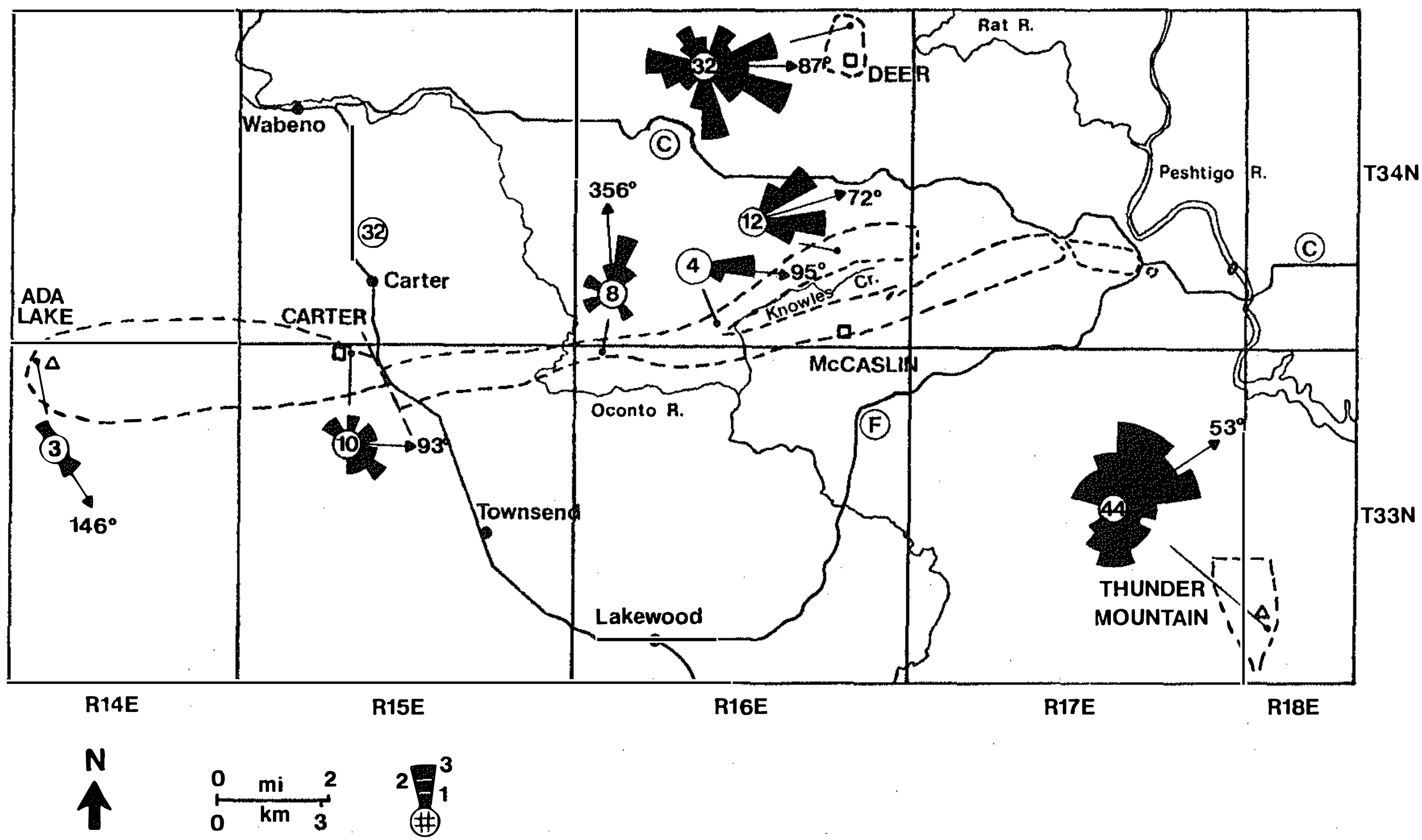

FIGURE 7.--Paleocurrent plots of cross-bedding. Number in center is number of readings, arrow is vectorial mean.

absent. These features seem to best fit a braided stream model. Most pre-Silurian streams were braided (Cotter, 1978). The absence of vegetation restricted the formation of overbank deposits and also permitted extensive movement of sand by the wind, thus aiding in production of a mature sand. Most likely the McCaslin Formation was deposited in a braided stream environment although aeolian processes were probably active over the alluvial plain.

However, there are several features of the McCaslin Formation which do not easily fit the braided stream model. Braided streams typically have an overall unimodal paleocurrent distribution. The paleocurrent distribution of the McCaslin is somewhat unidirectional, but there is a considerable amount of variance. One possibility may be a tidal influence in a sea at the edge of the alluvial plain. However, features typical of tidal marine environments such as herringbone cross-strata and associated carbonates and shales are not present. Other possible causes for the lack of unimodality include the variability inherent in braided stream cross-bedding (Smith, 1972) and local irregularities in the Waupee topography at the time of deposition.

There are six types of braided stream models (Miall, 1977). The McCaslin Formation most resembles the Donjek River model which occurs in the more distal reaches of alluvial fans (Rust, 1975). The Donjek characteristics are somewhat variable, but generally cyclic with an upward decrease in grain size, bed thickness and scale of sedimentary structures. Poorly-bedded gravel comprises between 10 and 90 percent of the Donjek with small-and large-scale cross-beds in the sandy layers. In summary, the McCaslin Formation was probably deposited by a series of braided streams moving over a broad alluvial plain on a fairly stable but subsiding continental margin.

PROVENANCE

Since the dominant paleocurrent direction is generally from the west towards the east, the source area was probably located to the west, although sediment also could have been supplied from the north and south. Multiple sources of sediment are indicated by the various types of pebbles in the metaconglomerate as well as the various sizes and amounts of rounding of zircon grains. Iron-formation and chert pebbles indicate weathering and erosion of sedimentary rocks. The rutilated quartz and vein quartz pebbles are probably igneous, and the quartzite pebbles probably came from a metamorphic terrane. A possible source of the iron-formation is the Black River Falls iron-formation located approximately 200 kilometers to the southwest. Quartz-rich metasedimentary rocks occur in the Waupee Volcanics (Lahr, 1972) and may have produced some of the quartz sand. The quartz sand could have been reworked from an older sedimentary source, but because of metamorphism and recrystallization, multiple overgrowths can not be detected. Nevertheless, the overall compositional maturity and high ZTR Index indicate some reworking of older sands may have occurred.

CORRELATION AND AGE

The McCaslin Formation must be older than the Wolf River Batholith, dated at 1,500 Ma (Van Schmus, Thurman, and Peterman, 1975). However, the Waupee Volcanics which underlie the McCaslin have not been dated, therefore a maxiumu age for the McCaslin has not been determined.

The McCaslin Formation was previously correlated with the Baldwin Conglomerate because of similarities in stratigraphic position and litologic type (Mancuso, 1960). The Baldwin Conglomerate crops out near Mountain, 23 km south of McCaslin Mountain Lookout Tower. Like the McCaslin, it overlies the Waupee Volcanics and underlies the Hager Rhyolite Porphyry. The Baldwin is a poorly sorted metaconglomerate with angular to subrounded clasts of quartz, Waupee, and feldspar in a matrix of quartz, feldspar and mica.

Anderson (1978) concluded that the Baldwin and McCaslin Formations were not deposited simultaneously. The Baldwin has primarily subangular clasts of rock fragments suggesting a close source area with fairly high relief. In contrast, the McCaslin has mainly rounded quartzite and quartz pebbles indicating a more distant source and lower relief. The radioactivity of the Baldwin is also higher as a result of more immature rock fragments.

Sims and Mudrey (personal communications, 1981, and as shown in Morey and others, 1982) suggest a possible origin for the Baldwin. They believe there is evidence of shearing along an east-northeast trending zone in the Waupee Volcanics. The Baldwin may be a breccia deposited along the edge of this zone, which was later lithified and covered by the Hager Rhyolite Porphry. Therefore the Baldwin Conglomerate may have been deposited at approximately the same time as the McCaslin Formation, but they are not lithologic correlatives.

There are several Precambrian quartzites in the Lake Superior region which have been studied most recently by Ojakangas and Morey (1982). These include the Bessemer Formation, the Sibley Group, the Puckwunge Formation, and the Nopeming Formation. These quartzites range in age from 1,100 to 1,340 Ma and are all younger than the McCaslin. Other older quartzites in the region have also been correlated, namely the Sioux, Flambeau, Barron, Baraboo, and Waterloo Quartzites (Dott and Dalziel, 1972; Weber, 1981; and Campbell, 1982). The ages of these quartzites have been placed between 1,630 and 1,760 Ma on the basis of radiometric dating of associated igneous rocks (Van Schmus, 1978). These erosional remnants may represent a single sheet or at least more extensive deposits.

The McCaslin resembles this older group of quartzites and may be correlative with them. The sedimentation, metamorphism, regional structure, and compositions are all similar. Compositional similarities consist of clast lithologies, the types of quartz sand grains, the heavy mineral suites, and the phyllosilicates (table 1).

Sedimentation of these quartzites also appears to have occurred under analogous conditions since the quartzites are all fairly thick. The environments of deposition of the Flambeau (Campbell, 1982), the Baraboo and Waterloo (Dott, in press), and the McCaslin appear to be fluvial. The Barron (Campbell, 1982) and Sioux (Weber, 1981) are possibly a combination of fluvial and marine. Both fluvial and marine environments may have occurred at different times in different areas.

The McCaslin has the highest metamorphic grade of the quartzites under consideration, reaching the hornblende hornfels facies. Generally the other quartzites have been subjected to regional metamorphism, ranging from greenschist to lower amphibolite facies (Dott, in press). The high grade of the McCaslin results from contact metamorphism of the Wolf River Batholith. This

TABLE 1.--Comparison of composition of McCaslin Formation with other Proterozoic quartzites. Information compiled from Dott and Dalziel, 1972; Campbell, 1982; and Weber, 1981. Listed in order of decreasing abundance

	McCaslin	Baraboo	Barron	Sioux	Flambeau
Pebble Types (>2 mm)	Vein quartz Jasper Chert Iron-formation	Vein quartz Chert Jasper	Vein quartz Quartzite Jasper Slate	Vein quartz Chert Jasper Iron-formation Rhyolite Quartzite	Vein quartz Chert Rhyolite Iron-formation
Sand Types (<2 mm)	Strained Unstrained	Strained Polycrystalline Chert	Unstrained Strained Polycrystalline Chert	Strained Polycrystalline Unstrained Chert	Strained Polycrystalline Chert
Heavy Minerals	Hematite Zircon Rutile Pyrite Tourmaline	Zircon Magnetite Pyrite Rutile Barite	Zircon Ilmenite Leucoxene Rutile Apatite	Zircon Rutile Tourmaline Magnetite Hematite	Magnetite Hematite Zircon Tourmaline
Phyllosilicates	Muscovite Kaolinite	Muscovite Pyrophyllite Kaolinite	Kaolinite Illite	Pyrophyllite Muscovite Illite	Muscovite

may have been superimposed on an older low grade regional metamorphism similar to the other quartzites, however evidence of only one metamorphic event can be observed in the McCaslin.

The deformation of some of the quartzite units is also remarkably similar. The Baraboo, Waterloo, and McCaslin form asymmetrical synclines oriented northeast-southwest. The Flambeau Quartzite also forms a syncline, opening to the northwest. In contrast, the Barron is almost flat, dipping slightly to the north, and the Sioux is very gently folded, generally dipping to the south and southwest.

The McCaslin Formation appears to correlate with the Baraboo, Waterloo, Barron, Flambeau, and Sioux on the basis of maturity, depositional environment, degree of metamorphism and style of deformation. If the McCaslin is correlative with the other quartzites, it may be between 1,630 and 1,760 Ma or Early Proterozoic in age.

TECTONIC SETTING

The overall tectonic setting must have been fairly stable to produce a thick extensive deposit of quartz sand. However, some basin subsidence or uplift would be necessary to enable these thick formations to develop. The primary aluminum-rich clay minerals such as pyrophyllite and kaolinte indicate intensive chemical weathering typical of a warm, humid climate with fairly low relief. This combination would permit weathering and leaching of less stable constituents such as feldspar. The lack of land vegetation would have allowed the resulting fine material to be removed by wind or water action.

The paleocurrent patterns for the six possibly correlative (?) units appear to surround a fairly extensive highland located in east-central Minnesota and central Wisconsin (fig. 8). Broad coalescing alluvial fans may have developed on the flanks of this highland with a sandy coastal plain along the edge of the alluvial plain.

Marine transgression may have started with the deposition of the quartzites. Black slates and iron-formation-bearing dolomite overlie the Baraboo (Dott, 1982). The Sioux Quartzite has been interpreted as fluvial in the lower two-thirds and marine in the upper third (Weber, 1981). The later deformation of these quartzites marks the end of the stable tectonic setting.

URANIUM POTENTIAL

Interest in the uranium potential of the McCaslin developed in 1955 with the discovery of uraniferous conglomerate east of the McCaslin Mountain Lookout Tower (Kalliokoski, 1976). Attempts to find similar conglomerate in this area have been unsuccessful. The uraniferous samples could have originated in the conglomerate along the northern branch, or they may be part of the glacial drift.

Exploration in the McCaslin area began with geochemical and geophysical reconnaissance during 1957 (Kinneman and Illsley, 1962). Anderson (1978) included the McCaslin in his radiometric survey of Middle Precambrian quartzites in Wisconsin. Western Nuclear drilled three test holes into the McCaslin in 1978. The cuttings were studied by Miller (1980) who concluded that zircons were the cause of radiation in the McCaslin.

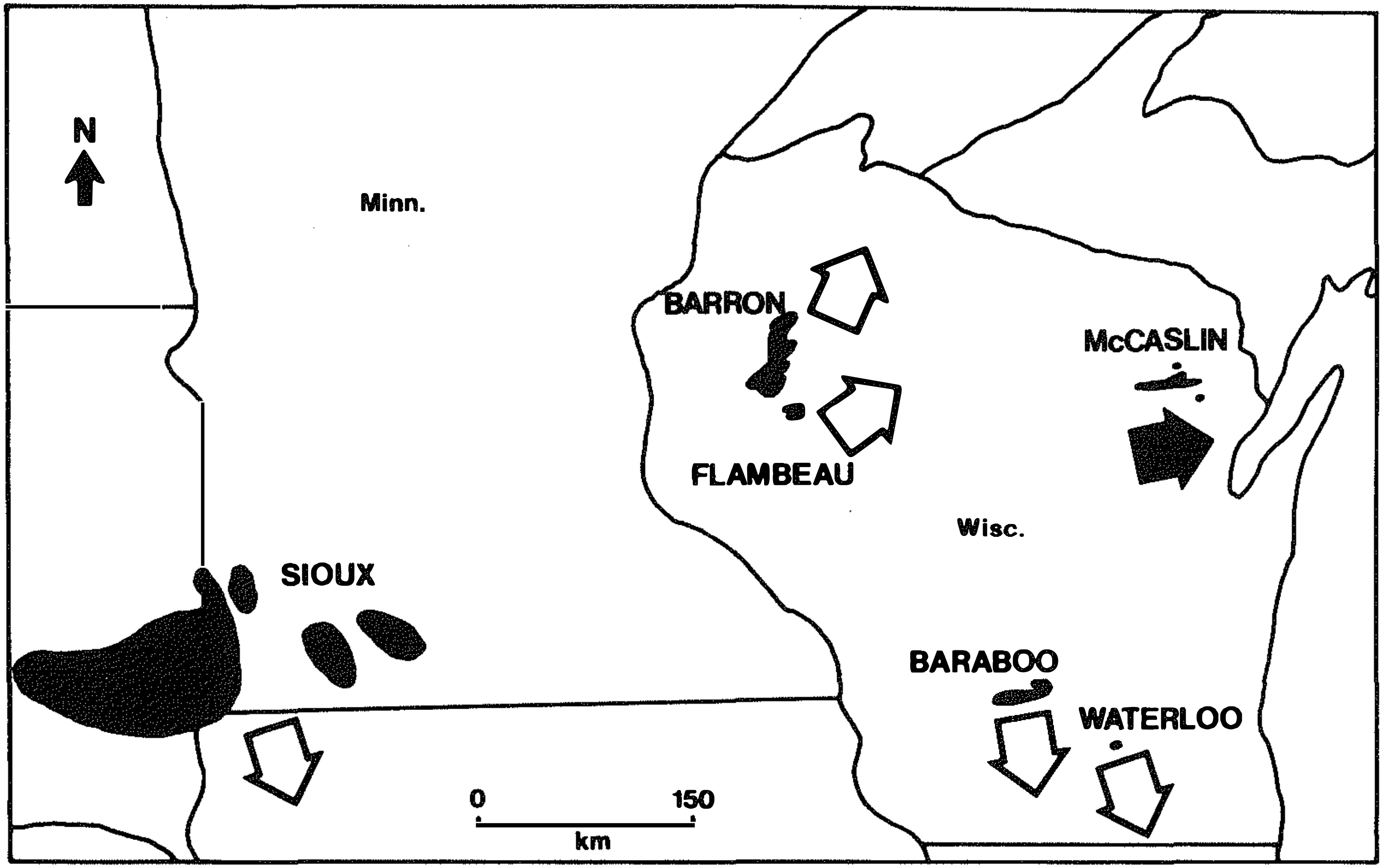

FIGURE 8.--Location of Proterozoic orthoquartzites and their dominant paleocurrent directions.

Airborne radiometric and magnetic surveys were flown over most of the McCaslin area during August, 1980. Flight lines and contour maps were made available to the author by the U.S. Geological Survey. Radioactive anomalies appear to be scattered randomly throughout the area. Many are related to the Hager Rhyolite Porphry and High Falls Granite, but some seem to be associated with the McCaslin-Waupee contact.

A ground survey of the McCaslin during this investigation disclosed that the conglomerate is more radioactive than the quartzite. Uranium and thorium analyses of nine samples were also conducted by the USGS. The overall amount of thorium ranges between 3.3 and 99.9 ppm, and uranium between 1.31 and 9.45 ppm (Olson, 1982). The highest thorium reading is from the southern side of Deer Lookout Tower Hill. The highest uranium value is from a sample just north of the McCaslin Mountain Lookout Tower.

Luxophotographs (alpha-prints) were also made on samples of the McCaslin. The results show that the source of radioactivity in the McCaslin is probably zircon grains.

A uranium deposit could still conceivably be found at the base of the McCaslin which is not exposed and was not reached in the test holes. A quartz-pebble conglomerate-type deposit is unlikely if the McCaslin is younger than 2,000 Ma. Oxygenation of the atmosphere at about this time could have prohibited subsequent deposition of placered uraninite and pyrite (Kalliokoski, 1976). The potential for an unconformity-type deposit appears more likely. The regolith along the McCaslin-Waupee contact, if present, could supply uranium and act as a host for deposition. The uranium potential of the McCaslin cannot be fully analyzed until this unconformity is studied.

SUMMARY AND CONCLUSIONS

The McCaslin Formation is at least 1,220 m thick and is composed of a basal metaconglomerate and an overlying quartzite. It is a mature quartz arenite derived from multiple sources. The pebbles are predominantly vein quartz, with lesser amounts of iron-formation, chert, quartzite, and jasper. The detrital non-opaque heavy mineral suite is very mature, primarily composed of zircon with trace amounts of red rutile and tourmaline. Most zircons are angular to subrounded, but some are very well rounded. Opaque minerals include hematite and magnetite. The euhedral pyrite is probably not detrital.

The McCaslin has been metamorphosed to the hornblende hornfels facies by the intrusion of the Wolf River Batholith. Principal metamorphic minerals include andalusite, andradite, sillimanite, chloritoid, and epidote. The structure is that of a syncline plunging moderately to the south-southwest. The southern branch of the McCaslin Range is overturned.

The environment of deposition was probably a braided stream with the overall paleocurrent direction from west to east. The tectonic setting was fairly stable but with continued slow subsidence. Deposition probably occurred on broad alluvial fans along the flank of an extensive highland.

On the basis of lithology, the McCaslin may correlate with the Baraboo, Waterloo, Barron, Flambeau, and Sioux Quartzites. If correlative, it is probably between 1,630 and 1,760 Ma, or Early Proterozoic in age.

The source of the minor radioactivity within the McCaslin is most likely zircon grains. The McCaslin may be too young for a quartz-pebble conglomerate-type of uranium deposit. However, there is some potential for an unconformity-type deposit at the base of the formation since it is not exposed and therefore has not been studied.

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STRATIGRAPHY AND HISTORY OF GLACIAL DEPOSITS ALONG WISCONSIN'S LAKE SUPERIOR SHORELINE--WISCONSIN POINT TO BARK POINT

by

Edward A. Need[1,2] and Mark D. Johnson[1,3]

ABSTRACT

Detailed investigations of the materials exposed in the bluffs along the shoreline of Lake Superior between Wisconsin Point and the mouth of the Bark River, Wisconsin, disclose the presence of three till units. This three-fold till stratigraphy has been verified in numerous multiple-unit exposures and through laboratory analysis. It was possible to extend this till stratigraphy 18 to 24 km southward from the shoreline with subsurface data on file at the Wisconsin Geological and Natural History Survey.

The oldest till unit is named the Jardine Creek Member of the Copper Falls Formation. The till is a reddish brown, slightly stony, sandy loam. The till unit overlies bedrock and may compose the moraine along the southern edge of the study area. The next youngest till unit is named the Hanson Creek Member of the Miller Creek Formation. The till is calcareous, dark reddish brown, stone-poor clay that commonly contains complexly patterned stingers of red and gray material. This till unit is present west of the mouth of the Iron River and appears to pinch out in the subsurface 6 to 13 km south of the shoreline. The youngest till unit is named the Douglas Member of the Miller Creek Formation. The till is calcareous, dull reddish brown, stone-poor, massive clay or clay loam. This unit is the surface unit throughout the northern part of the study area.

These three till units indicate that glaciers advanced and retreated through the study area at least three times. The earliest advance, recorded by the Jardine Creek Member, was strongly erosive causing large amounts of local bedrock to be incorporated in the till. The two red-clay till units were deposited by ice that incorporated lake sediment while advancing into a proglacial lake.

Some tentative correlations are suggested. The Jardine Creek till is correlated to till of the St. Croix, Automba, Split Rock, and Nickerson Phases of Wright and others (1973). The Hanson Creek till may be correlative with a compact pebbly clay near Duluth, Minnesota. The Douglas till is correlated to the massive red clay near Duluth, Minnesota; red-clay till in Cook County, Minnesota; red-clay till south and east of Ashland, Wisconsin; and red-clay till near Ontonagon, Michigan.

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Though no sediment in the study area is dated, dates on correlative units suggest the following history: the Jardine Creek till was deposited before 12,000 B.P.; the Hanson Creek till around 11,000 B.P.; and the Douglas till around 10,000 B.P.

INTRODUCTION

During Late Wisconsin time, ice of the Superior Lobe repeatedly covered part of northwestern Wisconsin. This study is concerned with the stratigraphy of the deposits in the bluffs of the Wisconsin shoreline of Lake Superior, the correlation of these deposits to previously studied deposits in the region, and the glacial history that can be interpreted from these deposits. The location of the the study area is shown in figure 1.

The stratigraphy of the shoreline from Wisconsin Point to the Bark River was examined in detail during the summer of 1979. A mile-by-mile survey of the shoreline was made; in each mile, two to three stratigraphic sections and bluff profiles were measured. Numerous samples were taken from each of the stratigraphic units for standard laboratory analysis. Oriented samples were taken at several sites along the shoreline for thin-section studies. The engineering properties of the units were determined from geotechnical borings made at eight sites along the shoreline. The shoreline stratigraphy was extended inland in part of the study area with well-log data on file at the Wisconsin Geological and Natural History Survey.

In this paper, the lithologic characteristics, geographic extent, stratigraphic relationships, and subsurface extent, as determined from laboratory analyses shoreline exposures and the well-log data are described first. The historical interpretations of the stratigraphy, regional correlations, and tentative dates are discussed in the second part of the paper.

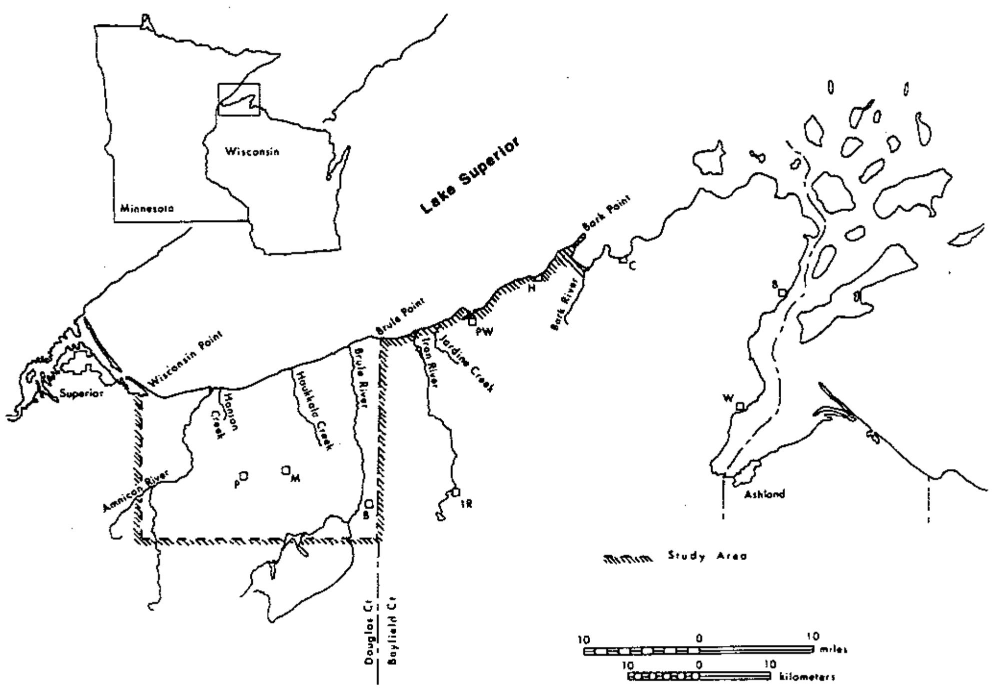

Figure 1.--Location and reference map of study area. P--Poplar, M--Maple, BR--Brule, IR--Iron River, PW--Port Wing, H--Herbster, C--Cornucopia, B--Bayfield, W--Washburn.

PREVIOUS WORK

Early work on the glacial history of the Superior Lobe concentrated on mapping abandoned shorelines of glacial lakes (Lawson, 1893; Taylor, 1897; Winchell, 1898). A regional assessment of postglacial lake levels in the Superior basin was made by Leverett (1929) and later by Farrand (1960).

Deposits of red clay in the Superior basin were noted as early as 1852 by Whittlesey. Leverett (1929) discussed the positions of end moraines of the Superior Lobe and suggested that some of the red clay was deposited subglacially and some in a lake. Whittlesey (1852) and Taylor suggested a lacustrine origin for the red clay--an interpretation upheld by later geologists (Mengel, 1973; Moss, 1977; Zarth, 1977). Johnson (1980) used microfabric analysis to show that the red clay was deposited subglacially. Red-clay till was mapped along the shoreline in Cook County, Minnesota by Sharp (1953b) and in the Ontonagon area of Michigan by Hack (1965).

The glacial history of the Superior Lobe has been outlined by Wright (Wright and Ruhe, 1965; Wright and Watts, 1969; Wright, Mattson, and Thomas, 1970; Wright, 1972; Matsch, and Cushing, 1973). He described a four-phase Late Wisconsinan history based on stratigraphic and geomorphic relationships in Minnesota.

In the study area, few detailed investigations exist. Whitson and others (1914) mapped soils in the Bayfield area and considered the red clay of the region to be of glacial origin. Slope stability factors for the red clay in Douglas County, Wisconsin, were determined by Mengel and Brown (1976, 1979). Mengel (1973) interpreted the red clay of Douglas County to be lake sediment.

STRATIGRAPHY

Introduction

The material exposed in the bluffs along the Lake Superior shoreline between Wisconsin Point and Bark Bay is predominantly till. Three till units were identified in the study area and are described in detail below. They are the sandy Jardine Creek Member, the clayey Hanson Creek Member, and the clayey Douglas Member.

In addition to till, discontinuous beds of sand and gravel locally predominate within the bluffs. Laminated lake sediment has been described in the region (Mengel, 1973; Moss, 1977; and Zarth, 1977), but only isolated outcrops located on Bark Point were found in the study area.

The characteristics of each till unit, summarized in table 1, are discussed below in order of age from oldest to youngest. A complete listing of all samples analyzed and their locations can be found in Need (1980). The distribution of the till units and other materials along the shoreline is shown in figures 2 through 9. These shoreline profiles were derived from data presented by Need and others (1980). Type sections are described in Mickelson and others (in press).

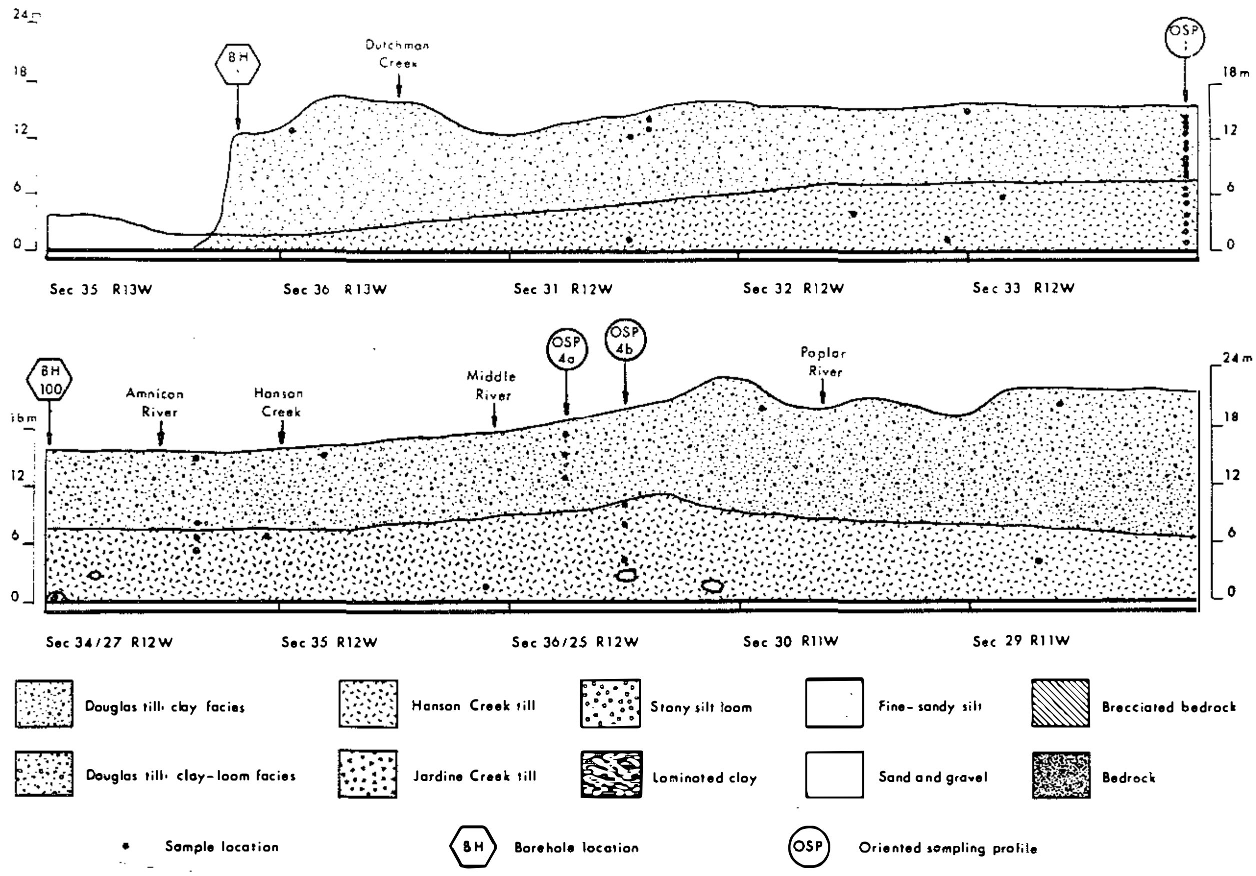

Figure 2.--Shoreline profile: Wisconsin Point to Bardon Creek.

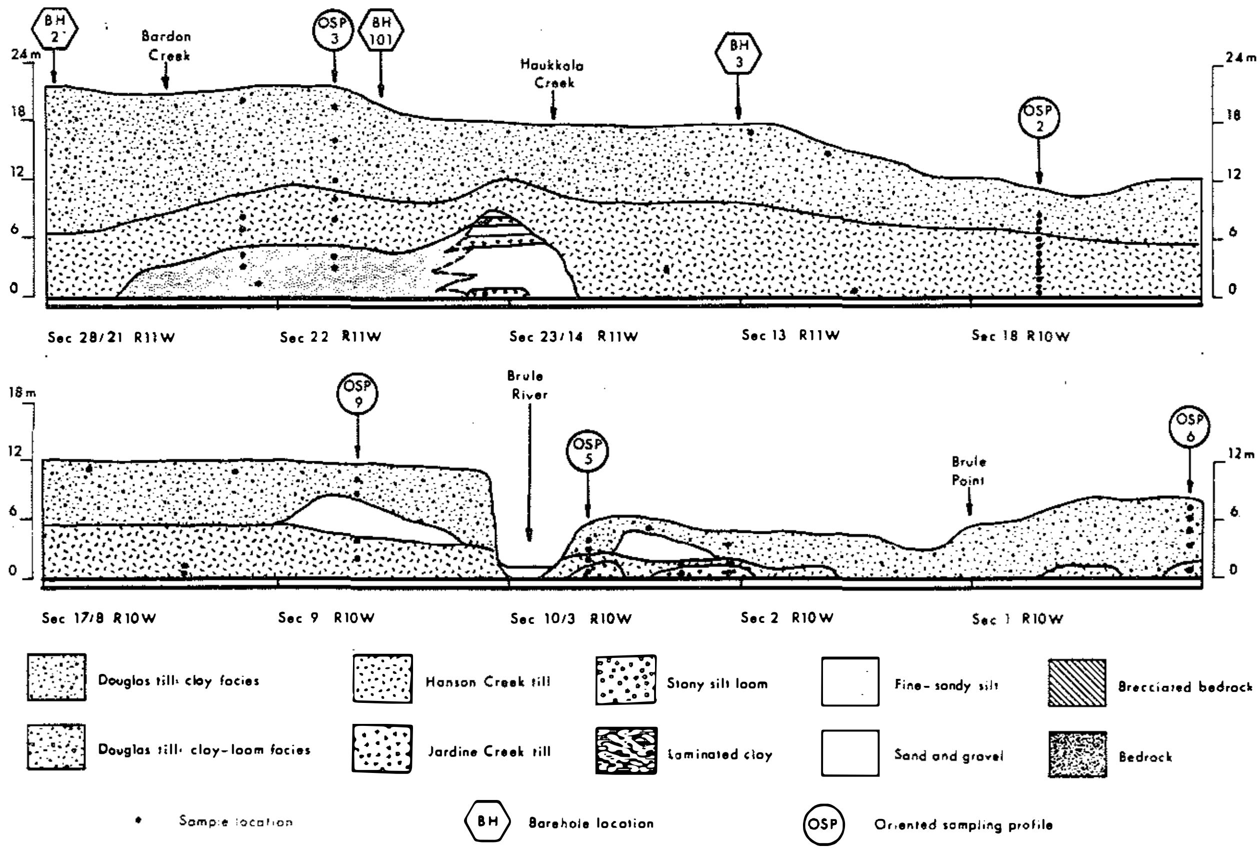

Figure 3.--Shoreline profile: Bardon Creek to Brule Point.

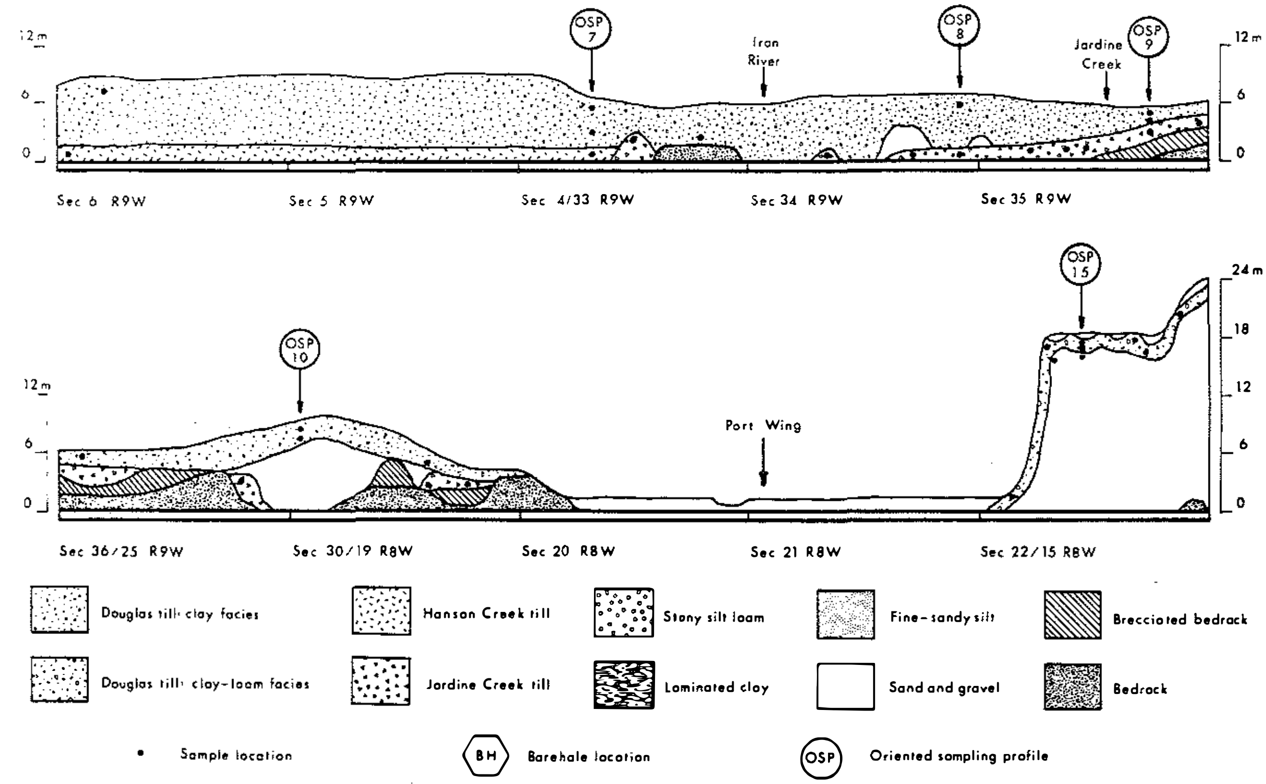

Figure 4.--Shoreline profile: Brule Point to Port Wing.

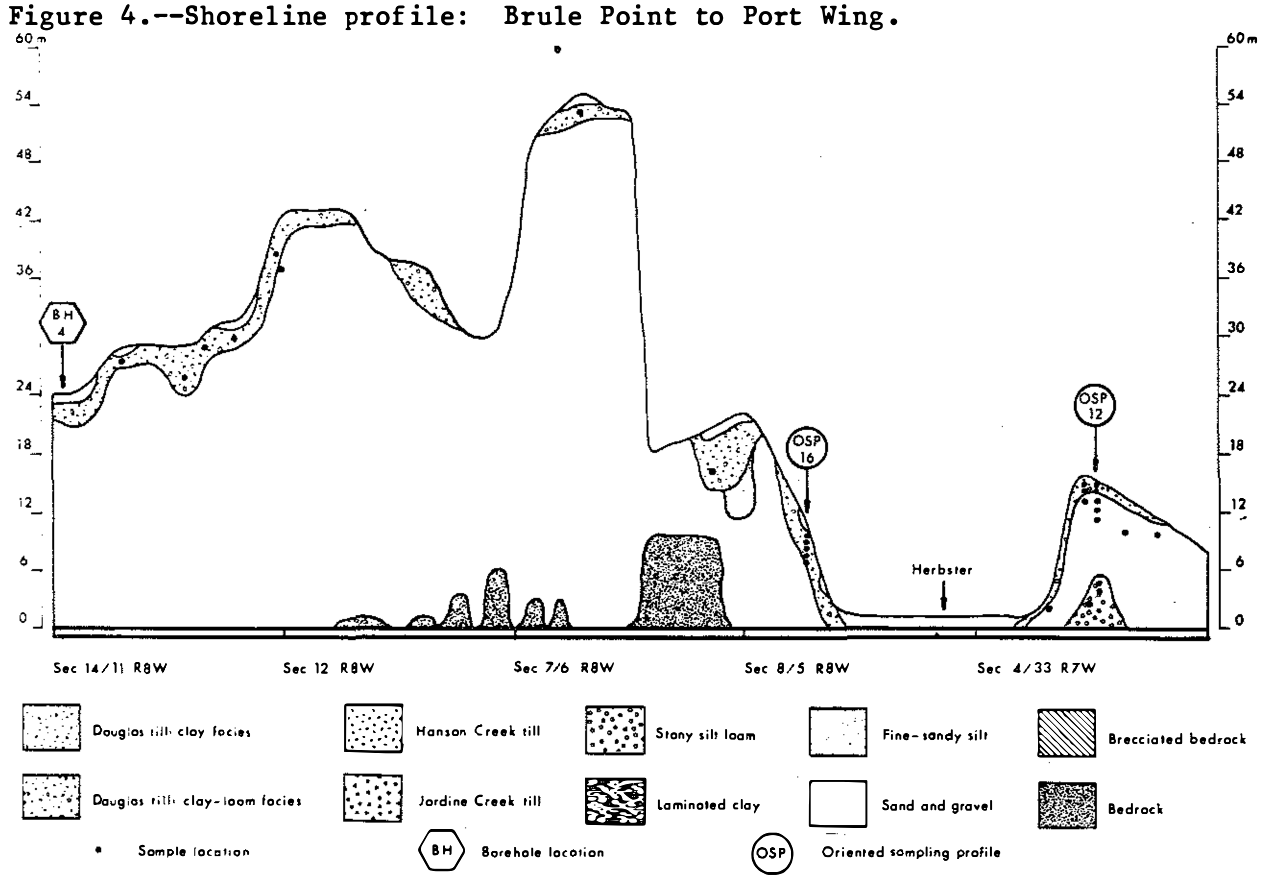

Figure 5.--Shoreline profile: Port Wing to Herbster.

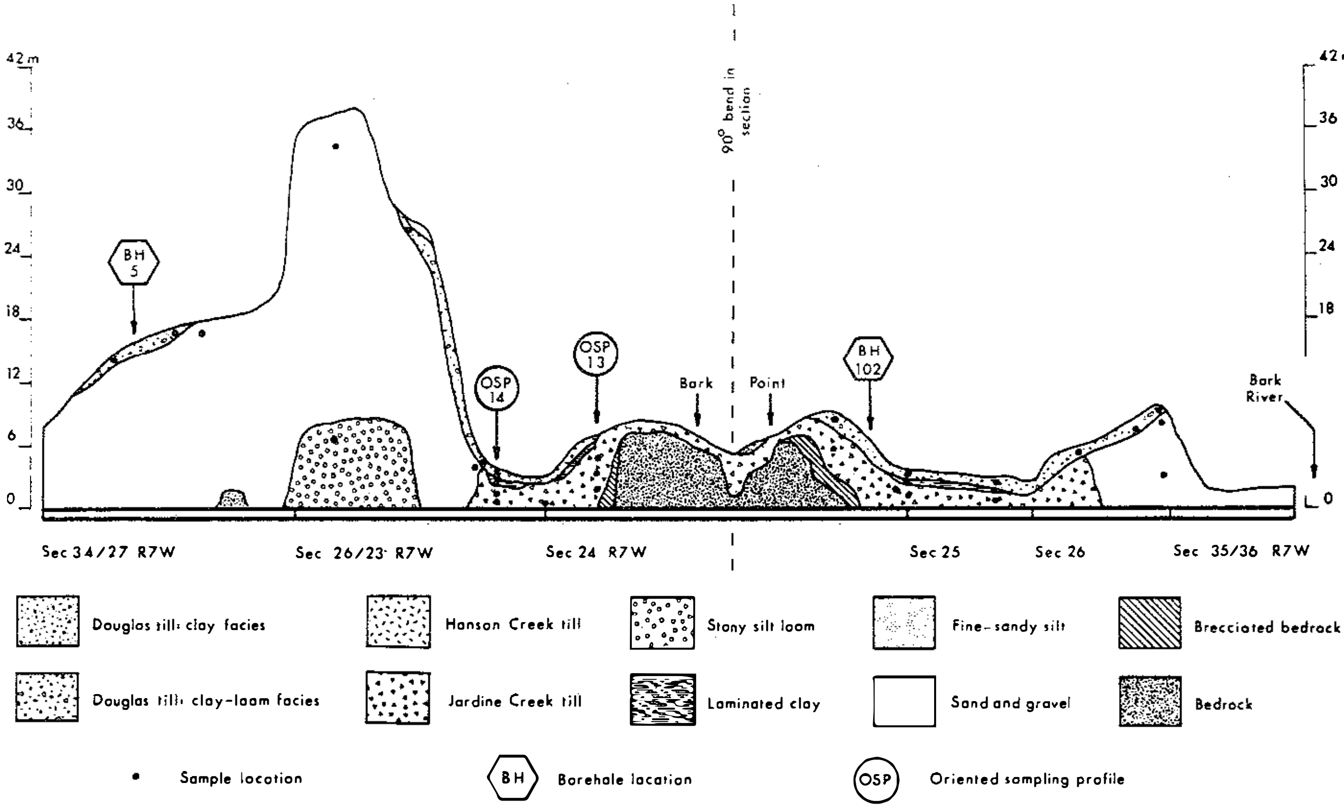

Figure 6.--Shoreline profile: Herbster to Bark River

Jardine Creek Member

The sandy till unit is named the Jardine Creek Member of the Copper Falls Formation for exposures in the bluffs near the mouth of Jardine Creek, Orienta Township, Bayfield County, Wisconsin (SW¼NE¼NE¼ sec. 35, T. 50 N., R. 9 W.).

The till of Jardine Creek Member is a sandy loam. Stones (larger than 2 mm) compose 5 to 15 percent of the till. The average grain-size distribution of the matrix (smaller than 2 mm) and the range of grain sizes are shown in figure 7. The till of the Jardine Creek Member is much sandier than the till of the Hanson Creek Member and the clay facies of the Douglas Member. Although the grain size range of the Jardine Creek till overlaps with that of the clay-loam facies of the Douglas Member, they can be distinguished on the basis of carbonate content.

The Jardine Creek till is typically dark red (2.5YR 3/6) to red (2.5YR 4/6). Browner hues (5 YR) were noted toward the eastern end of the study area.

The Jardine Creek till cannot be distinguished from other till on the basis of its clay mineralogy because all till in the area is rich in illite and smectite (table 1). However, the Jardine Creek till does have a distinctive X-ray diffractogram pattern. The combined kaolinite and chlorite 0.7 nm peak of the Jardine Creek till is much sharper than those of other till. This difference, shown in figure 8, could also be used to distinguish the Jardine

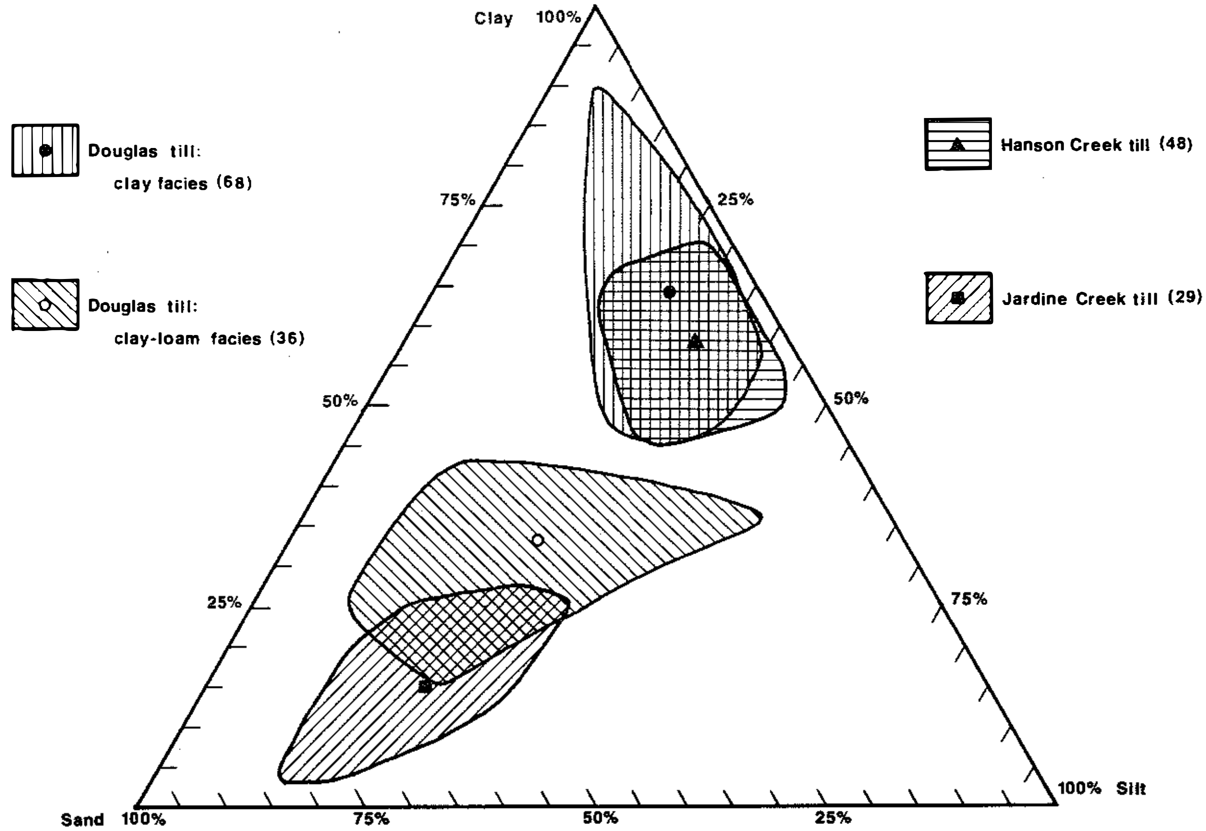

Figure 7.--Triangular diagram of grain-size distributions.

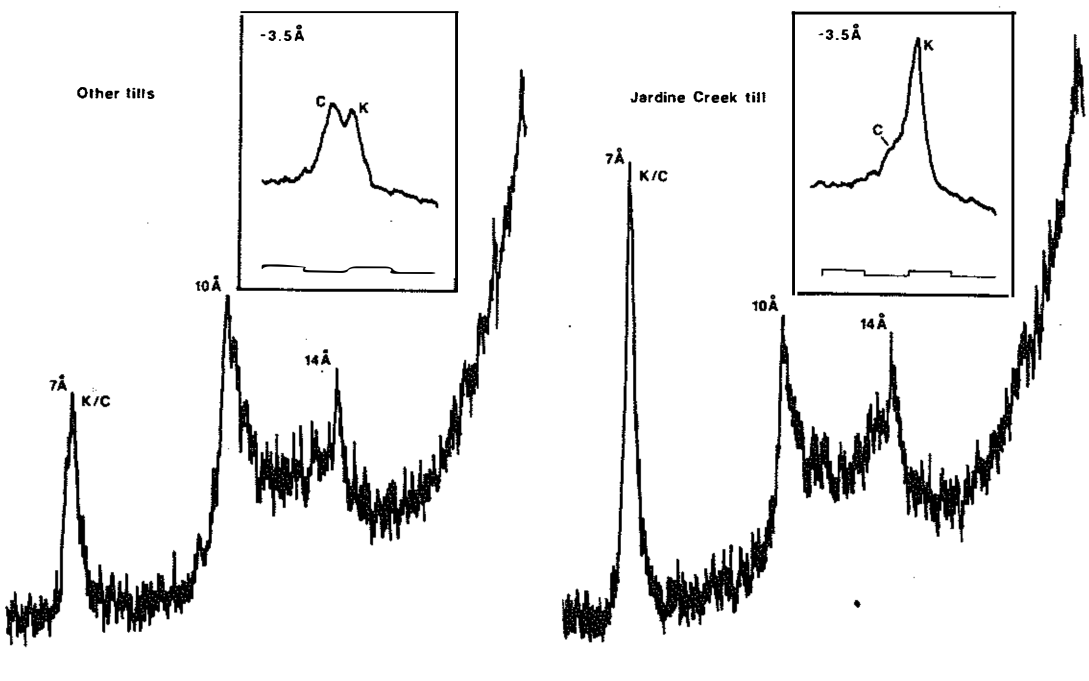

Figure 8.--X-ray diffractogram patterns (Cu radiation). Note the sharp, relatively noise-free 0.7 nm peak of the Jardine Creek compared with that of the other units. Also note the predominance of the kaolinite peak near 0.35 nm in the Jardine Creek compared with the bimodal pattern of the other units. All runs are dry-air runs. C--chlorite, K--Kaolinite.

TABLE 1. -- Summary of till characteristics (mean plus or minus one standard deviation)

Characteristics	Jardine Creek till	Hanson Creek till	Douglas till clay facies	Douglas till clay-loam facies
Typical color (moist)	2.5YR 3/6	5YR 3/4	2.5YR 4/4	2.5YR 4/4
Grain-size distribution (n)	(29)	(48)	(68)	(36)
weight % sand	61 ± 10	10 ± 6	10 ± 5	40 ± 12
weight % silt	24 ± 6	32 ± 5	26 ± 7	27 ± 9
weight % clay (0.002 mm)	15 ± 6	56 ± 6	64 ± 9	33 ± 6
Clay mineralogy (n)	(5)	(7)	(7)	(7)
% illite	51 ± 3	54 ± 5	54 ± 8	62 ± 4
% smectite	36 ± 4	34 ± 4	32 ± 6	25 ± 2
% vermiculite	7 ± 2	6 ± 3	9 ± 4	8 ± 4
% kaolinite & chlorite	6 ± 1	6 ± 1	5 ± 1	5 ± 1
Carbonate content				
silt & clay (n)	(7)	(4)	(10)	(5)
weight % carbonate	3 ± 2	11 ± 2	13 ± 3	9 ± 6
calcite/dolomite ratio	2.00	0.80	1.60	1.25
coarse silt (n)	(7)	(5)	(10)	(5)
weight % carbonate	1 ± 0.4	3 ± 2	4 ± 3	3 ± 2
calcite/dolomite ratio	4.00	0.50	0.33	1.00
Fine-sand mineralogy (n)	(2)	(7)	(12)	--
% heavy minerals	3 ± 0	5 ± 2	4 ± 2	--
% quartz	62 ± 6	59 ± 3	59 ± 2	--
% plagioclase	12 ± 3	13 ± 1	14 ± 4	--
% potassium feldspar	23 ± 3	23 ± 3	23 ± 3	--
Coarse-sand lithology (n)	(17)	(7)	(12)	--
% shale	0 ± 0	1 ± 2	0.3 ± 0.9	--
% limestone & dolomite	9 ± 8	3 ± 4	13 ± 12	--
% red sandstone	16 ± 9	14 ± 8	20 ± 14	--
% rhyolite & agate	10 ± 7	17 ± 13	13 ± 11	--
% mafic igneous	14 ± 7	42 ± 11	29 ± 10	--
% gray & green metamorphic	0.4 ± 1	3 ± 3	4 ± 5	--
% granite & gneiss	15 ± 10	16 ± 10	17 ± 11	--
% quartz	38 ± 12	5 ± 6	6 ± 8	--

Creek till from the clay-loam facies of the Douglas Member. The separated kaolinite and chlorite peaks near 0.35 nm spacing show that the difference is due to the well-crystallized, unweathered character of the kaolinite in the Jardine Creek till.

The carbonate content of the silt and clay fraction (less than 0.063 mm) and the coarse-silt fraction (0.031 to 0.063 mm) of the Jardine Creek till are quite low, averaging 3 percent and 1 percent by weight respectively. The corresponding calcite/dolomite ratios are 2.0 and 4.0. As mentioned above, this property distinguishes the Jardine Creek till from the calcareous clay-loam facies of the Douglas Member. Quartz and potassium feldspar predominate in the fine-sand fraction (0.125 to 0.25 mm), whereas quartz and red sandstone fragments are important constituents of the very-coarse-sand fraction (1.0 to 2.0 mm). These characteristics are summarized in table 1.

The engineering properties of the Jardine Creek till were determined from two samples. These properties are presented in table 2. The large difference between the properties of the Jardine Creek till and those of other till are due to the considerable differences in grain size.

As shown in figures 2 through 6, the Jardine Creek Member extends throughout the study area. Exposures west of the Iron River are restricted to discontinuous appearances at the toe of the bluff. The till unit is well exposed between the Iron River and Port Wing, rising mid-way up the 6- to 9-m bluffs. It is also well exposed in the low bluffs of Bark Point. The unit is absent between Port Wing and Herbster and in the higher bluffs of Bark Point where sand and gravel are the predominant materials.

TABLE 2. -- Engineering properties of the till (mean plus or minus one standard deviation)

Property	Jardine Creek till	Hanson Creek till	Douglas till clay facies
Natural water content (n)	(1)	(4)	(11)
percent	23.0	37.0 ± 8.6	38.4 ± 7.4
Liquid limit (n)	(1)	(6)	(12)
percent	17.0	59.3 ± 11.7	72.7 ± 7.1
Plasticity index (n)	(1)	(6)	(12)
percent	5.0	36.1 ± 8.4	45.1 ± 7.9
Bulk density (n)	(1)	(2)	(6)
kg/m^3	2.00	1.94 ± 0.03	1.86 ± 0.05
Angle of internal friction (n)	(1)	(2)	(4)
degrees	40.0	28.0 ± 0.0	28.4 ± 3.5
Cohesion (n)	--	(2)	(4)
kg/m^2	--	0.00 ± 0.00	0.01 ± 0.03
Std. penetration resistance (n)	(1)	(1)	(5)
blows/foot	81	21	14 ± 5
Overconsolidation ratio (n)	--	(2)	(2)
	--	2.2 ± 0.1	3.7 ± 0.2

Inland from the bluffs, the Jardine Creek Member is correlated to material referred to as "hard pan" and "clayey gravel" in water-well construction reports. The location of wells used in this study and the location of four subsurface profiles are shown in figure 9. The Jardine Creek Member can be tentatively traced to the southern edge of the study area where the correlations, shown in the profiles, become somewhat speculative. It is difficult to determine the actual extent of the till at the edge of the study area because older deposits of the Superior Lobe further south contain till similar in color and grain size to the Jardine Creek till.

As exposed in the bluffs, the Jardine Creek Member ranges in thickness from 2 to 7.5 m and averages about 3 m. The differences in thickness seem to be related to irregularities in the underlying bedrock surface. The till unit tends to be thicker where the bedrock surface is more uneven.

The Jardine Creek Member directly overlies Precambrian sandstone which is either firm or brecciated. Where the rock is brecciated, the contact is defined by the occurrence of erratic stones. Most of the Jardine Creek Member is unconformably overlain by the Hanson Creek Member or the Douglas Member. The upper contacts with these units are typically abrupt. Some exposures of these contacts show textural graduations and interbedding. The Jardine Creek Member is overlain by an unnamed laminated clay unit on Bark Point and by unnamed units of sand and fine-sandy silt between Bardon and Haukkala Creeks. These contacts are abrupt but their conformity is uncertain. The Jardine Creek till unit is the surficial unit at the tip of Bark Point.

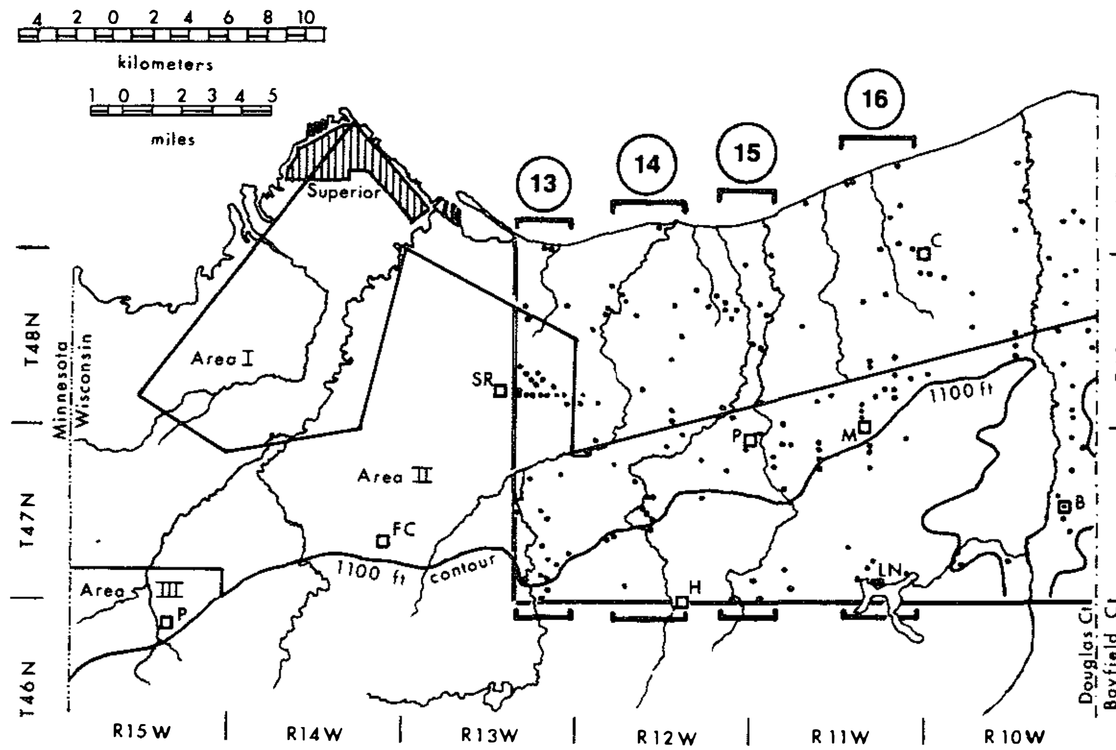

Figure 9.--Reference map for subsurface stratigraphy. The study area is bordered by the double line and the dots show the locations of wells used in this study. The numbered brackets show the locations of the subsurface profiles and the widths of the slices they represent. Areas I, II, and III are those defined by Mengel and Brown (1979).

Hanson Creek Member

The next youngest unit is named the Hanson Creek Member of the Miller Creek Formation for excellent exposures in the bluffs about 1.5 km west of the mouth of Hanson Creek, Douglas County, Wisconsin (SE¼SW¼ sec. 37, T. 49 N., R. 12 W.).

The Hanson Creek till is clay with a stone (larger than 2 mm) content of less than 5 percent. The average grain-size distribution of the matrix and the range of grain sizes found are shown in figure 7. The Hanson Creek till is readily distinguished from the Jardine Creek till and the clay-loam facies of the Douglas Member on the basis of its grain-size distribution. Although there is considerable overlap with the clay facies of the Douglas Member, the Hanson Creek till typically contains more silt at any given site. There is a noticeable decrease in the sand content of the till from east to west. This trend will be discussed in more detail below.

The till is dark reddish brown (5YR 4/3) to dark reddish brown (5YR 3/4) and commonly contains dark gray (5YR 4/1) and reddish brown (2.5YR 4/4) stringers. These stringers have complex, intermingling patterns, shown in figure 10, that give the till a marbled appearance. The overlying clay facies of the Douglas Member is noticeably redder and has no marbling. In the field, the till of these two units can be distinguished solely on the basis of their color differences.

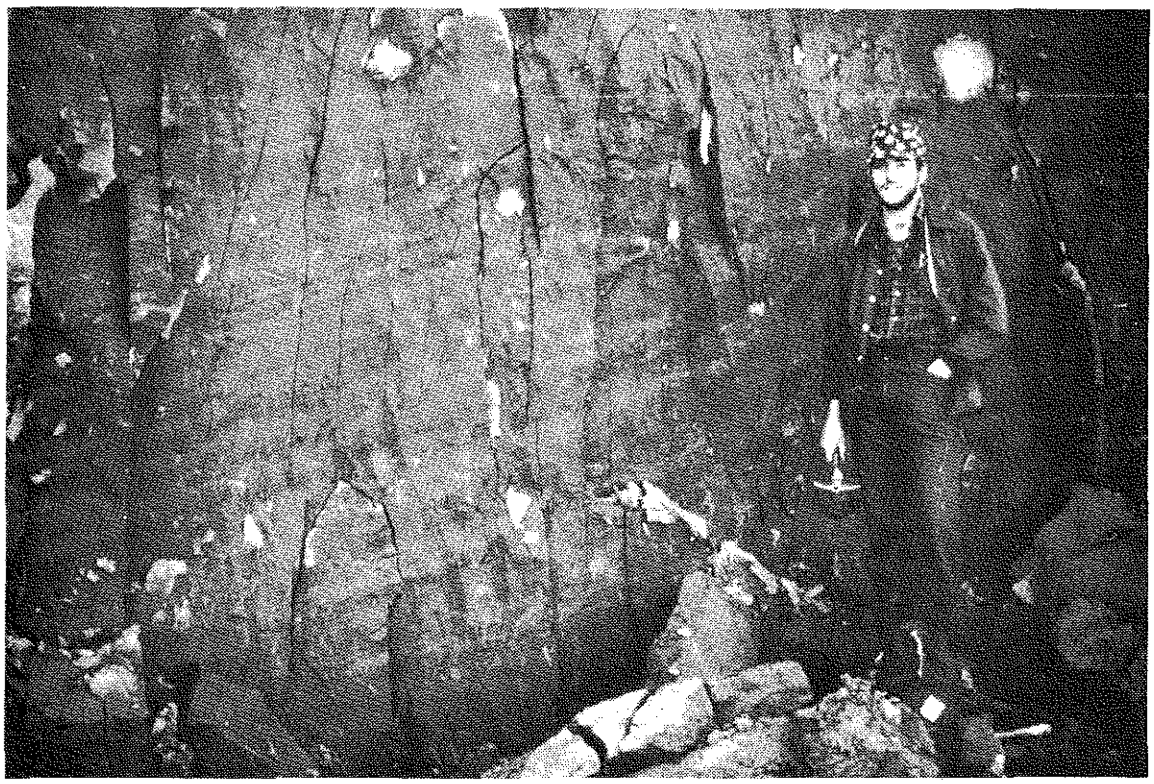

Figure 10.--Clay stringers in the Hanson Creek Member. Ice flowed from left to right. Exposure is 1.5 km west of the mouth of the Amnicon River. Figure reproduced with the permission of The Journal of Sedimentary Petrology, v. 53, p. 859-874, fig. 4.

The Hanson Creek till contains an average of 34 percent smectite and 54 percent illite, with lesser amounts of the other clay minerals. The till is calcareous. The average carbonate content of the silt and clay fraction is 11 percent and the calcite/dolomite ratio is 0.8. The average carbonate content of the coarse-silt fraction is 3 percent and the calcite/dolomite ratio is 0.5. Quartz and potassium feldspar predominate in the fine-sand fraction, whereas mafic igneous fragments are the major constituents of the very-coarse-sand fraction. These characteristics are summarized in table 1.

The engineering properties of the Hanson Creek till were determined from six samples. The average properties of the till are shown in table 2. Compared to the clay facies of the Douglas Member, the Hanson Creek till has a lower plasticity index, a slightly higher dry unit density, and a higher standard penetration resistance. The till is overconsolidated, having once supported a greater load than it does now.

As shown in figures 2 through 6, the Hanson Creek Member extends from the western end of the study area to the Iron River. Good exposures begin a mile east of Dutchman Creek and continue eastward to the Brule River. The till generally makes up the lower one- to two-thirds of the bluffs in this reach. East of the Brule River, exposures are limited to discontinuous appearances at the toe of the bluff.

Inland from the bluffs, the Hanson Creek till is correlated with two types of material described in well-construction reports: "red clay," where it underlies "blue clay," and "gray clay." From the shoreline, where the unit is the thickest, it can be traced discontinuously for about 8 to 13 km to the apparent limit of its extent, which seems to coincide with a sharp steepening of the top of bedrock as seen in figure 16. This limit may be depositional, erosional, or merely a result of insufficient information in well-construction reports for the area further north.

The exposed thickness of the Hanson Creek Member ranges from 0.5 to 11 m and averages around 7.5 m. The unit is thickest in the western part of the study area and is notably thinner east of the Brule River.

The Hanson Creek Member unconformably overlies the Jardine Creek Member and unnamed units containing sand and sandy silt between Bardon and Haukkala Creeks. Where it can be seen, the contact with the Jardine Creek Member is generally abrupt, but variations occur as mentioned above. The contacts with the sand and sandy silt units are abrupt. Most of the Hanson Creek Member is unconformably overlain by the clay facies of the Douglas Member. This contact ranges from abrupt to diffuse, but it can usually be located to within 0.3 m. Near the mouth of the Brule River, lenses of sand overlie the Hanson Creek Member. The contacts with these lenses are abrupt but their conformity is uncertain.

Douglas Member

The upper clayey till unit is named the Douglas Member of the Miller Creek Formation for its occurrence as the surface material of northern Douglas County, Wisconsin, where it is known as the "red clay" (SE¼SW¼SW¼ sec. 27, T. 49 N., R. 12 W.). Two facies with nonoverlapping geographic extents can be distinguished within the Douglas till: a clay facies and a clay-loam facies.

Both facies have stone (larger than 2 mm) contents of less than 5 percent. The average grain-size distributions of the matrix and the range are shown in figure 7. The grain-size range of the clay facies of the Douglas Member and the Jardine Creek till overlap, but their contrasting carbonate contents can be used to distinguish them. The two facies of the Douglas Member appear to result from a broad geographic trend in the grain-size of the Douglas till. This trend is discussed below in more detail.

The clay facies of the Douglas Member is characteristically reddish brown (2.5YR 4/4). The Hanson Creek till is noticeably browner and contains the stringers of gray and red that the Douglas till lacks. In the field, these tills may be distinguished solely on the basis of their color differences. The clay-loam facies is reddish brown (2.5YR 4/4, 5YR 4/4) to dark reddish brown (5YR 3/6) or yellowish red (5YR 4/6).

The clay facies contains an average of 32 percent smectite and 54 percent illite, with lesser amounts of the other clay materials. The till is calcareous. The average carbonate content of the silt and clay fraction is 13 percent, and the corresponding calcite/dolomite ratio is 1.6. The average carbonate content of the coarse-silt fraction is 4 percent and its calcite/dolomite ratio is 0.3. Quartz and potassium feldspar predominate in the fine-sand fraction whereas mafic igneous and red sandstone fragments are important constituents of the very-coarse-sand fraction. These characteristics are summarized in table 1. The clay-loam facies contains an average of 25 percent smectite and 62 percent illite. This till is also calcareous. The average carbonate content and calcite/dolomite ratio of the silt-clay fraction are 9 percent and 1.2, respectively. Those of the coarse-silt fraction are 3 percent and 0.5. No mineralogical or lithologic analyses were performed on the sand subfractions of this till.

The engineering properties of the clay facies of the Douglas Member were determined from 12 samples. These properties, presented in table 2, allow it to be distinguished from the Hanson Creek till as discussed above. This till is overconsolidated. The engineering properties of the clay-loam facies of the Douglas Member were not determined.

As shown in figures 2 through 6, the clay facies of the Douglas Member extends from Wisconsin Point to Port Wing, and makes up the upper one- to two-thirds of the bluffs in this reach. It is usually well exposed in fresh, 2.5 to 3.5 m scraps below the crest of the bluff, but the lower parts are often obscured by slumped debris. The clay-loam facies extends discontinuously from Port Wing to the Bark River as shown in figures 2 through 6. Where present, it is well exposed.

Inland from the bluff, the Douglas till is correlated to the surface or near-surface material, which is generally referred to as "red clay" in the well construction reports. Based only on interpretive correlation of the well construction reports, the Douglas till seemed to grade into a "sandy clay" at a distance of about 1.5 to 5 km from the southern end of the cross-sections. However, subsequent field work in that area indicates that the grain-size character of the Douglas Member is not gradational at its southern limit (Clayton, oral communication).

The thickness of the clay facies of the Douglas Member ranges from 1 to 15 m and averages about 7.5 m. The clay facies is thickest in the western end of the study area and thins considerably east of the Iron River. The clay-loam facies ranges from 0.5 to 6 m in thickness. It is typically 1 m thick and has the appearance of being draped over the top of the bluff.

The clay facies of the Douglas Member unconformably overlies the Hanson Creek Member, the Jardine Creek Member, and the sandstone of the Precambrian Bayfield Group. The contact with the sandstone is abrupt; the contacts with the other till units have been described above. The clay facies is the surface unit throughout its extent. The clay-loam facies unconformably overlies deposits of sand and gravel, an unnamed unit containing laminated clay, and the Jardine Creek Member. The contacts with the laminated-clay unit and the Jardine Creek Member are abrupt. The contacts with the deposits of sand and gravel are generally abrupt, but the generally sandy unit immediately below the contact for 2.5 to 3.0 m contains as much as 50 percent silt and clay. In these cases, the contact is more difficult to locate. Channels, now filled with well-sorted sand, were cut into the clay-loam facies in some places. These channels are thought to be of postglacial origin. Where present and not cut by these channel-fill deposits, the clay-loam facies is the surface unit east of Port Wing.

Geographic trends in texture

The presence of geographic trends in the grain-size distribution of Hanson Creek and Douglas till was noted above. In both units, the sand content is greatest in the east and decreases westward. These relationships are shown as scatter diagrams of sand content and distance in figures 11 and 12.

Although some of the westward decrease in sand is associated with one or two rather abrupt local changes, regional trends seem to be present. This is illustrated by the calculation of least-squares linear regressions for the scatter diagrams. The line calculated for the Douglas till data has an r-squared value of 0.52; that calculated for the Hanson Creek data has an r-squared value of 0.64. These regional trends could have been produced by one or more glacial processes acting within the western end of the Lake Superior basin.

Comminution processes can produce a geographic trend in the grain-size of till. With prolonged transport, the amount of finer-grained material in the glacial debris increases at the expense of the coarser-grained material. Thus, a till could become finer grained in the down-ice direction if no additional coarse-grained material was incorporated at the same time.

Although this process was probably active while Hanson Creek and Douglas tills were deposited, its contribution to the observed trend was apparently small. Most of the sand in the till is quartz and feldspar. According to Dreimanis and Vagners (1971), the finer terminal mode for these minerals is silt. Thus comminution of this sand would result in an increase in silt rather than clay. The average grain-size distribution for the Douglas till east of Port Wing, between Port Wing and Haukkala Creek, and west of Haukkala Creek, shown in figure 12, indicate that this did not occur.

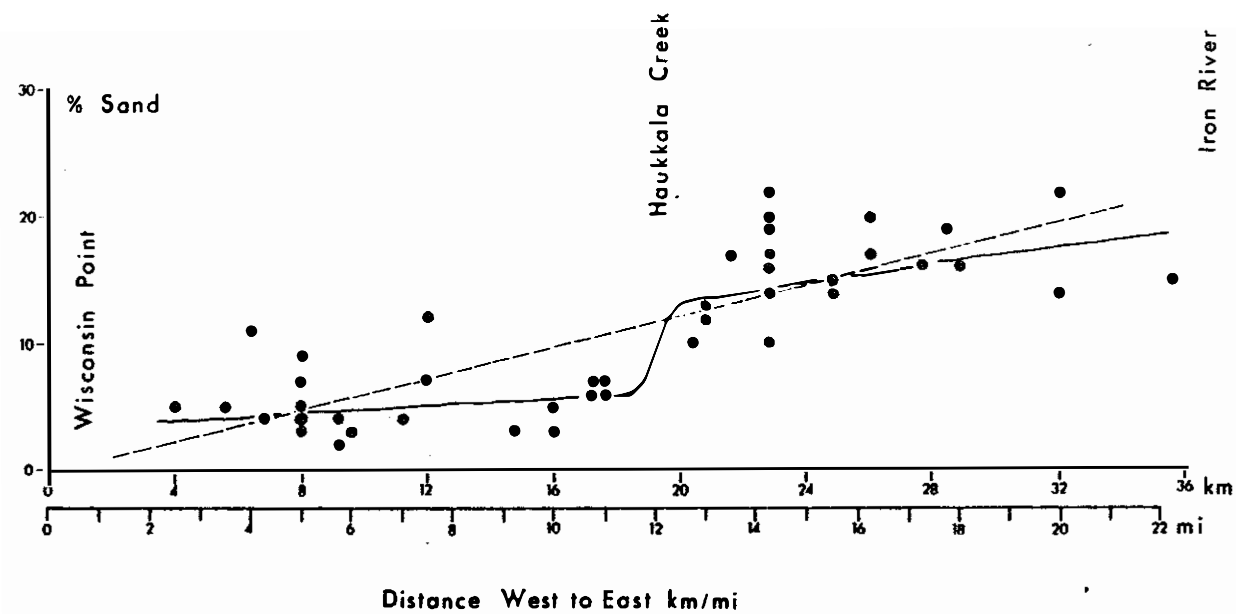

Figure 11.--Scatter diagram of sand content and distance--Hanson Creek Member. The dots are sample data, the solid line is a visual best-fit line, and the dashed line is a regression line (y = 0.96x; r-squared = 0.64).

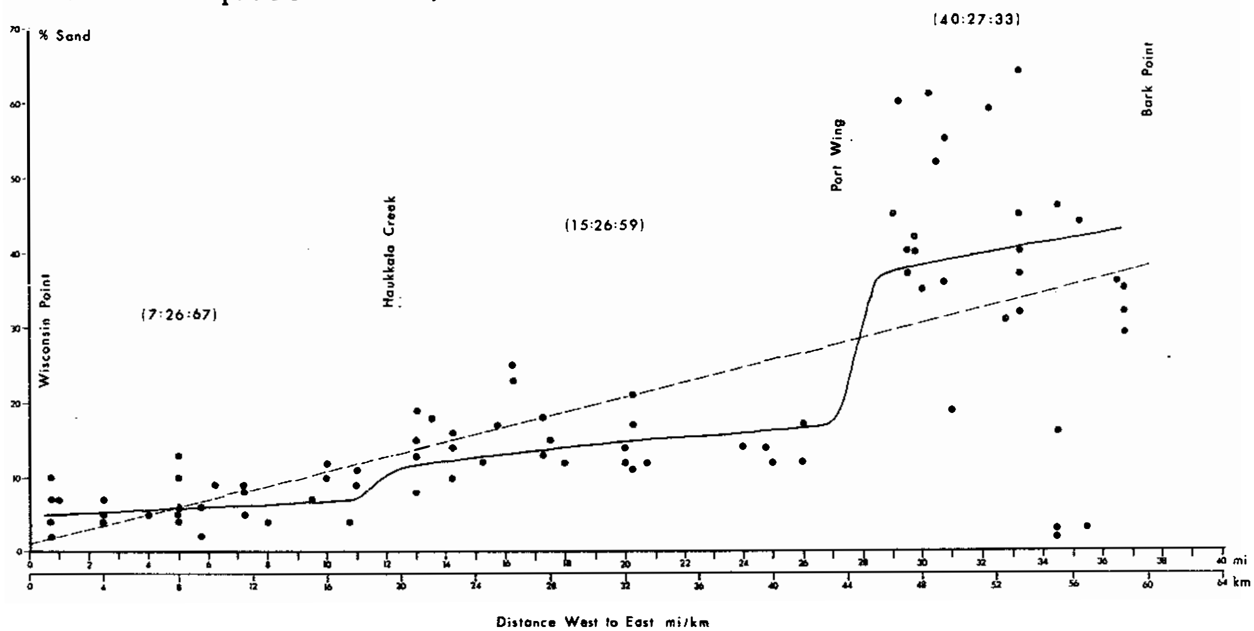

Figure 12.--Scatter diagram of sand content and distance--Douglas Member. The dots are sample data, the solid line is a visual best-fit line, and the dashed line is a regression line (y = 0.97x + 1.1; r-squared = 0.52). The numbers in parentheses are the average grain-size distributions (sand:silt:clay) of the samples between the geographic features indicated.

Gross and Moran (1971) proposed that the mixing of materials derived from sources having contrasting characteristics produced geographic trends in till on the Allegheny Plateau. Through mixing, the initial grain size of the till, influenced by its up-ice source, is altered by the incorporation of material from a down-ice source. With increased distance from the source contact, continued erosion and incorporation of down-ice material produces a continuum of grain-size distributions. This process probably produced the regional trends in grain size observed in the study area. Westward decrease in the sand in this till can be explained as the result of sand derived from Bayfield Group sandstone mixing with proglacial lake sediment during readvances of the ice. Variations were caused by the incorporation of sand from localized sources within the study area, such as the large deposit of sand and gravel between Port Wing and Herbster.

Microfabric analysis of clayey till

In the past, the physical characteristics of Hanson Creek and Douglas till have been the basis for two conflicting interpretations of its origin. The high clay content, unbedded appearance, and low stone (smaller than 2 mm) content led some workers to interpret this material as a lacustrine deposit (Whittlesey, 1852; Leverett, 1929; Mengel, 1973; Moss, 1977; Zarth, 1977). Other works suggested it was till (Whitson and others, 1914; Leverett, 1929). Microfabric analysis (the study of fabric in thin sections) was used to help clarify the origin of the red clay in the study area. Procedures and results were discussed by Johnson (1980).

In microfabric analysis, an analogy is made between sand grains dispersed in a clay matrix and gravel-sized stones dispersed in a sand, silt, and clay matrix. In both situations, the larger particles acquire a preferred orientation in response to ice-flow stresses. These particles are able to rotate because the stress experienced by them is large relative to the smaller particles and there is generally an absence of grain-to-grain contact with particles of equivalent size.

Nearly all of the red-clay samples analyzed had a preferred orientation of elongate sand grains. Other geologists have concluded that this type of preferred orientation can indicate ice-flow directions (Sitler and Chapman, 1955; Harrison, 1957; Gravenor and Meneley, 1958; Ostry and Dean, 1963; Evenson, 1971; Kujansuu, 1976). The preferred orientation of sand grains in the red clay supports a glacial origin for these deposits. Such features would not be anticipated in deep-water lacustrine environments.

Microfabric in Hanson Creek and Douglas till show that ice flow was variable, ranging from north-northwest to northeast. Significant independent evidence of ice-flow directions that strongly affirms a glacial origin for the Douglas till was found at a site along the bluffs 5 km west of Port Wing. At this site, a striated boulder pavement is present at contact between the Douglas till and the underlying Jardine Creek till. Striations on the boulders have an average orientation of N. 25° E. These correspond well with orientation of sand grains in the overlying till.

In addition to microfabric analysis, other evidence supports a glacial origin for the red clay. As shown in table 2, these materials are preconsolidated, a property that can be attributed to loading by ice. The geographic trends in the grain-size distribution of the material discussed above are more

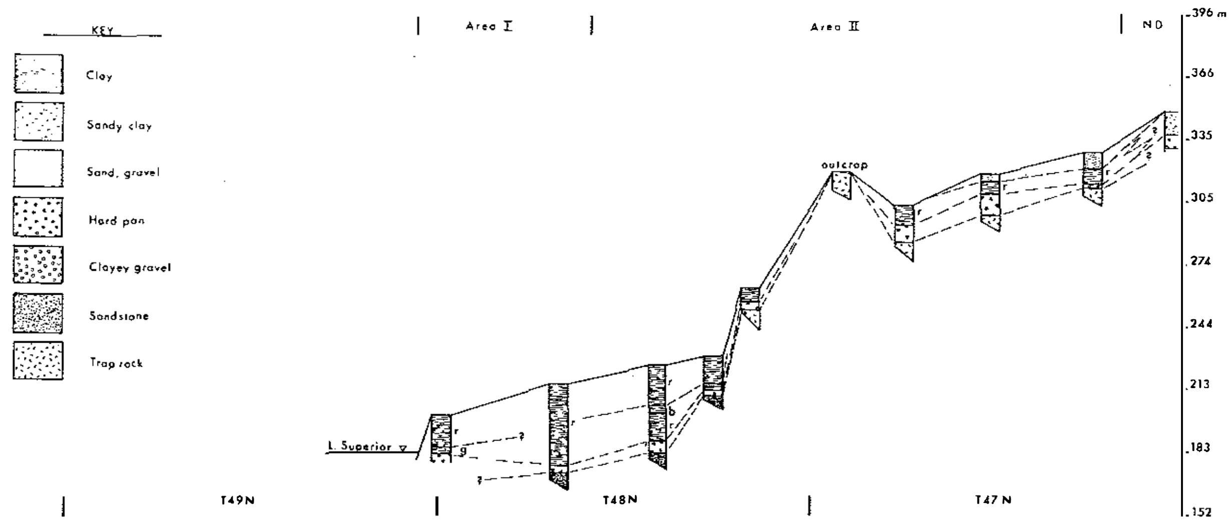

Figure 13.--Subsurface cross section--Dutchman Creek to County Highway B. Areas I and II shown at the top of the figure are the type areas defined by Mengel and Brown (1979); ND--not defined. The Douglas Member is correlated with the surface and near-surface unit containing red clay (r); the Hanson Creek Member is correlated with units containing gray clay (g), brown clay (bn), and red clay (r) underlying blue clay (b); the Jardine Creek Member is correlated with units containing hard pan and clayey gravel. Note the southern limit of the Hanson Creek Member in T. 48 N. and the graduation of clay to sandy clay at the southern edge of T. 47 N.

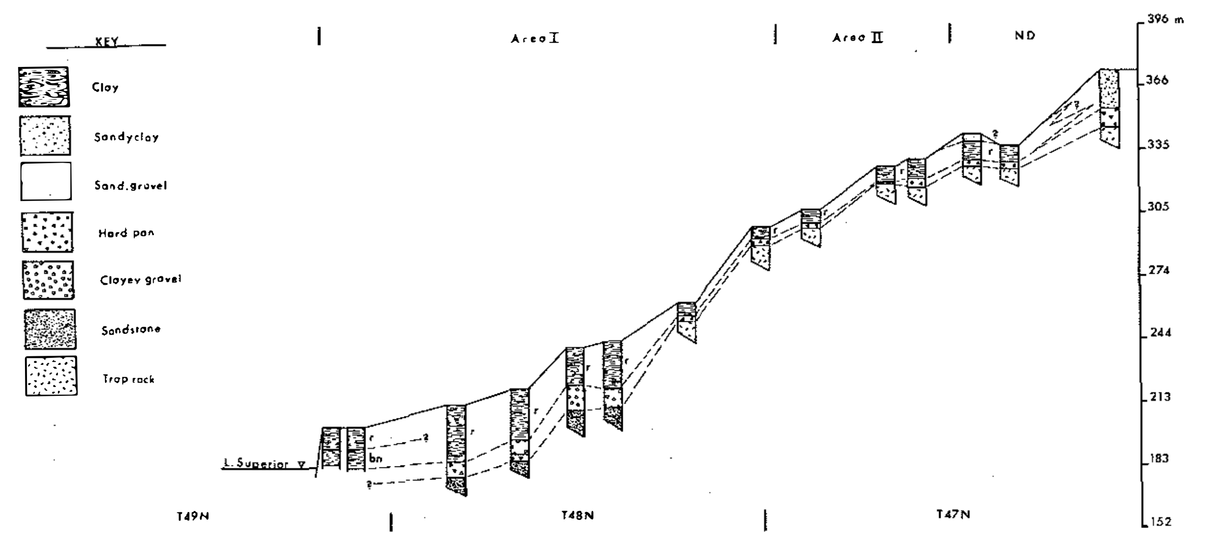

Figure 14.--Subsurface cross section--Amnicon River to Hawthorne. Areas I and II shown at the top of the figure are the type areas defined by Mengel and Brown (1979); ND--not defined. The Douglas Member is correlated with the surface and near-surface unit containing red clay (r); The Hanson Creek member is correlated with units containing gray clay (g), brown clay (bn), and red clay (r) underlying blue clay (b); the Jardine Creek Member is correlated with units containing hard pan and clayey gravel. Note the sudden thinning of the clay in T. 48 N. and the gradation to sandy clay at the southern edge of T. 47 N.

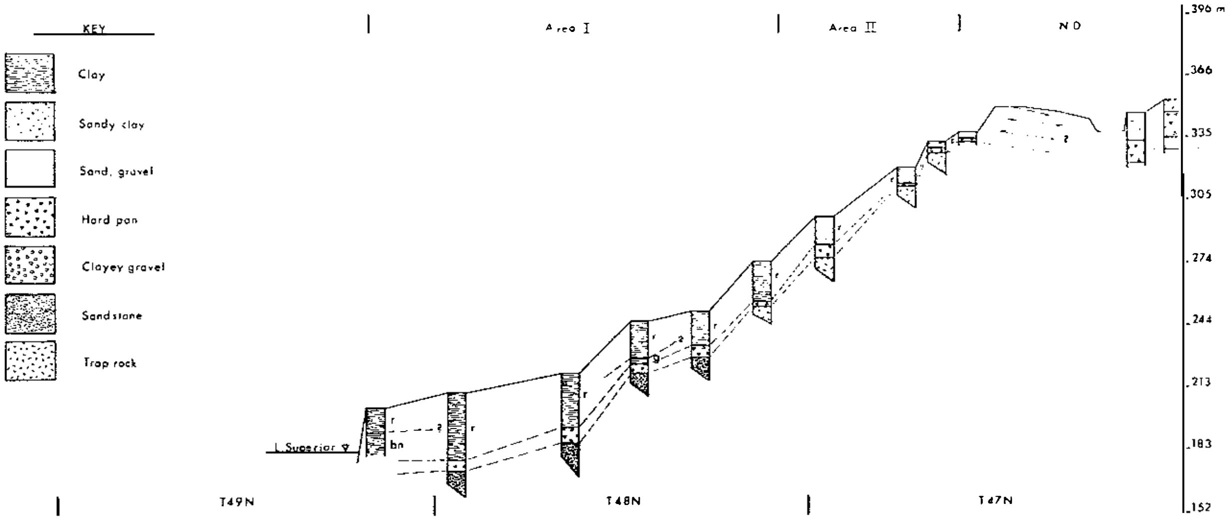

Figure 15.--Subsurface cross section--Poplar River to County Highway B. Areas I and II shown at the top of the figure are the type areas defined by Mengel and Brown (1979); ND--not defined. The Douglas Member is correlated with the surface and near-surface unit containing red clay (r); the Hanson Creek Member is correlated with units containing gray clay (g), brown clay (bn), and red clay (r) underlying blue clay (b); the Jardine Creek Member is correlated with units containing hard pan and clayey gravel. Note that the wells in the southern half of T. 47 N. do not penetrate to rock; the crest of the divide is just under 335 m in this figure.

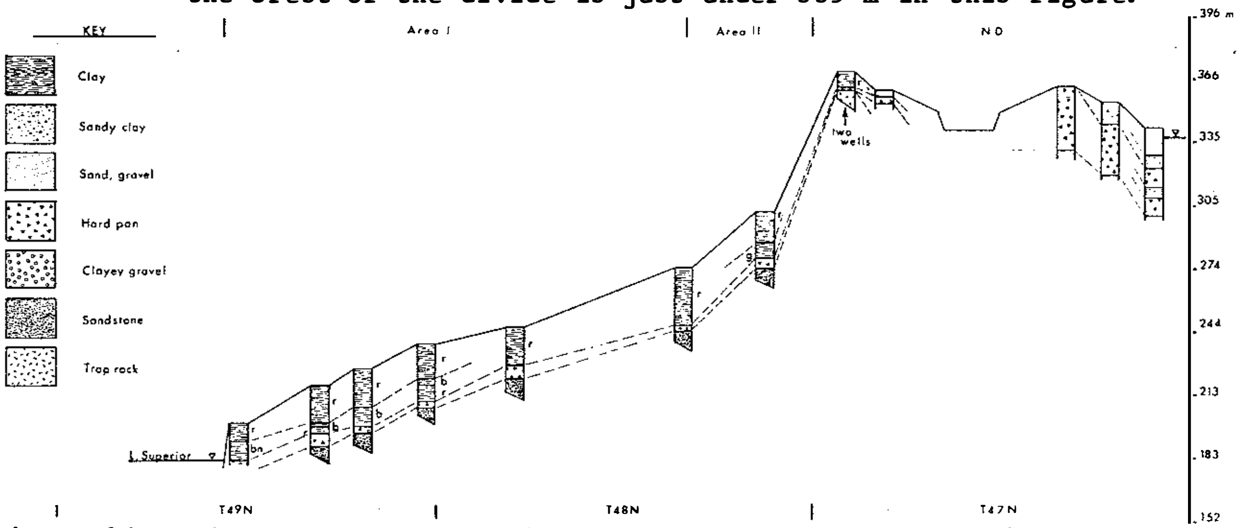

Figure 16.--Subsurface cross section--Haukkala Creek to Lake Nebagamon. Areas I and II shown at the top of the figure are the type areas defined by Mengel and Brown (1979); ND--not defined. The Douglas Member is correlated with the surface and near-surface unit containing red clay (r); the Hanson Creek Member is correlated with units containing gray clay (g), brown clay (bn), and red clay (r) underlying blue clay (b); the Jardine Creek Member is correlated with units containing hard pan and clayey gravel. Note the southern limit of the Hanson Creek Member at the southern edge of T. 48 N. and the two wells at about 366 m encountering red clay. (The highest proglacial lake level was 341 m.) Also note the buried valley south of these wells in T. 47 N.

easily explained using a glacial model. The marbled appearance of the red and gray stringers in the Hanson Creek till suggest shearing by glacial movement, and flutes and low hummocks are present on the surface of the Douglas till in Douglas County. Considered collectively, this evidence leads us to conclude that the two red-clay units are composed of till and not lake sediment.

GLACIAL HISTORY

The three till units identified in exposures along the Wisconsin shoreline of Lake Superior between Wisconsin Point and Bark Bay record the occurrence of at least three glacial events during Late Wisconsin time. The history of these events, as interpreted from the physical evidence collected during this study, is presented first. Correlations between this history and previous studies in the western Lake Superior region are then suggested. On the basis of these correlations, the absolute ages of the glacial events are briefly discussed. No datable material was found in the study area.

The oldest of the glacial events is recorded by the Jardine Creek Member and related sandy deposits. Analysis of pebble orientations within the Jardine Creek till indicates that ice was flowing from the northeast at the time of deposition. Figure 17 presents the pole plots for three measurement sites contoured by pole density. Striations on the underlying bedrock are rare due to the friable nature of the Bayfield sandstone; but where present, their orientations agree with the macrofabric data.

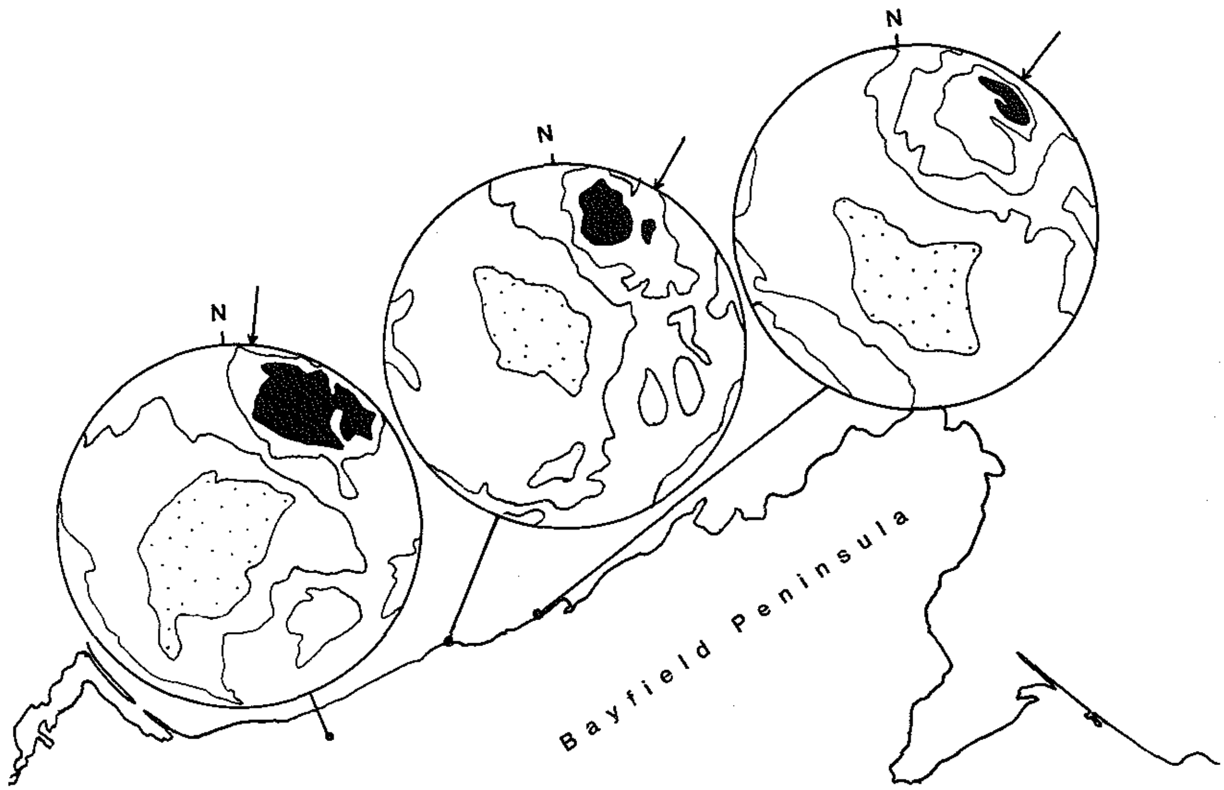

Figure 17.--Macrofabric in till of the Jardine Creek Member; n = number of pebbles counted. Pebble long-axis orientations with a contour interval of twice the standard deviation around the mean orientation axis; highest values in black region. Arrow is the mean aximuth, which shows ice-flow direction.

Evidence in the study area indicates that a substantial amount of erosion occurred during this glacial event. The sandiness of the Jardine Creek till suggests that it is composed of materials eroded from the Bayfield sandstone. Striated surfaces and, more commonly, zones of brecciated sandstone directly beneath the till indicate glacial erosion of sandstone during this event. Any unlithified deposits predating this event would have been eroded as well, but the amount of erosion that occurred cannot be determined.

Near Haukkala Creek, a recessional ice-margin position can be inferred from exposures in the bluff. As shown in Figure 6, a unit of moderately to well-sorted, fine-sandy silt grades eastward into a unit of well-sorted medium to coarse sand. Within the sand unit are layers of material that are indistinguishable from the Jardine Creek till. The fine-sandy silt unit is interpreted as a proximal lacustrine deposit, and the sand is believed to have been interbedded with flow till originating at the ice margin. In addition to this ice-margin feature, the large deposits of sand and gravel that compose nearly all of the bluffs between Port Wing and Herbster shown in figure 5 may have been deposited at this time. Although origin of the sand and gravel is not clear, it is possible that this material was deposited at the mouth of a major subglacial drainage outlet like those hypothesized by Wright (1973) for the tunnel channels of east-central Minnesota.

Because the Hanson Creek Member is not present east of the Iron River, two possibilities exist regarding the extent of ice retreat following deposition of the Jardine Creek Member. The study area east of the Iron River may not have been deglaciated, in which case the eastern limit of the Hanson Creek Member approximates the maximum retreat position. Alternatively, the entire study area may have been deglaciated at this time, and the limited extent of the Hanson Creek till unit is due simply to later erosion.

The second glacial event recorded in the Superior bluffs is indicated by the Hanson Creek Member. Flow direction of the ice that deposited the Hanson Creek till is indicated by microfabric analysis and orientation of inferred shear planes within the till. Microfabric analysis (Johnson, 1980) indicates that some of the till was deposited by ice flowing from the north-northwest--nearly perpendicular to the axis of the basin--and some was deposited by ice flowing from the northeast. Microfabric showing flow from the northeast generally occurs in samples located in the lower part of thick exposures. This fabric presumably reflects the strong, local control of the deep trough in the lake bottom on the ice flow during the initial stages of the advance. Microfabric showing flow from the northeast occurs in samples from the upper part of thick exposures and from the exposures west of the Brule River. They indicate a shift in flow direction as the basin filled with ice.

The red and gray stringers within the Hanson Creek till, if correctly interpreted as shear zones, indicate deformation by flowing ice. One stringer at the site shown in figure 10 was determined to have a dip direction of N. 67° E. and a dip of 14°. This orientation is consistent with the ice-flow direction indicated by microfabric data. However, it is not clear if the ice that deposited the Hanson Creek till or the ice of a later advance did the shearing.

The lenses of sand between the Hanson Creek and Douglas Members near the Brule River shown in figure 4 may have been deposited during the retreat following this episode -- perhaps as subaqueous outwash at the ice margin.

The lenses could also represent deposition of sand subglacially in melt-water tunnels. A third possibility is that they were carried by ice to that location during a later advance. Part or all of the large deposit of sand and gravel between Port Wing and Herbster shown in figure 5 may also date from this retreat.

The eastward extent of the Douglas Member indicates that the study area was completely deglaciated following the deposition of the Hanson Creek till unit. However, there is no further evidence of how far eastward the ice margin retreated.

The youngest glacial event is recorded by the Douglas Member. Microfabric, striated boulder pavements, and flutes indicate that the Douglas till was deposited by ice flowing from the northeast. As with the Hanson Creek till, there is some indication of flow from the north-northwest in the lower parts of thick exposures of the Douglas till, but most of the microfabrics indicate flow from the northeast. At a site about 5 km west of Port Wing there is a striated boulder pavement at the base of the Douglas till. The striations are oriented N. 25° E., and microfabrics from the overlying till have orientations of N. 30° E. and N. 40° E. Clayton (in press) identified numerous, low-relief flutes oriented from N. 25° E. to N. 55° E. on the gently sloping plain of north central Douglas County.

A lake formed in the Superior basin following the last glacial advance. No lacustrine sediment overlies the Douglas Member in the bluffs probably because of erosion by waves or non-deposition.

The glacial history as interpreted from the physical evidence in the study area can be extended and supported by correlating with chronologies described elsewhere in the region. In a number of publications, Wright presents a four-phase history for the Superior Lobe in Minnesota during late Wisconsin times (Wright and Ruhe, 1965; Wright and Watts, 1969; Wright, 1972; Wright, Mattson, and Thomas, 1970; Wright, Matsch, and Cushing, 1973). Work has also been done in the Duluth area by Moss (1977), in Cook County, Minnesota by Sharp (1953), and in the Ontonagon, Michigan area by Hack (1965).

During the St. Croix Phase, the first of Wright's phases, the Superior Lobe advanced southwestward to the St. Croix moraine of central Minnesota (see fig. 18). Erosion and incorporation of Precambrian sandstone during ice advance caused the till deposited during this phase to be red and sandy. This till is included in the Cromwell Formation (Wright, Mattson, and Thomas, 1970). Basal organic sediment in Weber Lake, a lake formed after St. Croix retreat, yielded a date of 14,690 $\pm$ 390 B.P. (W-1763), and a bog within the St Croix moraine itself has been dated at 13,270 $\pm$ 200 B.P. (Y-1326) (Wright and Watts, 1969). Based on these two limiting dates, Wright suggests a date of 16,000 B.P. or older for this phase (Wright and Watts, 1969).

Following the St. Croix Phase, ice of the Automba Phase deposited red sandy till indistinguishable from the St. Croix till. Partly on the basis of grain size, Wright argued that the ice margin did not retreat very far into the Lake Superior basin prior to the Automba Phase. A more extensive retreat would have allowed proglacial lakes to form and the subsequent re-advance during the Automba Phase would have incorporated the lake sediment causing the till to be finer. The till of this phase is also included within the Cromwell Formation. No dates are reported for this phase.

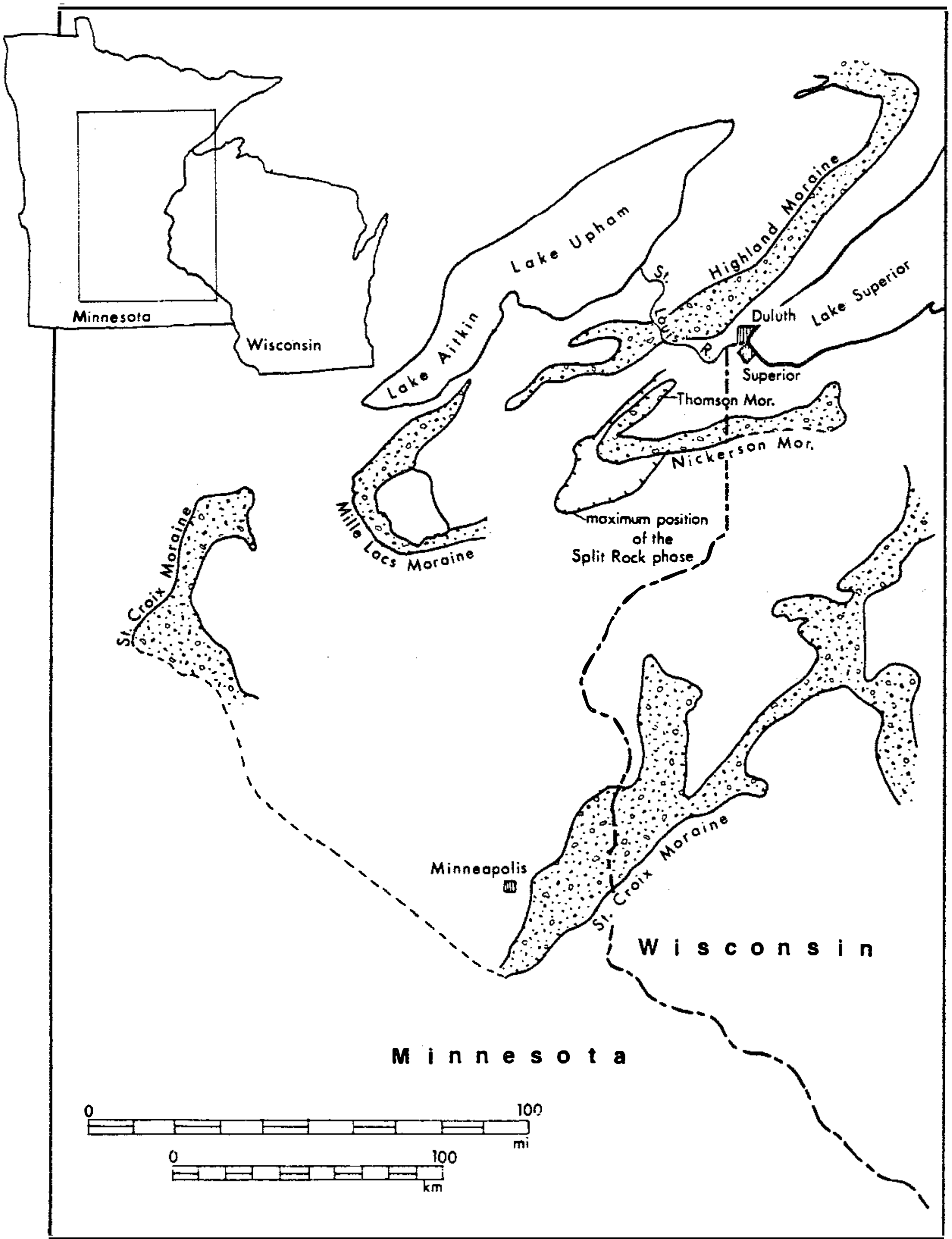

Figure 18.--Glacial features of northeastern Minnesota (from Wright and others, 1973).

Prior to the third phase of the Superior Lobe, the Split Rock Phase, ice retreated far enough into the Lake Superior basin to allow a proglacial lake to form. The lake sediment deposited in this lake was incorporated in the till of the Split Rock Phase. This till forms a thin veneer over the pre-existing topography and is present only at elevations below 380 m (Wright, Matsch, and Cushing, 1973). There are two dates from an ice-block depression (Kotiranta Lake) in outwash associated with the Split Rock Phase, 13,480 ± 350 B.P. (W-1762) and 16,150 ± 550 B.P. (W-1973) (Wright and Watts, 1969). A date of 15,250 ± 220 B.P. (I-5051) was obtained from White Lily Lake on the Split Rock end moraine. (Wright, Matsch, and Cushing, 1973). Because these dates are similar to the dates of the St. Croix Phase, Wright argued that the St. Croix Phase must be older than 16,000 years.

Between the Split Rock Phase and the fourth phase, the Nickerson Phase, the ice margin retreated into the Lake Superior basin. Fine-grained lake sediment was incorporated by the ice during the advance of Nickerson Phase ice and redeposited, perhaps by one or more surges (Wright and Watts, 1969), as red, clayey, stone-poor till. This till, included in the Barnum Formation (Wright, Mattson, and Thomas, 1970), makes up the Nickerson moraine on the south side of the Superior Lobe and forms a cap on the Thompson moraine on the northwest side of the lobe. The till reaches but does not exceed an elevation of 365 m (Wright, Matsch, and Cushing, 1973). Several dates are associated with the Nickerson advance. Wood in sediments from glacial Lake Aitkin II (see fig. 19) yielded dates of 11,710 ± 325 B.P. (W-502) and 11,560 ± 400 B.P. (W-1141) (Wright and Watts, 1969). Based on the relationship between the outlets of this lake and the Nickerson ice position, the Nickerson Phase must have been earlier than these dates. Lake-bottom material from two lakes on the Nickerson moraine were dated at 10,400 ± 300 B.P. (L-794F) and 10,800 ± 300 B.P. (L-794 A-D). Several diversion channels that flowed into a proglacial lake as the Nickerson ice margin retreated contain material dated at 10,630 ± 500 B.P. (W-1677) and 10,420 ± 300 B.P. (W-1714) (Wright and Watts, 1969). These dates, as well as the others mentioned, are younger than the Nickerson Phase. They suggest a 12,000 B.P. date for the Nickerson Phase (Wright and Watts, 1969).

Because of the similarity of Wright's sequence (two red-clay till units over-lying two red, sandy till units) and the sequence in the study area (two red-clay till units over one red, sandy till unit), it is tempting to correlate directly. This would indicate that the Douglas till was deposited during the Nickerson Phase, the Hanson Creek during the Split Rock Phase, and the Jardine Creek till during the St. Croix and Automba Phases. However, we do not believe this correlation is correct.

Firstly, the Nickerson moraine can be traced into Wisconsin where it is composed not of clayey till, as would be expected if the till of the Douglas Member is equivalent to the till of the Barnum Formation, but of red sandy-loam till similar to the till of the Jardine Creek Member. Secondly, the average sand:silt:clay ratio of till of the Split Rock and Nickerson Phases are 44:33:23 and 28:37:34 respectively (Howard Hobbs, written communication). Split Rock and Nickerson till is coarser than the till of the Hanson Creek Member (10:32:58) or the till of the Douglas Member (10:26:64). Finally, in northern Douglas and Bayfield Counties, the till of the Douglas Member is everywhere below 341 m whereas the till of the Nickerson Phase reaches 365 m (Wright, Matsch, and Cushing, 1973). If these elevations are assumed to represent ice-marginal positions, it is impossible for the same glacier to deposit both tills. Thus, the Douglas Member and the Nickerson Phase cannot be correlative.

A similar argument can be made for the Hanson Creek Member and the Split Rock Phase. Nowhere in Douglas and Bayfield Counties was the limit of the till of the Hanson Creek Member found outside the geographic limit of the till of the Douglas Member. In the subsurface, the till of the Hanson Creek Member could be traced only as high as about 285 m. Though erosion may have removed much of the till of the Hanson Creek Member, it appears that the Hanson Creek Member is less extensive than the Douglas Member. If this is true, the till of the Hanson Creek Member cannot correlate to the till of the Split Rock Phase which reaches 380 m in Minnesota (Wright, Matsch, and Cushing, 1973). Likewise, the Hanson Creek Member cannot be considered a correlative of the Nickerson Phase.

The Douglas Member and the Hanson Creek Member must be younger than the Nickerson till and thus represent two younger phases of the Superior Lobe. This indicates that the till of the Jardine Creek Member is equivalent to all of the till deposited during Wright's four phases and suggests that northern Douglas and Bayfield Counties may not have been deglaciated during the time represented by the four phases. It is also possible that deglaciation did occur in our study area but only one till unit is preserved or that two or more red sandy tills are preserved but are similar and difficult to differentiate.

Duluth area

In Duluth and northeastward along the Lake Superior shoreline, loam to silt-loam till of two stratigraphic units referred to as the "lower" and "upper" till units, are overlain by massive red clay (Moss, 1977). The "lower" till is dark reddish brown, and has a sand:silt:clay ratio of 36:46:18. Gravel makes up 25 percent of the till. The 1 to 2 mm sand fraction is dominated by basalt. The "upper" till is dark reddish brown and has a sand:silt:clay ratio of 30:50:20 although it is quite variable. Gravel makes up 20 percent of the till. The till of both units was deposited by ice flowing from the east-northeast out of the Lake Superior basin. These two till units are correlated with the St. Croix and Automba Phases respectively by Moss (1977). The massive red clay that occurs at the bluff top along the shoreline contains 2 to 3 percent pebbles and has a sand:silt:clay ratio of 5:26:69 (Moss, 1977). Moss (1977) interpreted the massive red clay to be lake sediment associated with an early stage of Lake Superior.

If previously stated correlations are correct, the Jardine Creek Member correlates to the "lower" and "upper" till units along the north shore. This indicates that the ice margin did retreat into the basin, at least northeast of Duluth, between the St. Croix and Automba Phases, but probably not east of the Brule River where only one till unit is found.

In table 3, a comparison is made between the red clay described by Moss (1977) and the till of the Douglas Member. The similarity strongly suggests they are the same unit. Because the red clay of the Douglas Member is till (Johnson, 1980), the red clay described by Moss (1977) is probably till and not lake sediment.

TABLE 3. -- Comparison of unbedded red clay near Duluth (Moss, 1977) and Douglas till

Characteristics	Unbedded red clay	Douglas till
Grain-size distribution (n)	(32)	(26)
mean; % sand: % silt: % clay	5:26:69	7:26:67*
Bulk density, (n)	(4)	(19)
range; kg/m^3	1.2-1.5	1.2-1.5
mean; kg/m^3	1.34	1.35
Water content (n)	(21)	(12)
mean; percent	41	38
Liquid limit (n)	(27)	(12)
mean; percent	61	73
Plastic limit (n)	(27)	(12)
mean; percent	27	27
Color (moist)	5YR 4/4	2.5YR 4/4

* Western end of study area, opposite Duluth.

Moss (1977) also describes "compact, pebbly clay" occurring in patches stratigraphically between the massive red clay and the "upper" till unit. This may be a correlative unit to the Hanson Creek Member or part of the Douglas Member, but the data are insufficient to correlate.

Cook County, Minnesota

Sharp (1953) described till stratigraphy along the Lake Superior shoreline in Cook County, Minnesota. He noted red-clay till overlying brown, sandy till of Cary age. The sandy till is stony and contains less than 5 percent silt and clay. This is not Superior Lobe till because it contains rock characteristic of the Rainy Lobe, which had a north to south ice-flow direction. Overlying this till is red-clay till occupying a belt 5 to 6 km wide along the shoreline. It is stone-poor, calcareous, and contains 60 to 80 percent clay. Lithologic content and color indicate it is Superior Lobe till. At one locality (see 27, T. 62 N., R. 3 E.), 28 m of brown, calcareous, clayey till is exposed below red-clay till. Sharp (1953) stated that this ". . . is provisionally included with the brown, sandy till although it might be older."

The brown, clayey till and the red-clay till are tentatively correlated to the till of the Hanson Creek and Douglas Members respectively. If these correlations are correct, the ice margin was at least as far as the Cook County brown-clay-till outcrop prior to the Hanson Creek advance and to the northeastern tip of Minnesota prior to the Douglas advance.

Ontonagan area, Michigan

Hack (1965) described a stone-poor, red, clayey till overlying a reddish-brown, stony till on the Ontonagon Plain in Michigan's Upper Peninsula. These till units are tentatively correlated to the Douglas and Jardine Creek Members, respectively. While ice was depositing till of the Hanson Creek Member, this area was either not deglaciated or the evidence has been eroded.

AGE DETERMINATIONS

No datable material was found in the study area, but using the correlations above, ages for the three tills in the study area may be suggested. The till of the Jardine Creek Member is dated 16,000 to 12,000 B.P. based on the Minnesota chronology (Wright and Watts, 1969). No datable material is associated with the units correlated to the Hanson Creek Member.

Hack (1965) reported three dates associated with the red, clayey till on the Ontonagon Plain. Wood in the till dates 10,230 ± 280 B.P. (W-964). Bog-bottom wood and gytta date 9,600 ± 350 B.P. (W-965) and 9,500 ± 350 B.P. (W-1150) respectively. This indicates a date of 9600 to 10,230 B.P. for till of the Douglas Member if it is correlative to Hack's red, clayey till.

This date may be corroborated by examining well-dated Lake Agassiz fluctuations. During Late Wisconsin deglaciation, Lake Agassiz drained into Lake Superior through channels in southern Ontario. When the Superior Lobe advanced, this outlet was blocked and Lake Agassiz rose. Arndt (1977) stated that the Agassiz outlet was blocked during a period 10,100 to 9,900 B.P., a period that overlaps with the age of the red clay on the Ontonagon Plain. The next older phase of Lake Agassiz is the Lockhart Phase which was present from about 11,300 B.P. to 10,700 B.P. (Clayton and Moran, 1982; fig.1). If the Hanson Creek advance is associated with the Lockhart Phase, the Hanson Creek Member dates from around 11,000 B.P.

Wright (1972)	Moss (1977)	Sharp (1953)	this paper	Hack (1965)
*	red clay	red clayey till	Douglas Member	red clayey till
*	compact pebbly clay"	? brown clayey till	Hanson Creek Member	*
Nickerson Phase	*	sandy till (Rainy Lobe)	Jardine Creek Mb**	red sandy till**
Split Rock Phase	*			
Automba Phase	upper till			
St. Croix Phase	lower till			

* no equivalent unit recognized
** may be equivalent to one or all of Wright's (1972) phases

Figure 19.--Summary of correlations.

The following tentative dates are suggested: before 12,000 B.P. for the Jardine Creek Member, 11,000 B.P. for the Hanson Creek Member, and 10,000 B.P. for the Douglas Member. These dates are based on the correlations suggested and require further study to refine them.

SUMMARY

Detailed stratigraphic investigations of the bluffs along the Wisconsin shoreline of Lake Superior reveal the presence of three till units. The oldest till unit is composed of the Jardine Creek till. This till can be distinguished by its grain size (average 61 percent sand, 24 percent silt, 15 percent clay) and by sharp kaolinite peaks at 0.7 nm and 0.35 nm spacings in x-ray diffractograms. Internal structures observed at a few locations suggest that some of the Jardine Creek till was deposited as subaquatic flow till. Subsurface data appear to indicate that the till unit extends beyond the southern edge of the study area.

The next youngest till unit is the Hanson Creek Member. This till can be distinguished by its grain size (average 10 percent sand, 32 percent silt, 58 percent clay), its browner color (5YR 3/4), and the complex intermingling patterns of red and gray color bands within it. This till also has a lower plasticity index (38) and higher standard penetration resistance (21 blows/ft) than the clay facies of the Douglas Member (45 and 14 blows/ft respectively). The Hanson Creek Member may pinch out in the subsurface 8 to 13 km south of the shoreline.

The youngest till unit is composed of the Douglas till. Two facies are present within this unit--the clay facies (average 10 percent sand, 26 percent silt, 64 percent clay) and the clay-loam facies (average 40 percent sand, 27 percent silt, 33 percent clay). In addition, this till can be distinguished by its characteristic red color (2.5YR 4/4) and its occurrence as the surface unit of the Lake Superior plain.

Geographic trends in the sandiness of the Hanson Creek and Douglas till are believed to be the result of progressive dilution of sandy debris, derived from Bayfield Group sandstone by proglacial lake sediment eroded by the readvancing ice that deposited the till. Microfabric analysis of clay till of the Douglas and Hanson Creek Members indicates a glacial origin for this material rather than lacustrine as previously reported. This interpretation is supported by overconsolidation of till in both units, geographic trends in grain-size distribution, glacial shearing in the Hanson Creek Member, striations at the base of the Douglas Member, and flutes and low hummocks on the surface of the Douglas Member.

The till of the Jardine Creek Member may be equivalent to one or all tills deposited during Wright and others' (1973) four phases. Following the St. Croix Phase, the western end of the study area may have been deglaciated, based on correlation to the lower and upper till units of Moss (1977) near Duluth. Alternatively, deglaciation within the study area during the period of Wright and others' (1973) phases may have occurred but no evidence was found.

Following the Nickerson Phase, the ice margin retreated at least as far eastward as the Iron River in Wisconsin, as indicated by the extent of the Hanson Creek Member in the study area, and perhaps further based upon the occurrence of brown, clayey till in Cook County, Minnesota. A more extensive retreat is also supported by the presence of two end moraines composed of red-clay till near the Wisconsin-Michigan border. These two moraines are tentatively correlated to the Hanson Creek and Douglas Members (Clayton, in press).

Following this retreat, ice advanced and deposited till of the Hanson Creek Member. Possible correlative units include a unit of compact, pebbly clay in the Duluth area (Moss, 1977), a unit of calcareous, brown clayey till in Cook County, Minnesota (Sharp, 1953), and a unit of red-clay till making up one of the two moraines on the Wisconsin-Michigan border.

Retreat prior to deposition of the till of the Douglas Member was extensive, likely farther east than Cook County, Minnesota and the Ontonagon area in Michigan, the eastern-most sites considered in this paper.

The final ice advance into the western Lake Superior basin deposited the till of the Douglas Member. This unit is correlated to a unit of massive red clay found near Duluth (Moss, 1977), a unit of red, clayey till in Cook County, Minnesota (Sharp, 1953), and a unit of red, clayey till on the Ontonagon Plain (Hack, 1965). A summary of the correlations is shown in figure 19.

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