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Geology of the Cloquet Quadrangle

CARLTON COUNTY, MINNESOTA

BY H. E. WRIGHT, Jr., L. A. MATTSON
AND J. A. THOMAS

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Abstract

The Cloquet quadrangle is bisected by the St. Louis River, a major stream that flows into the western end of Lake Superior. Precambrian rocks are extensively exposed in the river valley where overlying Pleistocene glacial deposits have been eroded.

The Precambrian rocks are dominated by the Thomson Formation, which consists of interbedded slates, slaty graywackes, and graywackes. Small-scale cross-bedding, graded bedding, flute casts, load casts, clastic dikes, and other primary and penecontemporaneous structures are common, as are calcareous and siliceous concretions. The formation probably was deposited in a relatively deep-water basin, in part by turbidity currents. It has only one conspicuous marker bed, the Otter Creek unit, so the stratigraphic thickness across the intricate folds of the region is difficult to determine, but it probably is about 20,000 feet. Normal and reverse faults with displacements of a few tens of feet are common, as are steeply dipping conjugate joints of northwest and northeast trends. Cleavage is well developed in slaty units.

The Thomson Formation is correlated with the Animikie Group. Abundant microgabbro dikes were intruded during subsidence of the Lake Superior syncline.

The Pleistocene glacial history was marked by three phases of advance and retreat of the Superior Lobe, preceded by a phase of the Rainy Lobe. Drumlins, moraines, outwash plains, eskers, lake plains, and diversion channels constitute distinctive landforms. During final withdrawal of the Superior Lobe from the area, the St. Louis River, which carried the outflow from Glacial Lake Upham, was diverted to form prominent erosional channels leading to the St. Croix River at progressively lower elevations, until it finally flowed into the proglacial Lake Nemadji, whose outlet formed a final channel in the sequence.

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PLATE IN POCKET: GEOLOGIC MAP OF CLOQUET QUADRANGLE

Geology of the Cloquet Quadrangle Carlton County, Minnesota

INTRODUCTION

The Cloquet quadrangle, located just southwest of the head of Lake Superior, occupies a key position in the geology of northeastern Minnesota for two reasons: (1) deep postglacial erosion by the St. Louis River has provided nearly continuous exposure of the Thomson Formation, a major metasedimentary unit of Precambrian age in the Lake Superior district, and (2) repeated advance of the Superior glacial lobe out of the Lake Superior basin has resulted in distinctive glacial landforms and deposits, particularly through the temporary damming and diversion of the St. Louis River.

The geology of the area was first explored by Winchell (1899, pp. 1–24), who presented an outcrop map of the Thomson Formation and described the glacial drift. Subsequently, the bedrock of the quadrangle was considered numerous times in the context of the Precambrian geology of the Lake Superior region (e.g., Van Hise and Leith, 1911; Leith and others, 1935), but the most comprehensive study has been that of Schwartz (1942a;b). The glacial sequence of the entire region was elaborated principally by Leverett (1929; 1932). More recently, revisions were proposed by Wright (1955; 1956; 1969; Farnham and others, 1964; Wright and Ruhe, 1965; Wright and Watts, 1969).

The present report is based initially on M.S. theses at the University of Minnesota by Mattson on the Precambrian geology of the southern half of the quadrangle, and by Thomas on the Precambrian of the northern half and the glacial geology of the entire quadrangle. Fieldwork was conducted in 1958 and 1959 under the auspices of the Minnesota Geological Survey. Additional fieldwork on the glacial geology was pursued in subsequent years by Wright, who is primarily responsible for the Pleistocene section of the report.

Scales of 1,000 and 500 feet to the inch were used for mapping of the bedrock. Aerial photographs were useful supplements to the topographic map for the study of glacial features, as well as for the location of outcrops of bedrock, which characteristically form linear ridges projecting above the glacial drift or peat bogs. Diabase dikes were traced with the aid of a Schmidt-type vertical magnetometer.

J. C. Craddock advised throughout the field and laboratory studies on the Precambrian rocks and aided extensively in the final compilation of the report. G. M. Schwartz, former Director of the Minnesota Geological Survey, kindly shared with the authors his broad knowledge of the Thomson Formation. Assistance at various stages was given by S. S. Goldich, H. M. Mooney, and G. B. Morey. Parts of the manuscript have been reviewed by P. K. Sims, E. J. Cushing, and J. E. Stone.

PRECAMBRIAN GEOLOGY

General

The rocks exposed in the Cloquet quadrangle area are of two major groups — folded metasedimentary slates and graywackes of the Precambrian Thomson Formation, and Keweenawan microgabbro dikes that have intruded this sequence. East of the quadrangle, these rocks are overlain unconformably by quartz-pebble conglomerate that is either the Lower Keweenawan Puckwunge Formation or a basal conglomerate of the Upper Keweenawan Fond du Lac Sandstone (Morey, 1968). This in turn is overlain by the Fond du Lac Sandstone. The Keweenawan formations here have a gentle southeasterly dip toward the axis of the Lake Superior Syncline.

Rock exposures in the quadrangle are restricted to the valley of the present St. Louis River and to its late-glacial courses, which are now occupied by Otter and Little Otter Creeks. The present St. Louis River flows mostly on bedrock.

The massive graywackes of the Thomson Formation form long, structurally controlled ridges that trend eastward. One slope is commonly a dip slope and the other a joint surface. The slate is less resistant and generally is exposed near the base of the graywacke ridges or as low outcrops rising a few feet above the surrounding swamps.

The microgabbro dikes are commonly less resistant than the graywacke and slate and in many places form gaps in ridges. These gaps are very distinct on aerial photographs, and in some cases the corresponding dikes can be traced for several miles. The stream courses in the area locally occupy such gaps — for example, the Midway River near the Thomson reservoir, and the St. Louis River south of the Thomson Dam between State Highway 39 and the Northern Pacific Railway bridge.

Thomson Formation

General. The Thomson slate was named by Winchell (Spurr, 1894, p. 160) for extensive exposures near the village of Thomson. Previously these slates were referred to as St. Louis slates, Carlton slates, or Cloquet slates. Schwartz (1942b, p. 1003) suggested that the term Thomson Formation replace Thomson slate, as much of the exposed rock is graywacke.

The Thomson Formation consists of a metasedimentary sequence of interbedded slates, slaty graywackes, and graywackes. To the southwest these rocks change with progressive metamorphism to phyllite, mica schist, and garnet-mica schist (Schwartz, 1942b, p. 1005). The mica and garnet-mica schists do not crop out in this area, but some phyllite and phyllitic slate is exposed in Section 16, T.48N., R.17W., near the southwest corner of the quadrangle.

Graywacke. The individual graywacke beds range in thickness from a few tenths of an inch to about six feet, locally within a few feet along the strike. Most of the graywacke beds are medium- or fine-grained. In hand specimen the fresh graywackes are dark gray to greenish-gray; after weathering the color ranges from light greenish-gray to nearly black. Much of the graywacke contains visible crystals of secondary pyrite and some carbonate.

In thin section the massive coarse-grained graywackes are poorly sorted and lack bedding; fragments are subangular to subrounded, and many show evidence of strain. Modal analyses yield an average composition of about 50 per cent quartz, 20 per cent feldspar, 20 per cent rock fragments, and 10 per cent accessory minerals and chlorite-sericite cement.

Cross-bedding is common in thin graywacke beds one-half to two inches thick, but it was not observed in thicker beds. This cross-bedding resembles "festoon" cross-bedding (Pettijohn, 1957, p. 169), but it is much smaller in scale. It occurs commonly in what appear to be small "troughs" or scoops up to two feet across and three and one-half to four feet long. Measurements of the orientation of small-scale cross-bedding were restored to "original" horizontal-bed position, plotted as poles on a lower hemisphere equal-area net, and contoured. Figure 1 shows a clustering of poles in the north-northwestern portion of the hemisphere, suggesting that the depositing bottom currents flowed rather consistently toward the south and southeast. Approximately 20 per cent of the cross-beds are inclined to the bedding at larger angles than would normally be expected. This is believed to have resulted from post-depositional deformation (Pettijohn, 1958, p. 475), the original inclination being modified by internal shear during folding.

Graded bedding is quite common in the graywackes of the Thomson Formation. Many beds exhibit a medium- to coarse-grained base, a uniform medium- to fine-grained mid-portion, and a top that grades into slaty graywacke and finally into slate. Where graded beds are thin, this sequence is generally complete, but in thicker beds the sequence may be interrupted by the medium- to coarse-grained base of the overlying bed.

Ripple marks of an asymmetric current type were observed on a large block of float near the mouth of the Midway River. Pseudo–ripple marks, common on some outcrop surfaces, were apparently caused either by the weathering of concretions lying parallel to the cleavage or by minute folding in the relatively incompetent slate beds.

Flute casts (Kuenen, 1957, p. 235) or flow marks are present at the contact between many of the more thickly graded beds of graywacke and slate. The flute casts observed were generally no greater than two inches wide, three inches long, and one inch deep. Orientation of the casts with the deep end toward the north indicates a bottom current from that direction, consistent with measurements made on small-scale cross-bedding (Fig. 1).

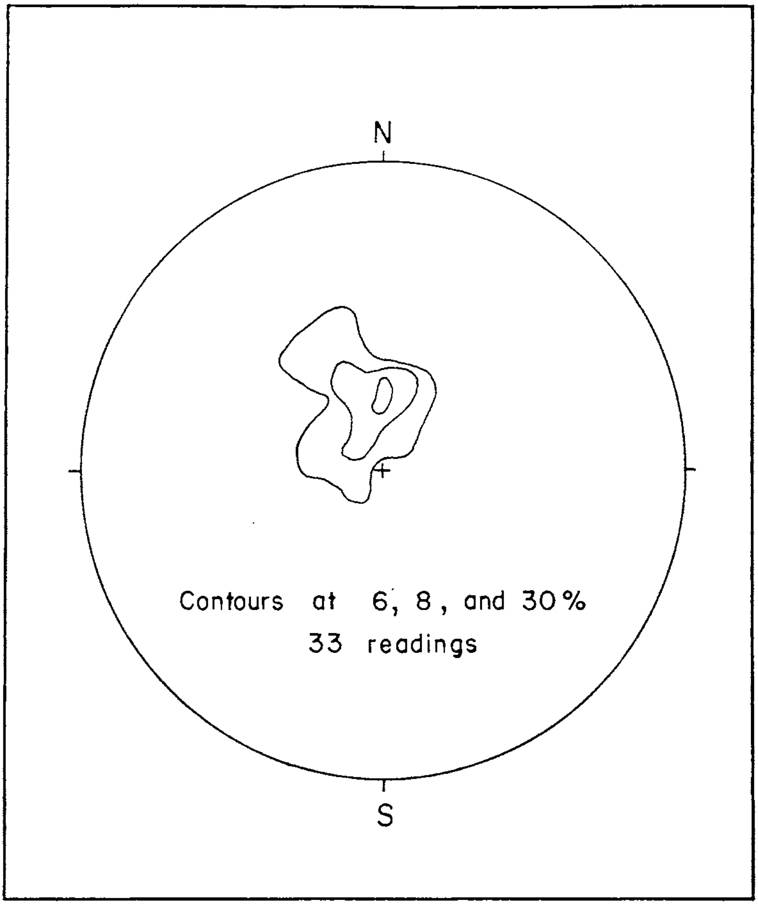

Figure 1. Restored orientation of cross-bedding in graywacke of Thomson Formation, plotted as normals on lower hemisphere of equal-area net.

Slaty Graywacke. Slaty graywacke, an abundant rock type in the Thomson Formation, is texturally intermediate between slate and graywacke. In exposures it resembles graywacke in color, but is not so massive and has the fairly well-developed cleavage generally lacking in the graywackes.

In thin section the slaty graywacke is poorly sorted; subangular to subrounded grains of quartz, feldspar, rock fragments, and accessory minerals make up about 65 per cent of the rock, and chlorite and sericite the remainder. The average grain size of clastic particles corresponds to very fine sand or coarse silt.

Many beds of slaty graywacke show evidence of penecontemporaneous deformation (Fig. 2). Some beds exhibit internal folds that were truncated either before deposition of the overlying beds or, more commonly,

Figure 2. Intraformational conglomerate. Very thin shaly fragments are imbedded in a more granular matrix of slaty graywacke.

after the overlying beds were deposited. Folds and contortions are very complex near the center of a bed but die out in normal undisturbed layers near the contacts. These folds are probably the result of sliding or slumping of unconsolidated materials on the basin floor.

Slate. The slate of the Thomson Formation is dark greenish-gray to black and commonly contains pyrite. The normal weathered appearance is very similar to a fresh surface, and only long periods of intense weathering alter the slate appreciably. Badly weathered, soft, greenish-gray slate is exposed in the bank of the St. Louis River across from the Northwest Paper Plant at Cloquet and just east of the quadrangle at the unconformable contact with the overlying quartz-pebble conglomerate.

In thin section the slate displays composition similar to that of the graywacke and slaty graywacke, but the proportions of minerals differ. Well-oriented chlorite and sericite compose about 50 per cent of the slate; clastic quartz, feldspar, and accessory minerals make up the remaining 50 per cent.

"Pockets" or load casts (Kuenen, 1957, p. 246) were observed in the slate beds of several localities. These structures occur in slate below a graywacke bed and range from a few millimeters to about three inches across. The "pockets" are believed to be caused by penecontemporaneous flowing of the unconsolidated argillaceous sediments where unequally loaded by the overlying graywackes (Shrock, 1948, p. 156).

Nine small clastic dikes were observed in the slate beds. These dikes of graywacke appear to have originated by upward injection. The dikes, when restored to their "original" position before folding, strike from N.35°

E. to N.82°E., but generally northeast. The average restored dip of five dikes is 72° N.W., and the average dip of the other four is 59° S.W. Apparently the clastic dikes were emplaced before the enclosing rock was well consolidated, as they show no direct relation to present structures. If these dikes were penecontemporaneous, their general strike might well be expected to parallel contours on the depositional basin floor.

Concretions. Concretions are common in the Thomson Formation, generally in zones parallel to and at or just below bedding planes. The concretions are very useful in determining bedding in small or massive exposures where bedding planes are not apparent. The shapes of individual concretions differ, but many have "a rough, flattened ellipsoidal shape with the ratio between the axes approximately 3:6:8" (Schwartz, 1942c, p. 493). The concretions range in size from less than one inch to as much as four feet in the longest dimension. Individual zones of concretions may continue laterally for hundreds of feet or disappear within 10 feet.

The concretions are mainly composed of calcium carbonate, with minor iron carbonate. The larger concretions and many of the smaller ones generally have a two-layer structure, consisting of a coarsely crystalline shell and a core of very fine clastic particles cemented by calcite. Some smaller concretions have a uniform composition throughout that is similar to the core of the larger ones.

Siliceous concretions are also abundant in some zones. They are resistant to weathering and stand in relief as rounded elongate forms. The uniform type is composed only of very fine quartz, but the two-layer type contains small pyrite particles at the boundary between layers.

The original bedding of the host rock can be seen passing through the concretions, according to observations both in the field and in thin section. In some places the bedding appears to be pushed aside by the concretion as well as to pass through it. This may be a result of further compaction of the sediments after formation of the concretions, or it may be the result of reorientation of the concretion during folding.

Thickness. The thickness of the Thomson Formation was unkown before Schwartz's (1942b, p. 1009) work. Allowing for flat dips and undiscovered causes of duplication, he estimated a thickness of more than 20,000 feet for the entire outcrop belt. The cross-section (Fig. 3) indicates a thickness of about 2,500 feet in the southern half of the Cloquet quadrangle. An undetermined thickness is exposed in the northern half of the quadrangle, but if the structure is similar to that in the southern part, the total estimated thickness of 20,000 feet for the entire outcrop area may be somewhat large.

Stratigraphy. Sections measured near Cloquet and Thomson proved to be of little use for stratigraphic correlation across the structures, but they demonstrate that the various lithologic types alternate from bed to bed and from unit to unit. Relatively large units may be composed predominantly of graywacke, slate, or slaty graywacke. The contacts of these large units are transitional and impossible to correlate in normal field exposures.

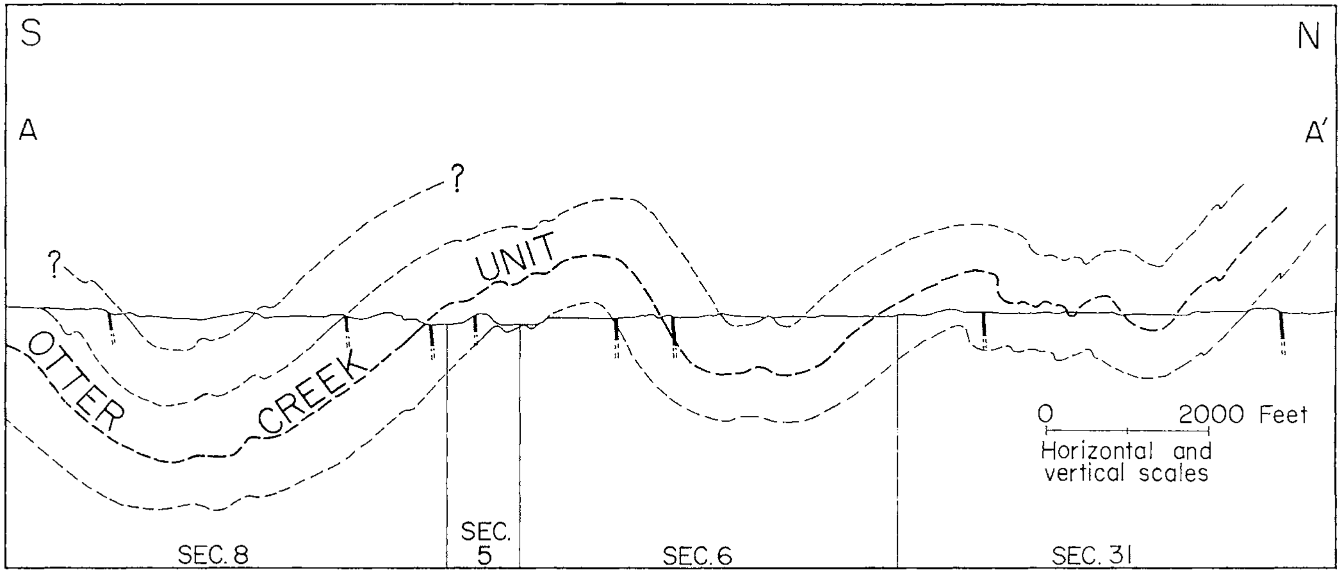

Figure 3. Cross-section of Thomson Formation along line A–A′, showing location of folds.

A section 330 feet thick was measured from the dam on the St. Louis River near the east edge of Section 13 to the mouth of the first small tributary downstream. The beds dip uniformly about 50° S. The interbedded units consist of 44 per cent graywacke, 28 per cent graywacke slate, and 28 per cent slate. The upper part of the section is separated from the lower by a dike and adjacent fault breccia. Displacement across the fault is unknown.

A marker unit, referred to herein as the Otter Creek unit, was recognized during the mapping, and it greatly aided the structural interpretation in the southern half of the quadrangle. This key bed is exposed at three localities: (1) along the south side of Otter Creek and the St. Louis River near the mouth of Otter Creek, (2) on the south side of an island in the Thomson reservoir near the east corner of Sec. 6, T.48N., R.16W., and (3) in the east bank of the St. Louis River approximately 0.65 mile north of the Thomson reservoir. The Otter Creek unit ranges in thickness from 17 to 19 feet and is characterized by beds of interbedded graywacke and slate one-half to two inches thick. The individual graywacke beds contain abundant small-scale cross-bedding and evidence of penecontemporaneous deformation. The slate beds are dark gray or black, are generally thinner than graywacke beds, and commonly show very fine undisturbed laminae. The Otter Creek unit differs from the remainder of the Thomson Formation in being a very thinly interbedded series of graywacke and slate. When weathered, the slate beds become pale red, whereas the thicker graywacke beds become greenish-gray.

Environment of Deposition. The Thomson Formation contains both coarse and very fine clastic detritus that commonly suggest shallow- and deep-water environments respectively. However, this formation probably accumulated in a relatively deep-water basin, with the coarser beds being deposited by turbidity currents. Slump structures, slate fragments in the base of graywacke beds, graded bedding, and the general lack of ripple marks and large-scale cross-bedding all indicate deposition by turbidity currents.

Correlation and Age. The correlation of the Thomson Formation has been the subject of considerable debate since an Animikie age was first suggested by Irving (1883, p. 162). The area of outcrop, of which the Cloquet quadrangle is part, is largely isolated from other formations by a thick cover of glacial drift; this fact has left the correlation in doubt.

Spurr (1894), Leith (1903), Schwartz (1942b), and Grout and others (1951) suggested correlation with the pre-Animikie Knife Lake Group, whereas several of the early writers in the late 1800's suggested correlations ranging from Keewatin to Lower Cambrian. Dating by the potassium-argon method indicates that the granite to the south that intrudes the Thomson Formation is 1.7 billion years (post-Animikie) in age (Goldich and others, 1957, p. 550) and that the Thomson Formation and the rocks of the Cuyuna and Mesabi districts were all deformed during this orogeny. The Knife Lake rocks, on the other hand, were folded and intruded by granite at least 2.5 billion years ago. These radioactive–age determinations, the similarity of the Thomson Formaton to other middle Precambrian formations in Minnesota, and the lack of evidence for more than one major period of folding all suggest that the Thomson Formation should be correlated with the Animikie Group.

MICROGABBRO DIKES

A parallel swarm of medium- to fine-grained, ophitic microgabbro dikes has intruded the Thomson Formation. The density of dikes perpendicular to their strike ranges from about 3 to more than 10 dikes per mile in the quadrangle. The dikes commonly weather more easily than the slates or graywackes and are expressed topographically as gaps in ridges. Where unexposed, they were traced by a sharp positive magnetic anomaly recorded on a Schmidt-type vertical-intensity magnetometer.

The larger dikes are medium-grained microgabbro with fine-grained basaltic chilled margins. The small dikes are fine-grained throughout and have dense margins. Flow banding is common near the edges of the dikes. Some dikes are multiple intrusions. The fresh surface of the microgabbro is greenish-gray to black and resembles massive graywacke. However, a distinctive rust-brown color of the weathered surface commonly permits easy identification of the dikes in the field.

The dikes range in width from a few inches to about 220 feet; the most common widths are 25–35 feet or less than 10 feet. The dikes parallel and probably occupy the N.30°E.-joint set and fault zones. Some dikes occupy the northeast-trending joint set and show off-sets along the northwest-trending joint set.

In thin section the dikes are ophitic microgabbro, containing about 60 per cent labradorite (An_{56}), 30 per cent augite, and 10 per cent accessory minerals. Much of the augite is altered to hornblende. The feldspar commonly shows sericitic alteration, especially near grain boundaries and fractures. The magnetite-ilmenite content ranges from 1 to 5 per cent.

The slates and graywackes generally are only slightly metamorphosed and baked by the intrusion of the dikes. Where the dikes are thick and closely spaced, contact metamorphism has altered the graywacke and slate to hornfels.

The dikes are of a dilation type, for concretion zones, individual beds, and structural features have all been offset perpendicular to the dike walls.

The dikes are probably Middle Keweenawan in age, but younger than the Duluth Complex. Relative age of individual dikes is generally uncertain. In several places southeast of Carlton, dikes apparently cross one another, but in each place the point of crossing is not exposed, and relative ages were not determined. However, the general composition of all dikes is similar, suggesting that even though they may represent different intrusive pulses, they probably do not differ greatly in age.

QUARTZ VEINS

The Thomson Formation contains numerous quartz veins ranging in width from less than one inch to nearly 10 feet. The veins are predominantly crystalline milky quartz with minor amounts of pyrite, chalcopyrite, and other sulfides. The wall rock next to the larger veins is commonly altered to sericite and/or idocrase.

The largest quartz vein observed in the area is below the Thomson dam and is now largely covered by the Highway 39 bridge over the St. Louis River. This large vein occupies an extension fissure near the crest of an anticline. Large veins also occupy troughs of folds, whereas small ones, generally less than six inches wide, occur along joint and bedding planes. In several places, veins that occur along bedding planes have been folded with the enclosing wall rock and now resemble ptygmatic folds.

The quartz veins were probably deposited during the late stages of the major period of folding, as indicated by the "ptygmatic" veins, the sheared texture of the quartz grains, and the occurrence of the veins in tension fractures related to the folds.

STRUCTURAL GEOLOGY

Folds. The Thomson Formation is intensively folded, and minor folds can be seen in most exposures. The wave length of the observed folds ranges from a few inches to several hundred feet, but most are a few tens of feet. The folds range from broad, open, symmetrical folds in graywacke to tight, asymmetric, overturned folds in the less competent slate units.

The minor folds in the quadrangle trend generally within 15° of east and are nearly vertical. In the northern half of the quadrangle, they plunge from 0 to 42° E. In the southern half, the folds plunge both to the east and to the west. The minor folds were of limited use in determining the major structure.

Before this study, no large-scale structural features had been accurately determined for any part of the outcrop belt of the Thomson Formation (Schwartz, 1942a). The recognition of the Otter Creek unit during this study made it possible to determine the major structural pattern for part of the southern half of the quadrangle. A three-mile-long north-south cross-section (Fig. 3) shows three large synclines and two large anticlines, as well as many minor folds on their limbs. The larger folds can be traced for distances of about one and one-half to two miles; further tracing is prevented by a lack of good exposure and by faults, now occupied by dikes, that offset the fold axes. These folds trend about S.85°E. and appear to plunge gently in that direction.

The lack of a well-exposed marker horizon in the northern part of the quadrangle prevented determination of the major structures in that area.

Faults. Faults of two types — normal and reverse — are common in the strongly deformed Thomson Formation, but most of them appear to have displacements of only a few tens of feet or less. They are difficult to recognize because good key beds are lacking, but slickensides, breccia zones, offset structural features, and in one case offset of the Otter Creek unit were used as criteria for faults.

The normal faults commonly strike N.30°E., approximately parallel to one of the joint sets. The fault planes are nearly vertical, and the relative movement is generally dip-slip. One fault occurs near the mouth of Otter Creek and offsets the Otter Creek unit of the Thomson Formation. The movement on it was nearly vertical, with the western block being lowered about 200 feet relative to the eastern block. Another normal fault controls the course of the St. Louis River east of the paper mill at Cloquet. For about a third of a mile it has a breccia zone as much as 40 feet wide, suggesting large displacement. The actual slip was not determined. At the northern end, the fault is intruded by a 4-foot microgabbro dike. Both dike and breccia have been altered. The adjacent beds of the Thomson Formation up-dip from the vertical dike have lost much of their calcite cement and have been bleached to a light-gray color. Numerous vertical quartz veinlets cut the beds. Iron was locally introduced. Apparently, solutions rose along the vertical dike and breccia and fed upward into the inclined beds of the Thomson Formation (Fig. 4).

The reverse faults, which strike approximately east and dip southward at angles of 20°–40°, were noted in the southern half of the quadrangle. The slip on these faults probably does not exceed 10 to 20 feet. There is generally little deformation of beds either above or below the slickensided fault plane. One of these faults is well exposed on the west side of an island in the St. Louis River, north of the Thomson reservoir. It strikes N.85°E. and dips 24°S. The beds below the fault dip steeply north, and the beds

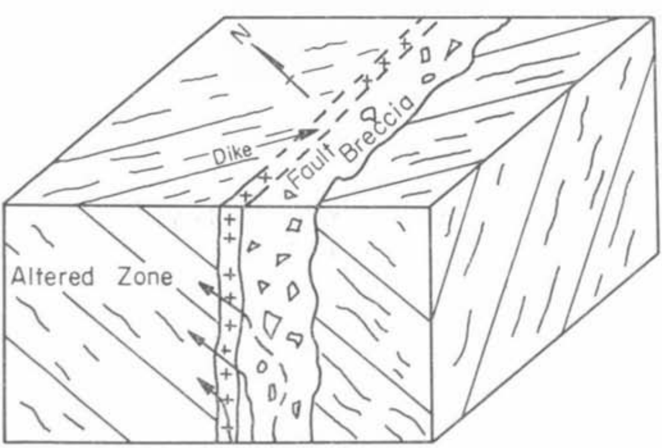

Figure 4. Structural relations of altered zone near the fault breccia and dike opposite Cloquet paper mill, showing presumed path of solutions that altered the rocks adjacent on one side.

above have been rotated slightly so that they dip steeply south. The slip on this fault is about 7 feet.

The reverse faults probably formed during the late stages of major folding in response to a regional stress. The normal faults appear to have been formed after the major period of folding and are probably related to the subsidence of the Lake Superior Syncline.

Joints. The Thomson Formation is characterized by abundant joints. Most exposures exhibit several joint sets having varied orientations and degrees of development. The preferred orientations of the joints were determined by the plotting of 900 joint measurements. The resulting diagram (Fig. 5) shows that the great majority of joints dip steeply and strike about N.30°W. and N.30°E. These sets define a conjugate joint system that probably formed in response to a north-south compressional stress acting at the time of folding. Figure 2 also suggests the presence of a set of steeply dipping joints that strikes about N.20°E. This set and the more

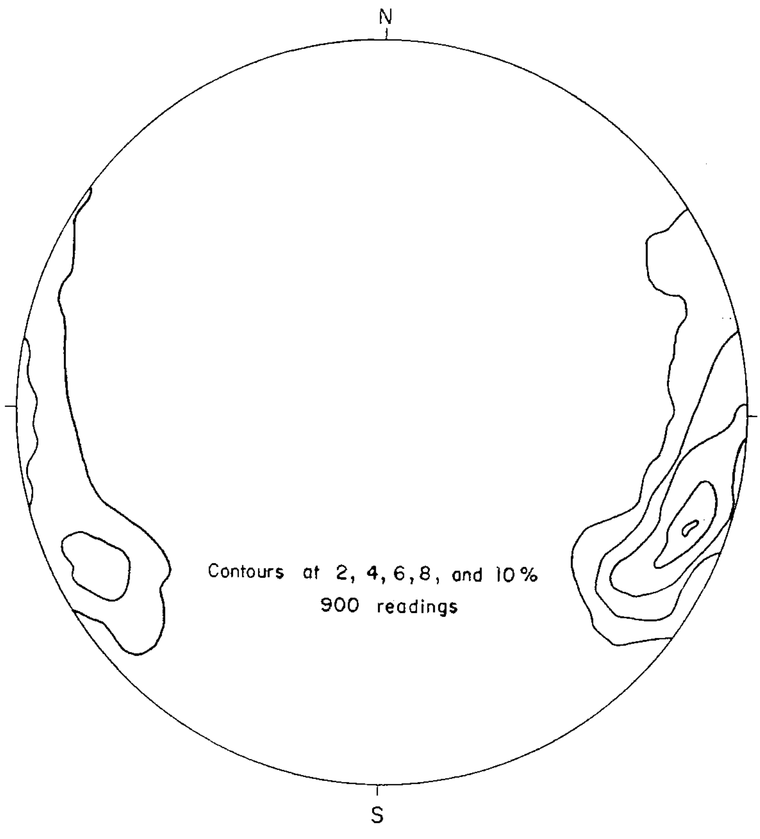

Figure 5. Orientation of joints in the Thomson Formation, plotted as normals on the lower hemisphere of equal-area net.

abundant northeast-trending joints probably resulted from post folding deformation.

Joints are better developed in graywacke and slaty graywacke than in slate and have densities averaging about 10 joints for each 10 linear feet. Joint density in the slates averages about 5 joints per 10 linear feet.

The microgabbro dikes that intrude the Thomson Formation generally have three joint sets; one set is parallel to the dike walls, one is nearly vertical, and one is nearly horizontal and normal to the walls. These joints are considered to be contraction joints, and presumably formed when the dikes cooled.

Striations. Two types of striations were noted in the Thomson Formation, those formed by slippage between strata during folding and those developed along fault planes. Striations formed by slippage between beds are well exposed on a quartz vein in the nearly vertical northern limb of an asymmetric anticline that crosses the Midway River near the southern edge of Section 32, T.49N., R.16W. The striations indicate nearly vertical slippage between beds — that is, movement in the *a* direction perpendicular to the anticlinal axis. Striations caused by faulting are numerous in ex-

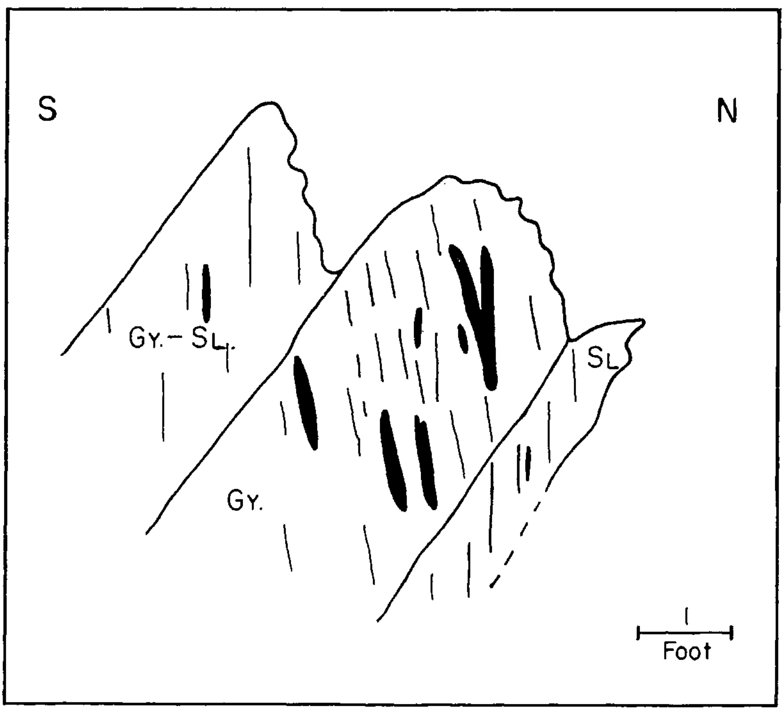

Figure 6. Large carbonate concretions parallel to cleavage in fine-grained graywacke and slate of Thomson Formation. Roadcut on U.S. Highway 61 just north of Carlton.

posures on the St. Louis River north of the Thomson reservoir. This concentration is related to the numerous small thrust faults in slate in that area.

Deformed Concretions. Many of the concretions in the Thomson Formation are flattened oblate spheroids oriented parallel to bedding planes, but some have been deformed and now parallel the cleavage. The carbonate concretions exhibit the greatest deformation (Fig. 6), whereas the siliceous concretions mainly have retained their original orientation. Elongation occurred in the plane of cleavage. In some cases bedding was distorted and folded within the concretions, in other cases it was pushed aside by reorientation. It seems apparent that concretions were reoriented in response to the stresses that acted during the major folding.

Cleavage. The Thomson Formation has a cleavage that ranges from well developed in the slate to poorly developed in the graywackes (Fig. 7). In small isolated exposures of slate it is difficult to distinguish bedding from cleavage unless thin interbedded graywackes are present. Bent cleavage is common; it apparently represents refraction of the cleavage as it passes from one unit into another of different competency.

Diagrams of cleavage orientation (Fig. 8) indicate a very similar strike, about N.85°W., for cleavage in different lithologic types, but each type has a distinct average dip. The slate shows a concentration of dips at 60°S., the slaty graywacke at 80°S., and the graywacke at about 84°N. This suggests a direct relation between the competence and/or grain size of the rock and the orientation of the cleavage. This relation prevails except near

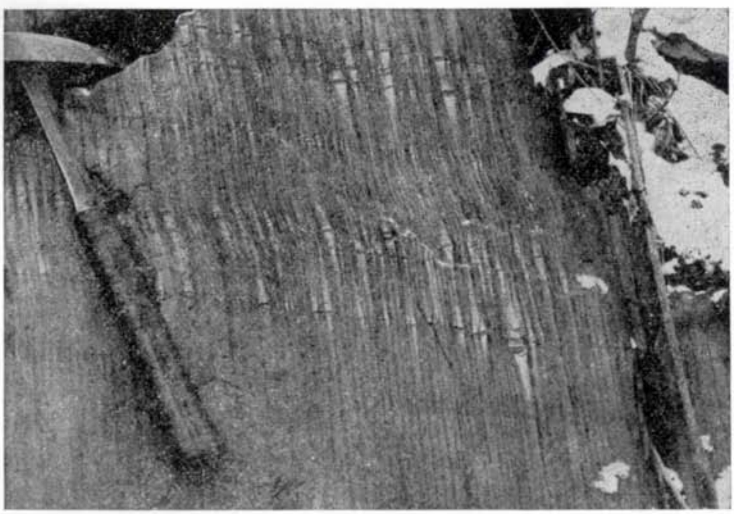

Figure 7. Vertical joint face showing vertical cleavage. Bedding makes horizontal traces on the face but dips 42° into the outcrop. Siliceous beds (white) have been broken and squeezed into lenses parallel to the cleavage planes.

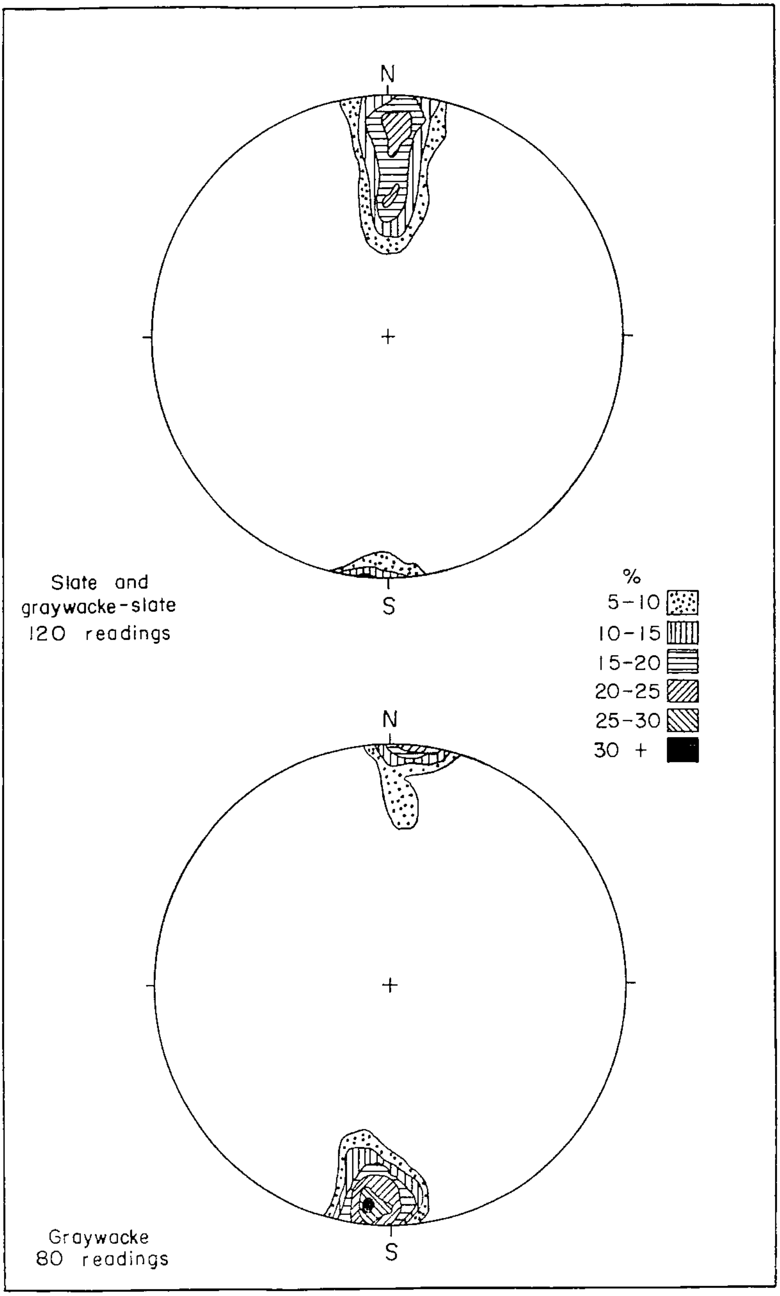

Figure 8. Orientation of cleavage in Thomson Formation, plotted as normals on lower hemisphere of equal-area net.

the axes of folds, where the dip angles of cleavage approach one another and correspond to the axial plane of the particular fold.

The cleavage proved very useful for identifying tops of beds in overturned and vertical strata, for determining relations of isolated exposures to nearby anticlines and synclines, and for establishing the plunge of folds by measuring the intersection of cleavage and bedding.

Nearly all the cleavage observed involves some parallel orientation of platy minerals, from almost complete parallelism in the slates to partial parallelism in the graywackes. The cleavage was formed during the period of major folding in response to regional stresses. Locally some of the cleavage planes have been slightly opened by a mild postfolding deformation. These planes are commonly emphasized by weathering and appear on joint faces as fine black to reddish-gray lines.

Boudinage. True boudinage or "sausage" structure was observed at only one locality in the quadrangle. On the south limb of an asymmetric anticline exposed in a railroad cut just west of Carlton, well-developed boudinage occurs in a competent graywacke between slate beds. The axes of the boudins plunge in the *b* direction of the fold.

Regional Structural Relations. The outcrop area of the Thomson Formation occupies a position central to many of the large structural features of Minnesota. The details observed during this study relate to problems in several of the large surrounding structural provinces.

The Lake Superior Syncline forms an elongate structural depression southeast of the Cloquet quadrangle. This syncline is probably more than 800 miles long, as indicated by gravity surveys (Thiel, 1956, Pl. 1), and apparently it was forming while considerable thicknesses of volcanic and sedimentary rocks accumulated. For example, Thiel (1956, p. 1085) reports 1,400 feet of sedimentary strata below the Keweenawan lava and an estimated 25,000 feet overlying the flows. White (1956, p. 9) estimates the thickness of lava at about 20,000 feet.

Analysis of Keweenawan dike orientations, gathered from many papers on various areas in the Lake Superior region, indicates a general parallelism to the margins of the syncline. The parallelism strongly suggests that the dikes were intruded into extension fractures developed during the subsidence of the Lake Superior Syncline.

The gentle postfolding deformation observed in the Thomson Formation is probably related to subsidence of the syncline. The slightly open cleavage planes and the widened northeasterly joint set are all extension features that may be accounted for by this subsidence.

Extension fractures also have been postulated by Leighton (1954, p. 410) to explain preferred orientation of diabase dikes in northern Wisconsin and by Hamblin (1958, p. 133) to explain orientation of clastic dikes in a Keweenawan or Lower Cambrian sandstone of northern Michigan.

The Cuyuna and Mesabi iron districts lie respectively about 75 miles west and 50 miles north of the quadrangle. There is some question about the correlation of the two districts, but the overall similarity of the two has led many geologists to believe that they are composed of roughly equivalent Middle Precambrian formations. Radiometric ages indicate that rocks of both districts and the Thomson Formation were involved in an orogeny about 1.7 billion years ago that marked the end of the Middle Precambrian (Goldich and others, 1957, p. 550).

Folding in the Cuyuna district is very similar to that observed in the Thomson Formation. The Virginia Formation of the Mesabi district lacks well-developed folds and cleavage, but this probably results from its much greater distance from the center of metamorphism and the orogenic axis than either the Cloquet-Carlton area or the Cuyuna district.

Leith (1903, pp. 203–204) and Schwartz (1942b, p. 1018) suggested that the Biwabik Iron-formation of the Mesabi district should occur on the south limb of a large syncline somewhere north of Cloquet. This syncline was postulated on the assumption that the Thomson Formation is Knife Lake (pre-Animikie) in age and that its belt of outcrop represents the axial portion of a large anticline. The present structural interpretation and data suggesting a Middle Precambrian age for the Thomson Formation make it improbable that the Biwabik Iron-formation occurs near the surface between the Cloquet quadrangle and the Mesabi range.

PLEISTOCENE GEOLOGY

Leverett's (1929; 1932) interpretation of the late-Wisconsin glaciation of the Cloquet area was based primarily on patterns of terminal moraines and drainage features. Stratigraphic studies in northeastern Minnesota by Wright (Wright and Ruhe, 1965), supported by radiocarbon dates, have revealed many complexities in the sequence, but the geomorphic relations remain vital to decipherment of the details, at least in the Cloquet quadrangle. Studies of drift lithology have been useful largely to confirm the geomorphic interpretation.

The surface features of the Cloquet quadrangle reflect primarily the activities of the Superior Lobe, which moved westward out of the head of the Lake Superior basin, carrying red to reddish-brown drift with stones characteristic of the Precambrian bedrock of the Lake Superior region. The ice formed drumlins, moraines, ice-contact stratified deposits, and outwash plains in the area. It blocked the eastward progress of the St. Louis River, which at times carried the outlet waters of Glacial Lake Upham. The river was first diverted to the southwest into the St. Croix River drainage, cutting progressively deeper channels through the moraines as the Superior Lobe retreated. In the final stage the river entered a proglacial lake, now recorded by dissected lake clays on the edge of the quadrangle.

Methods

Color of the till matrix was described in the field according to the following Munsell notations of hue. Chroma and value were ignored because they vary with moisture content (Schneider, 1961, p. 32). The following hues were noted: red (2.5 YR), reddish-brown (5.0 YR), brown (7.5 YR), and grayish-brown (10.0 YR). In the laboratory, representative samples were dried and crushed and then arranged on white paper according to hue in order to confirm the field notations.

Carbonate content of till and lake clay was estimated in the field by the application of a 10 per cent solution of HCl, according to the following scale: very calcareous (effervesces with evident gas bubbles and hissing), calcareous (effervesces audibly but not visibly), and noncalcareous (does not effervesce). Irregularly shaped calcareous concretions ("clay dogs") were noted; subsequent analyses revealed that these occurred only in tills and lake clays containing more than 5 per cent carbonate. Representative samples of till and lake clay were analyzed in the laboratory for acid-soluble content by the titration method described by Jackson (1958, p. 77).

Texture of the till matrix was described in the field as sandy, silty, or clayey. Stone content was described as stone-rich (abundant stones of all sizes scattered throughout) or stone-poor (boulders and cobbles rare, with or without pebbles and granules). In the laboratory, dried samples from which stones larger than 4 mm had been removed were split to 50-gram fractions and analyzed by the Bouyoucos (1927, p. 343) hydrometer method into three classes: 4 mm to .05 mm (granules and sand), .05 to .005 mm (silt), and smaller than .005 mm (clay).

Drift lithology was determined by a count of 100 stones taken from below the soil. Lithologic categories were selected on the basis of the regional bedrock geology (Arneman and Wright, 1959).

Till fabric was measured according to the methods used by Wright (1957, p. 25). Fifty stones were cleared at each site from below the soil; the direction and amount of plunge of the long axes were measured to the nearest 5° with a Brunton compass and were plotted on rose diagrams.

Lithology and Morphology

The principal features in the Cloquet quadrangle are so large that they are best introduced in the context of the regional relations, which are sketched in Figure 9. The samples on which the following descriptions are based were taken from localities not only in the quadrangle itself (Pl. 1) but also in adjacent areas. Several new names for formations and for morphologic features are here introduced. Other units in eastern Minnesota, and the glacial intervals that they represent, are described in more detail elsewhere (Wright and Ruhe, 1965).

Independence Till. The oldest map unit is the Independence Till, which is exposed at two localities in the Cloquet quadrangle beneath younger drift and which forms the prominent southwest-trending Toimi Drumlins of the Rainy Lobe north of the area (Wright, 1956). The grayish-brown color reflects the high percentage of gabbro from the North Shore Highland, iron-formation from the Gunflint iron range 125 miles to the north,

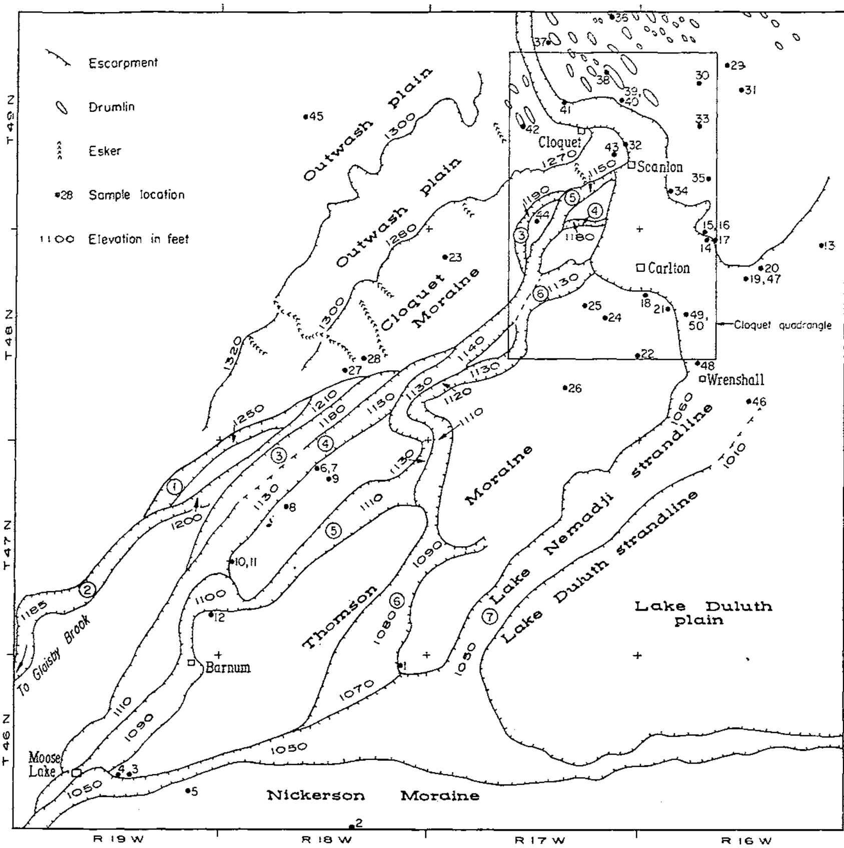

Figure 9. Map of major morphologic features near the Cloquet quadrangle.

and slate and graywacke locally derived from the Thomson Formation (Table 1). Red sandstone from the Lake Superior basin is rare. The till is sandy (Fig. 10, sample 40), very stony, and noncalcareous; its lithology resembles that of the Rainy Lobe Till in the Toimi Drumlins (Arneman and Wright, 1959). (Location of samples in Fig. 10 is shown in Pl. 1, except for those outside the Cloquet quadrangle, which are given in Table 2.) The stones at the gully cut in Section 13 (Pl. 1) show a preferred orientation of long axes parallel to the Toimi Drumlins (Fig. 11), which are visible at the surface less than 10 miles to the north. Little doubt exists that the grayish-brown Independence Till should be assigned to the Rainy Lobe. The till is here named from a 15-foot roadcut in a drumlin 1.3 miles west of the village of Independence (St. Louis County), 17 miles north of Cloquet. There the Independence Till has a 2-foot cap of clayey till from another source.

Cromwell Formation. The major till and associated stratified deposits

Table 1. Lithology of Pebbles in Till and Outwash in and near Cloquet Quadrangle, in Percentages*†

Sample No.	3	4	10	13 up	14 low	19	51 ow	52 ow	53 ow	26	30	32	34	37	38 ow	39 up	40 low	43
Basalt	10	11	12	19	20	11	14	19	12	9	13	21	20	15	13	11	13	13
Felsite	8	16	6	30	11	29	32	13	18	8	20	16	23	19	26	20	12	15
Gabbro‡	3	5	6	6	4	10	3	12	1	6	6	11	2	15	14	5	13	6
Redrock		5		1	15		7	8	10	5	6	6		6	7	4	1	7
Sandstone§	55	22	57	11	19	22	7	3	15	47	16	4	14	2	1	18		5
Granite‖	3	8	5	1	1	7	10	5	12	11	3	5	6	7	4	5	4	15
Weathered igneous				1	1		1	2			2	5		2	1	4		
Graywacke	8	15	12	27	18		21	21	21	8	25	16	15	15	15	18	28	15
Greenstone	4	1		1	6	4		3	2			3		2	1	1		2
Schist♯	1	11												5	1			2
Slate	4	1		1	2	6		2	5		2	2	4	3	13	11	20	7
Quartzite	3			1	2		4	5	2	1	5	3	4	5	4	1	2	2
Iron formation		4			1	2		3		1	2		8				7	4
Black chert	1					3		2		4		3	3	2		1		2
Light chert		1		1		5		1	2			4	1					1
Limestone			2															
Other						2	1	1				1		2	1	1		2

* Sample locations are shown on Plate 1 or listed in Figure 10 and Table 2.
† Abbreviations used are as follows: up = upper; low = lower; ow = outwash.
‡ Anorthosite included. § Predominantly red. ‖ Quartz, diorite, and gneiss included. ♯ Phyllite included.

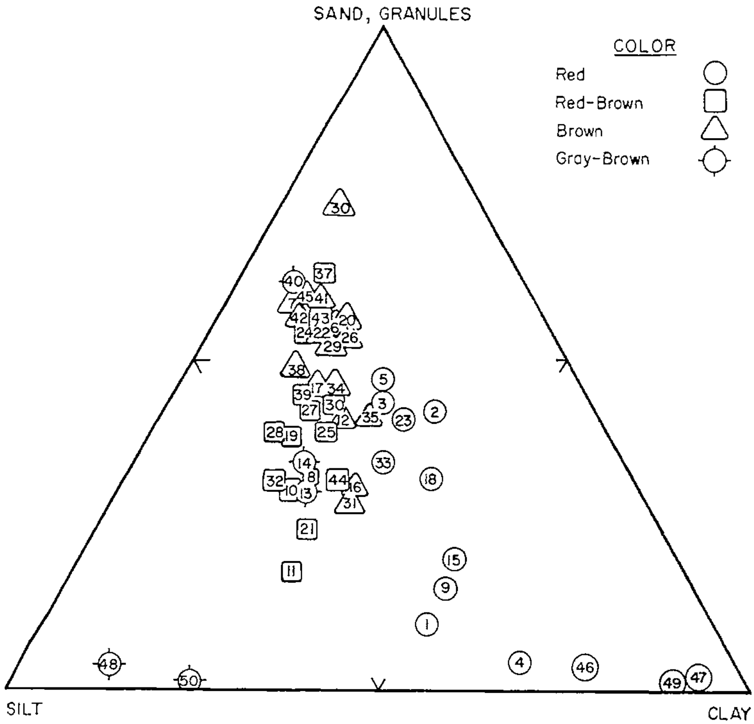

Figure 10. Grain-size distribution of samples of till and lake sediment, showing the relation of texture to color. Location of samples inside Cloquet quadrangle is shown on Plate 1; those outside the Cloquet quadrangle are given in Table 2.

in the quadrangle compose the Cromwell Formation. It is named from a village in Carlton County that is 18 miles west of the Cloquet quadrangle on U.S. Highway 210, where exposures of reddish-brown sandy till and associated sand and gravel are numerous. The name is intended to apply to the generally reddish-brown sandy to silty till and associated sand and gravel containing red sandstone of the Precambrian Hinckley or Fond du Lac Formations. It was deposited by the Superior Lobe and its associated streams in eastern Minnesota from southern St. Louis County west to Crow Wing and Todd counties and south to Dakota County. Its base is not exposed at the type locality, but it presumably rests on Independence Till in that area, as it does in Section 13 in the Cloquet quadrangle and more conspicuously in the long roadcut 0.2 mile north of Brookston, which is 20 miles northeast of Cromwell. In central Minnesota west of the Mississippi River it rests on Wadena Lobe till. At the type locality it is exposed at the surface, but from Brookston to the northwest it has a cover of St. Louis Sublobe drift. At places in the Cloquet quadrangle and to the

TABLE 2. LOCATION OF SAMPLES OF TILL AND LAKE SEDIMENT TAKEN OUTSIDE THE CLOQUET QUADRANGLE

Sample No.	¼ ¼ Sec.	¼ Sec.	Sec. No.	Township North	Range West
1	SW	NW	1	46	18
2	SE	SE	27	46	18
3	SE	NW	22	46	19
4	SW	NW	22	46	19
5	SW	SW	24	46	19
6, 7	SE	SE	4	47	18
8	SW	SW	9	47	18
9	NE	NW	10	47	18
10, 11	SE	NW	19	47	18
12	SE	SE	25	47	19
13	SE	NW	1	48	16
17	SE	NW	4	48	16
19	SE	NW	10	48	16
20	NE	NE	10	48	16
23	SW	SE	6	48	17
26	SW	NW	26	48	17
27	SE	SE	22	48	18
28	NE	SW	23	48	18
29	SE	NE	9	49	16
31	NE	NW	15	49	16
34	SW	SW	29	49	16
35	SE	NW	28	49	16
36	SE	NE	1	49	17
37		SE	3	49	17
45	SW	SE	16	49	18
46	SE	SW	27	48	16
47	SE	NW	10	48	16
48	SE	SE	20	48	16
51	NE	NW	15	48	17
52	NW	NW	26	49	17
53	NE	NW	23	48	17

south it is overlain by Barnum Till; in east-central Minnesota, from Pine County south to Dakota County and west to Hennepin and Stearns counties, it is covered by Grantsburg Sublobe drift.

The till of the Cromwell Formation ranges in color and texture from brown and sandy to reddish-brown and silty (Fig. 10). Redder colors reflect a higher content of red clay.

Carbonate content of the till matrix also varies considerably; the carbonate may be derived from the Precambrian red clastic sedimentary rocks of the Lake Superior basin, which locally contain as much as 18 per cent acid-soluble carbonate (Nelson, 1942; Morey, 1968). At a few localities fragments of limestone occur; they may have a source in or near the eastern part of the Lake Superior basin. Stone content is characterized by relatively high percentages of red sandstone from the Lake Superior basin (Table 1). Southwest of the Cloquet quadrangle the higher content of schist reflects progressive metamorphism of the Precambrian rocks in that

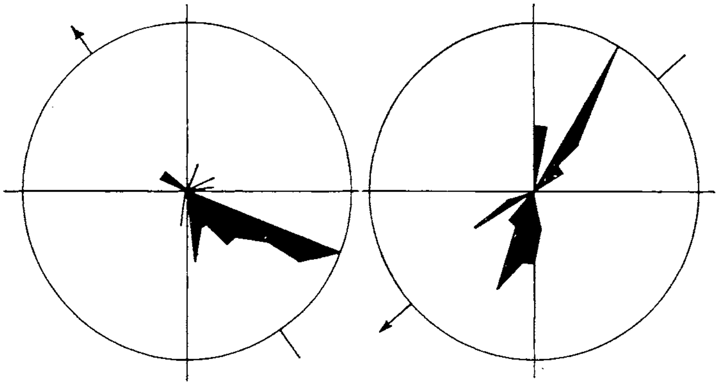

Figure 11. Rose diagrams showing plunge direction of 50 elongate stones in Cromwell Till (a) and underlying Independence Till (b) at gully exposure in Section 13 ½ mile north of Cloquet paper mill. Arrow in (b) shows trend of Automba Drumlins in Cromwell Till in the immediate area. Arrow in (a) shows trend of Toimi Drumlins in unburied Independence Till 12 miles to the north.

direction, and the higher content of red sandstone reflects proximity to shallow bedrock of that lithology.

Stone orientation of the reddish-brown till at the river cut in Section 13, where the till overlies the grayish-brown Independence Till, shows a strong preference of plunge of long axes to the southeast (Fig. 11); the orientation implies glacier flow from this direction (Wright, 1957), consistent with the trend of the drumlin near which the exposure is located.

The stratified facies of the Cromwell Formation in areas of morainic topography generally consists of poorly sorted sand and gravel, probably deposited by streams in close contact with the ice. The differential distribution of the till and outwash is so complex that it was not mapped in detail. Under proglacial outwash plains, however, the stratified facies consists of well-sorted sand and pebble gravel.

The Cromwell Formation is expressed in different geomorphic features within the Cloquet quadrangle. North of the latitude of Cloquet are several dissected or partly buried drumlins of the Automba Drumlin Field. They trend about N.35°W., having been formed by the Superior Lobe advancing in this direction out of the Lake Superior basin. The Automba Drumlins are named from the village of Automba in southwestern Carlton County, 25 miles southwest of the Cloquet quadrangle, where the drumlins trend about N.65°W. Only about 2 miles north of the Cloquet quadrangle the Automba Drumlins terminate at the Highland Moraine, which clearly buries the southwest-trending Toimi Drumlins of the Rainy Lobe (Wright and Ruhe, 1965).

The Cloquet Moraine is a strip of irregular topography trending southwest from Cloquet. Its most remarkable feature is a pitted ice-contact slope as much as 80 feet high, which leads up to the Cloquet frontal outwash plain at an elevation of 1,280 feet. This plain consists of five coalescing fans, each having a distinct esker-handle. The largest esker, just south of Cloquet, is a winding ridge a mile long and almost 100 feet high. It is certainly the most striking terminal esker in Minnesota and perhaps in the entire Great Lakes region. Adjacent to it on the northeast is an oval kame of equal height. The Cloquet Outwash Plain that extends to the west from the esker has small islands of unburied Cromwell Till projecting a few feet above the well-sorted outwash of the plain; some of the larger islands are probably Automba Drumlins (Secs. 9, 10, 15, 16).

The Cloquet Moraine as thus mapped consists of the irregular topography between the Cloquet frontal outwash plain and the oldest erosional diversion channel of the St. Louis River. The Cloquet Moraine was named by Leverett (1929, p. 25) without particular discussion of its genesis.

The Thomson Moraine occupies an area of irregular topography on the Cromwell Formation near Chub Lake in the southern part of the quadrangle. The relief is sharp and locally exceeds 50 feet, with the high points reaching elevations of 1,200 feet. It is also bordered by a frontal plain (the Thomson Outwash Plain), which is much dissected by diversion channels of the St. Louis River. It is bordered on the east by the strandlines of Glacial Lake Nemadji. Northeast of Chub Lake the moraine is marked by a northwest lineation, which may represent former channels that fed the Thomson Outwash Plain, but no discrete eskers could be identified. The moraine was originally named by Leverett (1929, p. 25); it extends southwestward for about 15 miles to Moose Lake.

The Thomson Outwash Plain generally has a transitional border to the Thomson Moraine, from which it was graded to the west, although north of Chub Lake the two features are sharply separated by an east-facing ice-contact slope. The plain has an elevation of about 1,200 feet.

Even though features of three phases of ice activity are represented by the Cromwell Formation — Automba Drumlin Field, Cloquet Moraine, and Thomson Moraine — the tills cannot easily be distinguished in the field on the basis of lithology alone. Particle-size analysis and careful color descriptions, however, show that the till of the Thomson and Cloquet moraines is redder and less sandy than the till of the Automba Drumlin Field (Fig. 12). The higher content of red clay in the matrix may have resulted from incorporation of proglacial lake sediments formed before the readvance of the Superior Lobe to the moraines in question.

Barnum Till. At two localities about a mile south of Carlton is exposed red clayey stone-poor till similar to the Barnum Till, which forms a thick cap on the Thomson Moraine near Barnum about 12 miles southwest of the Cloquet quadrangle (Baker, 1964). The till at these two localities is only a few feet thick and rests on stratified sand and gravel of the Cromwell Formation. The high content of red clay is believed to represent re-

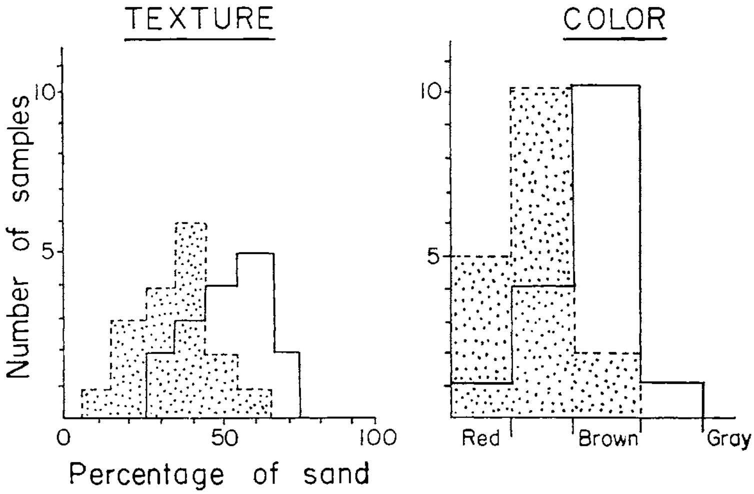

Figure 12. Graph to show that the Cromwell Till in the Thomson and Cloquet moraines (dotted line around 17 samples) is siltier and redder than the Cromwell Till of the Automba Drumlins and related ground moraine (solid line around 16 samples).

worked lake deposits. Its main area of distribution is in the Nickerson Moraine from Barnum eastward (Fig. 9).

Diversion Channels. Four erosional channels at different levels represent former courses of the St. Louis River when it carried the outlet waters of Glacial Lake Upham and was diverted southwestward by the retreating Superior Lobe to the Kettle River and thence to the St. Croix and Mississippi rivers (Fig. 9). The channels are now occupied by bogs or underfit streams. The first two channels are beyond the limits of the quadrangle (Fig. 9); they lead to Glaisby Brook. The third channel, at an elevation of about 1,190 feet, is relatively narrow. It cuts the Cloquet Moraine and may have taken meltwater from the Thomson Outwash Plain as well as from the St. Louis River. A small boulder-covered terrace at Scanlon just west of State Highway 45 at 1,210 feet may also represent this level. The fourth channel, only slightly lower at 1,180 feet, is also narrow. It partially cuts the Thomson Outwash Plain. These four unnamed channels are less than 1,000 feet broad; the flow from Lake Upham was probably not yet large.

The fifth channel, at an elevation of about 1,150 feet, extends from Scanlon to the southwest and is here called the Scanlon channel. It exceeds 2,000 feet in breadth and has low terraces along its flanks. It occupies the area between the Cloquet Moraine and the Thomson Outwash Plain, against both of which it has eroded sharp scarps.

The sixth channel extends southwestward from Carlton at an elevation of 1,130 feet and is here called the Carlton channel. It intersects the Scanlon channel in Section 16 and then diverges again to leave the quadrangle at the very southwestern corner. It has a minimum width of about 1,500 feet. It bisects the Thomson Outwash Plain and part of the Thomson Moraine.

Wrenshall Formation and Nemadji Lake Plain. When the Superior Lobe withdrew still farther east, the St. Louis River entered the narrow proglacial Lake Nemadji, which occupied the southeastern corner of the Cloquet quadrangle and extended southward along the ice front. The strandline is visible west of Wrenshall at an elevation of about 1,070 feet. The outlet channel (No. 7 on Fig. 9, elevation 1,050 ft.) was southwestward to Moose Lake, where it cut into the Carlton channel described above. The Nemadji Lake Plain is now largely dissected close to the St. Louis River, which cuts a deep canyon in its fall to Lake Superior.

The Wrenshall Formation contains shallow-water sands within a mile or two of the beaches, especially close to the St. Louis River, where a delta presumably was located. Most of the lake deposits are clay and silt, however. The abandoned clay pits at Wrenshall formerly exposed at least 40 feet of fine-grained sediments, which are blue-gray in the lower part and yellow and red in the upper (Winchell, 1899, p. 31); these pits are designated as the type locality. North of Wrenshall along the St. Louis River gorge, where U.S. Highway 210 crosses the 960-foot contour, the following section was exposed in 1957; it may be considered an alternate type section of the Wrenshall Formation.

Wrenshall Formation
- 3.2 feet. Clay; red, with irregular concretions.
- 9.3 feet. Silt; yellow, with thin red clay interbeds and regular concretions.
- 2.6 feet. Silt; gray.

Cromwell Formation
- 1.4 feet. Gravel; very coarse.
- 22.0 feet. Sand; brown to red-brown, with thin interbeds of silt.

The irregular carbonate concretions found in the red clay probably indicate a lack of intergrain permeability, with waters moving instead along the fissile fractures in the structureless clay. In the gray or yellow sediments, however, the rounded, concentric concretions imply water movement along intergrain pore spaces afforded by coarser grain size. Textural analyses show that the red sediments consist of 85 per cent clay, whereas the gray sediments consist of 80 per cent silt (Fig. 10). The carbonate content is 10 per cent higher in the gray and yellow silts than in the red clay.

The color differences in the Wrenshall Formation have been explained in various ways. Schwartz (1949, p. 120) attributed the red surface clays to weathering of gray clay. Swain and Prokopovich (1957, p. 539) propose, on the other hand, that the gray sediments result from the reduction of red iron oxide in deep lake water soon after deposition. Wright (1955, p. 410), following an earlier suggestion of Leverett (1929, p. 55), believed that the gray sediment was deposited by inflowing water from the St.

Louis River, which had a source in gray calcareous drift about 30 miles upstream, and that the red clay had its source in the nearby Superior Lobe. The differences in both texture and carbonate content support this explanation. The yellow color results from the oxidation of gray material. Postglacial climatic conditions in Minnesota have not been suitable for the formation of red soil colors by weathering.

Glacial History

The oldest event recorded by the glacial features in the Cloquet quadrangle is the deposition of the gray-brown Independence Till of the Rainy Lobe in the form of the Toimi Drumlins. Regional relations (Wright and Ruhe, 1965) place this event as part of the St. Croix phase of the Wisconsin glaciation. The Superior Lobe also was presumably active at this time alongside the Rainy Lobe, both lobes advancing southwest to the St. Croix Moraine in southeastern and central Minnesota.

Both lobes then retreated, and in the next phase, called the Automba phase (Wright and Ruhe, 1965), the Superior Lobe advanced westward out of the head of the Lake Superior basin. It cut northwest-bearing striae on the bedrock of the general area (Schwartz, 1949, Pl. 4), buried the margin of the Toimi Drumlin Field with Cromwell Till and outwash, molded the Automba Drumlins with parallel stone fabric, and terminated at the Highland Moraine a few miles northwest of the Cloquet quadrangle.

After retreat of the Superior Lobe sufficiently far to allow the formation of small proglacial lakes, the ice readvanced in the Split Rock phase, named from relations southwest of the Cloquet quadrangle, where it formed the Split Rock Drumlin Field of red clayey till (Wright and Ruhe, 1965). This and the subsequent ice advance have been attributed to a relatively rapid surge of thick ice out of the Lake Superior basin after a long interval of retention behind a near-stagnant ice front (Wright, 1969). The ice reached a few miles west of the Cloquet quadrangle, and its effluent streams deposited a frontal outwash plain. A slight retreat brought it to the Cloquet Moraine and its frontal outwash plain. The variable silty to sandy texture of the Cromwell Till in the Cloquet Moraine implies that this northwestern flank of the Superior Lobe may also have incorporated local lake sediments during its readvance in the Split Rock phase. Meltwaters from the ice front at this time drained westward up the St. Louis River at an elevation of 1,280 feet or lower to Glacial Lake Upham I, thence to Glacial Lake Aitkin I and into the Mississippi River (Wright and Ruhe, 1965).

The Superior Lobe continued its retreat, and in the Nickerson phase it stood at the Thomson Moraine, whose equivalent on the south side of the narrow lobe is the Nickerson Moraine. Meltwater formed the Thomson Outwash Plain at 1,200 feet and thence found its way southwestward around the lobe to Glaisby Brook, which flows into the Kettle River and thence into the St. Croix (Wright and Ruhe, 1965).

Meanwhile the St. Louis Sublobe of the Des Moines Lobe advanced from the west and filled the basins of Glacial Lakes Aitkin I and Upham I, reworking the lake deposits to produce a red-brown to brown silty till that was formerly confused with the Barnum Till (Wright, 1955). The St. Louis Sublobe terminated about 12 miles northwest of the Cloquet quadrangle and thence followed the Superior Lobe drainage out to Glaisby Brook. As the St. Louis Sublobe retreated, Glacial Lake Upham II formed, and its clear-water outlet down the St. Louis River cut diversion channels through the Thomson Outwash Plain. The oldest preserved channels are relatively narrow and shallow. They were cut through the Cloquet Moraine and probably connected with the Glaisby Brook channel, which served also as the outlet for meltwater from the Thomson Outwash Plain. Slight retreat of the Superior Lobe started the dissection of the Thomson Outwash Plain itself. Lake Upham was still quite small. Further ice retreat opened the Scanlon channel at an elevation of 1,150 feet, and at the same time the retreat of the St. Louis Sublobe enlarged the size of Lake Upham and its outlet stream. The Carlton channel at 1,130 feet was formed after another adjustment in the Superior Lobe front. By this time the waters of Glacial Lake Aitkin II were probably added to those of Lake Upham II (Farnham and others, 1964; Wright and Ruhe, 1965). One further retreat in the Superior Lobe ice front created proglacial Lake Nemadji, to which the Lake Upham meltwaters brought the calcareous gray silts of the Wrenshall Formation. Finally, however, the Upham meltwaters may have slowed, for top sediments in Lake Nemadji were red clays of local origin. Perhaps by this time Lake Upham was drained and separated from Lake Aitkin (Farnham and others, 1964).

The outlet of Lake Nemadji was the last of the St. Louis River diversion channels in Minnesota. Further retreat of the Superior Lobe opened a lower outlet down the Brule River in northwestern Wisconsin, causing Lake Nemadji to change to Lake Duluth at 1,010 feet. Thereafter the lake level continued to drop, and the St. Louis River and its tributaries began to dissect the thick lake sediments and tills that filled the head of the Lake Superior basin.

The correlation and absolute chronology of this glacial history is controlled by only a few radiocarbon dates, none from the Cloquet quadrangle itself. All of the events up through the Nickerson phase predate the Two Creeks interstadial interval of the Wisconsin glaciation. Carbon dates from the basal organic sediment of an ice-block depression in the Cloquet Outwash Plain 4 miles west of the quadrangle (or, more accurately, a slightly older outwash plain) read as old as 16,150 ± 550 (W-1973). More critical are the dates of 11,710 ± 325 (W-502) and 11,560 ± 400 (W-1141) from wood on a soil in the sediments of Glacial Lake Aitkin II (Farnham and others, 1964), which postdates the last advance of the St. Louis Sublobe, in turn correlative with the Nickerson phase through the drainage relations described above.

This chronology represents a revision of that which placed as Valders the clay-till moraines of the Superior Lobe (Split Rock and Nickerson phases) and their equivalents in the Cloquet quadrangle (Wright, 1955). In the revision, the Valders drift border is placed instead east or north of Minnesota (Wright and Ruhe, 1965).

REFERENCES

Arneman, J. F., and H. E. Wright, Jr., 1959, Petrography of some Minnesota tills: Jour. Sed. Petrology, v. 29, pp. 540–554.

Baker, R. G., 1964, Late-Wisconsin glacial geology and vegetation history of the Alborn area, St. Louis County, Minnesota: University of Minnesota M.S. thesis, 44 pp.

Bouyoucos, G. J., 1927, The hydrometer as a new method for the mechanical analysis of soils: Soil Sci., v. 23, pp. 343–353.

Farnham, R. S., J. H. McAndrews, and H. E. Wright, Jr., 1964, A late-Wisconsin buried soil near Aitkin, Minnesota, and its paleobotanical setting: Am. Jour. Sci., v. 262, pp. 393–412.

Goldich, S. S., H. Baadsgaard, and A. O. C. Nier, 1957, Investigations in A^{40}/K^{40} dating: Amer. Geophys. Union Trans., v. 38, pp. 547–551.

Grout, F. F., J. W. Gruner, G. M. Schwartz, and G. A. Thiel, 1951, Precambrian stratigraphy of Minnesota: Geol. Soc. Am. Bull., v. 62, pp. 1017–1078.

Hamblin, W. K., 1958, The Cambrian sandstones of northern Michigan: Mich. Geol. Survey Pub. 51, 146 pp.

Irving, R. D., 1883, The copper bearing rocks of Lake Superior: 3rd Ann. Rept., U.S. Geol. Survey, pp. 93–180.

Jackson, M. L., 1958, Soil chemical analysis: New York, Prentice-Hall, 498 pp.

Kuenen, Ph. H., 1957, Sole markings of graded graywacke beds: Jour. Geology, v. 65, pp. 231–258.

Leighton, M. W., 1954, Petrogenesis of a gabbro-granophyre complex in northern Wisconsin: Geol. Soc. Am. Bull., v. 65, pp. 401–442.

Leith, C. K., 1903, The Mesabi iron-bearing district of Minnesota: U.S. Geol. Survey Mon., v. 43, 316 pp.

Leith, C. K., R. J. Lund, and A. Leith, 1935, Precambrian rocks of the Lake Superior region: U.S. Geol. Survey Prof. Paper 184, 34 pp.

Leverett, Frank, 1929, Moraines and shorelines of the Lake Superior basin: U.S. Geol. Survey Prof. Paper 154-A, 72 pp.

———, 1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geol. Survey Prof. Paper 161, 149 pp.

Morey, G. B., 1968, Stratigraphy and petrology of the type Fond du Lac Formation, Duluth, Minnesota: Minn. Geol. Survey Rept. Inv. 7, 35 pp.

Nelson, C. A., 1942, A petrographic study of the lower Keweenawan sandstones of northern Minnesota: University of Minnesota M.S. thesis, 46 pp.

Pettijohn, F. J., 1957, Sedimentary rocks, 2nd ed.: New York, Harper, 718 pp.

———, 1958, Paleocurrents of Lake Superior Precambrian quartzites: Geol. Soc. Am. Bull., v. 68, pp. 469–480.

Schneider, A. F., 1961, Pleistocene geology of the Randall region, central Minnesota: Minn. Geol. Survey Bull. 40, 151 pp.

Schwartz, G. M., 1942a, Structures in the Thomson Formation, Minnesota: Econ. Geology, v. 37, pp. 39–63.

———, 1942b, Correlation and metamorphism of the Thomson Formation, Minnesota: Geol. Soc. Am. Bull., v. 53, pp. 1001–1020.

———, 1942c, Concretions of the Thomson Formation, Minnesota: Am. Jour. Sci., v. 240, pp. 491–499.

———, 1949, The geology of the Duluth metropolitan area, Minnesota: Minn. Geol. Survey Bull., 33, 136 pp.

Shrock, R. R., 1948, Sequence in layered rocks: New York, McGraw-Hill, 507 pp.

Spurr, J. E., 1894, The stratigraphic position of the Thomson slates: Am. Jour. Sci., v. 48, pp. 159–166.

Swain, F. M., and N. Prokopovich, 1957, Stratigraphy of upper part of sediments of Silver Bay area, Lake Superior: Geol. Soc. Am. Bull., v. 68, pp. 527–542.

Thiel, Edward, 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota: Geol. Soc. Am. Bull., v. 67, pp. 1079–1100.

Van Hise, C. R., and C. K. Leith, 1911, The geology of the Lake Superior region: U.S. Geol. Survey Mon. 52, 641 pp.

White, W. S., 1956, Regional structural setting of the Michigan native copper district: Houghton, Mich. Coll. Mining and Technology, Inst. Lake Superior Geol.

Winchell, N. H., 1899, The geology of Carlton County, Minnesota: Minn. Geol. Nat. Hist. Survey, Final Rept., v. 4, pp. 1–24.

Wright, H. E., Jr., 1955, Valders till in Minnesota: Jour. Geology, v. 63, pp. 403–411.

———, 1956, Sequence of glaciation in eastern Minnesota: Geol. Soc. Am. Guidebook, Minneapolis meeting, Pt. 3, pp. 1–24.

———, 1957, Stone orientation in Wadena drumlin field, Minnesota: Geog. Annaler, v. 39, pp. 19–31.

———, 1969, Glacial fluctuations and the forest succession in the Lake Superior region: Internat. Assoc. Great Lakes Research, 12th Conf. (Ann Arbor, 1969), Proc.

——— and R. V. Ruhe, 1965, Glaciation of Minnesota and Iowa, pp. 29–41 *in* H. E. Wright, Jr., and D. G. Frey, eds., The Quaternary of the United States: Princeton, N.J., Princeton University Press, 922 pp.

Wright, H. E., Jr., and W. A. Watts, with contributions by Saskia Jelgersma, Jean C. B. Waddington, Junko Ogawa, and T. C. Winter, 1969, Glacial and vegetational history of northeastern Minnesota: Minn. Geol. Survey, Spec. Pub. 11, 59pp.