MINNESOTA GEOLOGICAL SURVEY

PAUL K. SIMS, *Director*

SEDIMENTOLOGY OF THE MIDDLE PRECAMBRIAN THOMSON FORMATION, EAST-CENTRAL MINNESOTA

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CONTENTS

ILLUSTRATIONS

TABLES

MINNESOTA GEOLOGICAL SURVEY

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by

G. B. MOREY and RICHARD W. OJAKANGAS

ABSTRACT

The Thomson Formation is exposed in parts of Carlton, Pine, and southern St. Louis Counties of east-central Minnesota. The formation was folded and metamorphosed during the Penokean orogeny 1,700 million years ago, but primary sedimentary textures and structures are well-preserved in the Cloquet-Carlton area.

The formation is characterized by intercalated slate, siltstone, and graywacke. In two measured sections at the type locality, graywacke comprises 34 percent, siltstone 35-43 percent, and slate 23-31 percent of each section. Most beds are less than one foot thick. Because of abundant graded beds, lateral continuity of individual beds, well-defined internal structures common to turbidite sequences and consistent directional structures, the graywacke and siltstone beds are interpreted as individual sedimentation units, apparently deposited by waning, sediment-laden turbidity currents.

An analysis of cross-bedding suggests that much of the sediment was deposited by southward-flowing currents moving down a regional paleoslope. However, the presence of flute and groove casts which trend eastward and westward implies that some currents probably flowed parallel to the strike of the inferred paleoslope.

X-ray and thin section studies reveal that the graywackes are composed of 4-35 percent quartz, 2-28 percent feldspar, 1-10 percent rock fragments, 15-85 percent matrix material consisting of muscovite, chlorite, and quartz, and 1-17 percent calcite. Mineralogically, the siltstones are fine-grained equivalents of the graywackes.

The correlation of the Thomson Formation with other similar rocks in the Lake Superior region has been debated since Irving in 1883 first suggested a Middle Precambrian age, but the formation's physical isolation has left correlations in doubt. The marked similarity of the mineralogic and sedimentologic aspects of the Thomson Formation with those observed in the Middle Precambrian Rove Formation shows they were derived from a similar source terrane and were deposited by similar mechanisms. This, coupled with paleogeographic data, strongly suggests that they can indeed be correlated with each other.

INTRODUCTION

The Middle Precambrian Thomson Formation, consisting of intercalated metagraywackes, metasiltstones, and slates, occurs in a number of isolated exposures over an area of about 500 square miles in parts of Carlton, Pine, and St. Louis Counties of east-central Minnesota (fig. 1). The formation is best exposed in the valley of the St. Louis River from just west of Duluth, where it is overlain by Keweenawan sandstones (Morey, 1967a), to the vicinity of Cloquet and Carlton, 20 miles west of Duluth. The Thomson Formation also is exposed away from the river valley in the Cloquet-Carlton area as a series of elongate, structurally-controlled, eastward-trending ridges, which rise as much as 40 feet above surrounding areas. Most of our investigation was carried out along the St. Louis River valley and in the Cloquet-Carlton area.

The regional structure has remained obscure because of a lack of distinctive marker beds even though structural data can be determined from individual exposures. However, Wright and others (1970) were able to demonstrate in the Cloquet-Carlton area that the formation is folded into three major synclines and two anticlines, with many minor subsidiary folds. Most folds are open and symmetrical, strike approximately east, and plunge 10°-20° to the east or west.

The Thomson Formation was folded and metamorphosed during the Penokean orogeny, 1.7 b.y. ago (Goldich and others, 1961). In the Cloquet-Carlton area, the metamorphic grade is low (greenschist facies) and sedimentary textures and structures are well preserved. Hall (1901) and Schwartz (1942) have demonstrated that the metamorphic grade increases to the south; phyllite occurs 10 miles south of Carlton, garnet-mica schist appears 25 miles further southward, and granitic rocks emplaced during the Penokean orogeny intrude the formation still farther southwestward (Woyski, 1949; Goldich and others, 1961). Post-folding faults and mafic dikes, both trending north-northeast, are prominent in the study area.

The term "Thomson Slates" was introduced by Winchell (see Spurr, 1894) for this sequence of rocks. He named the rocks after a small village one mile east of Carlton. Subsequently, these rocks have been referred to as the St. Louis Slates, Cloquet Slates, and Carlton Slates. The name Thomson Slates has priority, but Schwartz (1942) suggested the name "Thomson Formation" for the rocks inasmuch as metamorphosed graywacke sandstones and siltstones make up a considerable part of the unit. The latter usage is retained here.

The total thickness of the Thomson Formation probably is great, but cannot be ascertained accurately from present data because of the marked deformation, a lack of continuous exposures, a general absence of recognizable marker beds, and

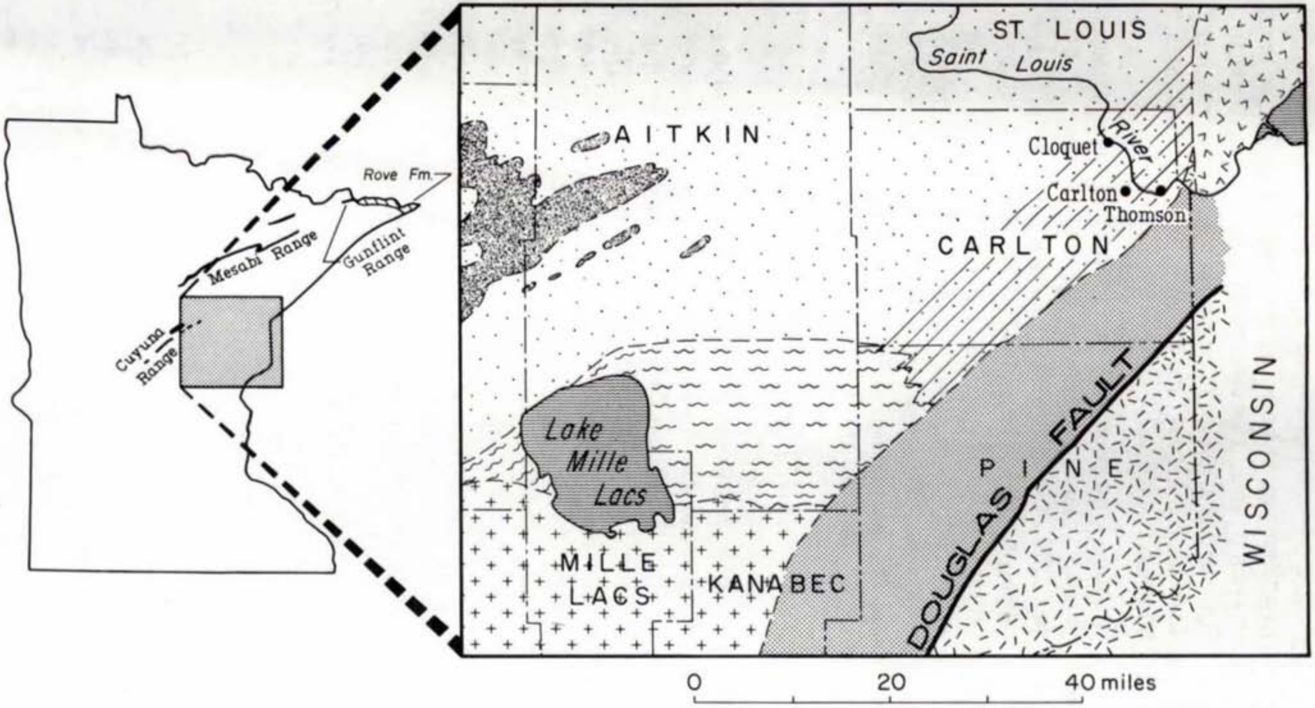

Figure 1 – Generalized geologic map of east-central Minnesota (modified from Goldich and others, 1961). The inferred distribution of the Thomson Formation and correlative rocks is shown by the stippled pattern; diagonal lined pattern outlines the area where bedrock is exposed at the surface.

because neither the top nor the bottom of the formation is exposed. Schwartz (1942, p. 1009) estimated a minimum thickness of more than 20,000 feet for the sequence in the entire outcrop area. However, Wright and others (1970) concluded from the configuration of a 19-foot thick marker member that extends throughout the Cloquet-Carlton area that the total thickness of the exposed rocks is only approximately 3,000 feet.

Correlation of the Thomson Formation with other similar-appearing formations has been conjectural since a Middle Precambrian age first was suggested by Irving (1883, p. 162). Exposures of similar rocks are lacking between the study area and other areas of exposed Middle Precambrian rocks, such as the Mesabi range 60 miles to the north, the Gunflint range 150 miles to the northeast, and the Cuyuna range 70 miles to the west (fig. 1). Therefore, this study was undertaken in part to facilitate a comparison of the Thomson Formation with other formations of Middle Precambrian age in Minnesota and elsewhere in the Lake Superior region.

PETROLOGY

Schwartz (1942, p. 1005) and Wright and others (1970) estimated the amount of graywacke, siltstone, and slate present in exposures in the vicinity of the type locality near the village of Thomson (fig. 1), and in the course of this study two other detailed sections were measured (fig. 2; tbl. 1). In general, the abundance of metagraywacke, metasiltstone, and slate apparently varies without regard to stratigraphic position. For example, one of our measured sections is composed dominantly of metagraywacke and slate, whereas the other is made up dominantly of metasiltstone and slate. Probably the measured sections are well exposed because they contain a high proportion of the more resistant metagraywacke and metasiltstone relative to the slate; the slate weathers more rapidly than either of the coarse-grained rocks and forms surfaces of relatively low relief. We were not able to piece together a definite stratigraphic succession, but the measured sections are representative of the lithologies in the area and are useful in discussing the sedimentologic aspects of the rocks.

Graywacke

Macroscopic character

Gray to greenish gray, very well indurated graywacke (Pettijohn, 1957a) constitutes one-third to one-half of the total thickness of the measured sections (tbl. 1). Most of the graywacke beds are fine- to medium-grained, but some are coarse-grained. Thin beds are fine-grained, whereas thick beds are medium-grained or, less commonly, coarse-grained. Individual beds range in thickness from one inch to 14 feet; 72 percent of the measured beds are less than one foot thick (fig.

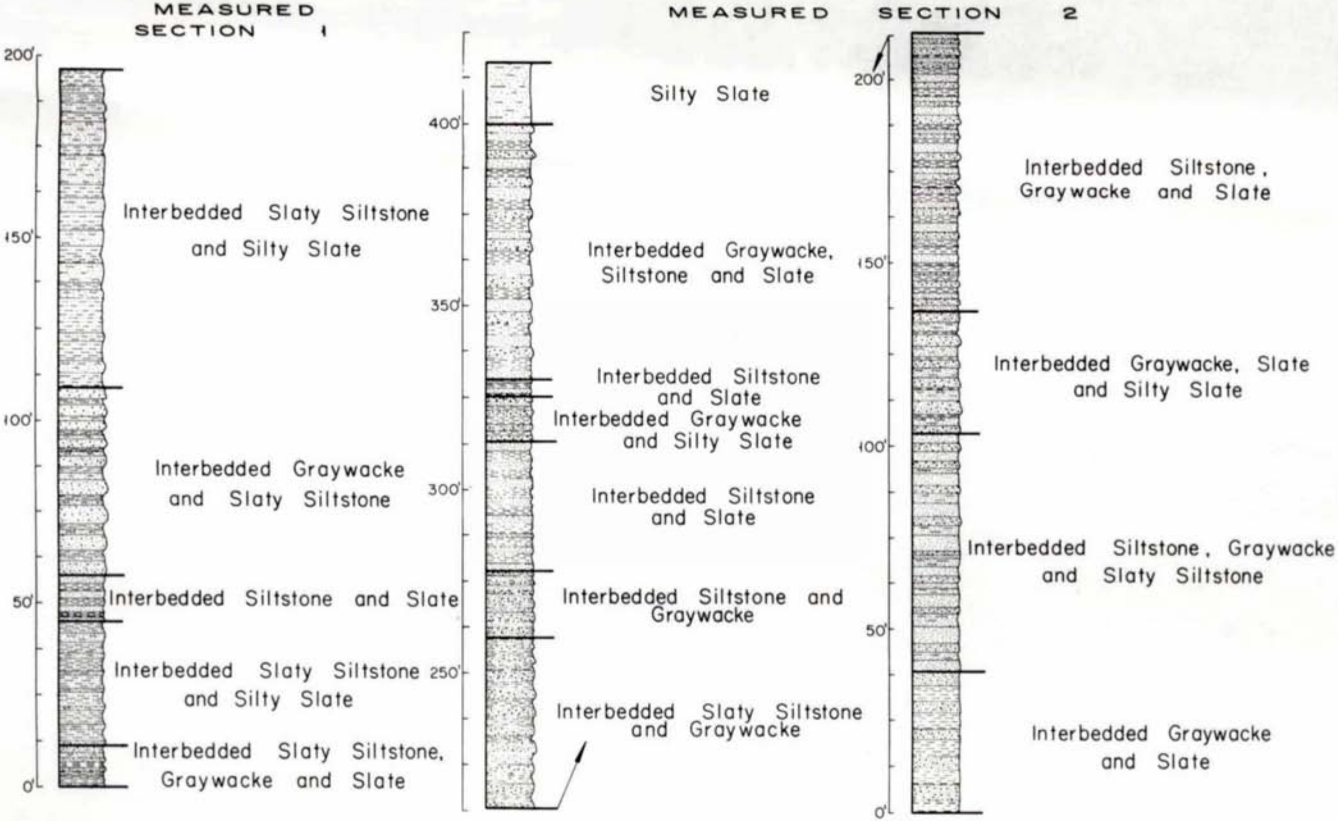

Figure 2 – Measured stratigraphic sections of the Thomson Formation from the type locality near Thomson, Minnesota. Locations of measured sections are summarized in Table 1.

Table 1 – Proportions of rock types in the Thomson Formation

Source	Locality	Thickness of Measured Interval in feet	Rock Type in Percent		
			Graywacke	Siltstone (1)	Slate
Schwartz, 1942	Type section	830	48.5	25.2	26.3
Wright & others, 1970	Type section	500	44	28	28
This paper	SW ¼, SW ¼, Sec. 5, T. 48 N., R. 16 W.	198	34	35	31
This paper	Center, Sec. 8, T. 48 N., R. 16 W.	430	34	43	23

(1) Schwartz (1942) and Wright and others (1970) referred to this material as graywacke-slate; texturally it is a siltstone.

3). Most beds apparently have consistent thicknesses over the lengths of the longest exposures -- a distance of several hundred feet -- and give the impression of having a relatively wide lateral extent (fig. 4). However, the thicknesses of some beds vary locally, and a few markedly lenticular beds were found.

Microscopic character

Twenty samples of graywackes selected at random from the study area were sectioned and studied. Photomicrographs of thin sections of representative graywackes are shown in Figure 5. The major framework constituents (tbl. 2 and fig. 6) are quartz, plagioclase and, in the coarser-grained samples, rock fragments. The matrix -- grains finer than 0.03 mm -- is composed mainly of microcrystalline chlorite, muscovite, and calcite. The size of the matrix particles as well as the shape and size of the framework grains have been modified by recrystallization, and the rocks now are strongly indurated.

An "average" grain size for each sample was estimated by measuring the apparent long dimension of 100 to 200 framework grains. Except for intraformational slate fragments, detrital grains rarely exceed one millimeter in diameter, and most are from 0.1 to 0.5 mm. There is a strong dependence of the constituent percentages (tbl. 2) on the grain size of the sample.

Quartz comprises 15 to 35 percent of the samples studied. The grains are generally angular or subangular, although some were definitely well-rounded prior to cataclasis and metamorphism. Their shapes are commonly modified by the encroachment of matrix minerals. The amount of quartz increases proportionately with increasing grain-size. Most of the grains, and especially the larger ones, have been affected by the tectonism; they are cracked and commonly have strong undulatory extinction. Despite the cataclasis, it was possible to distinguish four pre-deformation types of detrital quartz: (1) *Monocrystalline* grains, composed of a single optical "unit;" (2) *polycrystalline* grains, consisting of two or more units of differing optical orientation; (3) *metamorphic* grains, apparently composite grains which were deformed in the source areas; and (4) rare *volcanic* grains, which show pyramidal shapes and embayments.

Feldspar is the second most abundant framework constituent in the graywackes (tbl. 2). In the same way as quartz, but to a lesser extent, the percentage of feldspar increases directly with increasing grain-size. The fine-grained rocks have a quartz/feldspar ratio of approximately one, whereas the coarse-grained rocks have ratios of approximately two. Plagioclase is by far the most abundant feldspar, but orthoclase and microcline are sparingly present in more than half the samples. The presence of potassium feldspar in the samples was confirmed by staining slabs with sodium cobaltinitrite. The plagioclase generally occurs as angular, tabular grains, although some of the larger grains are anhedral and slightly rounded. The plagioclase is typically sodic; albite is dominant, but

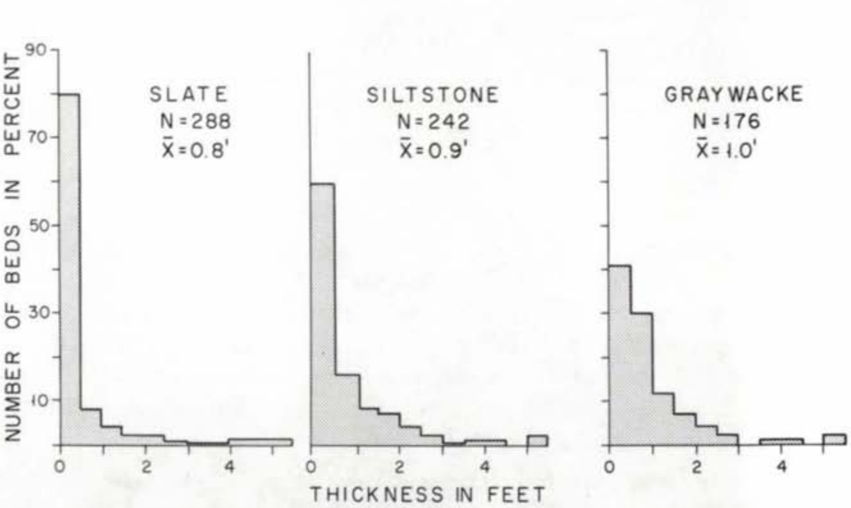

Figure 3 – Histograms summarizing bedding thickness by lithology in the Thomson Formation.

Figure 4 – Typical example of Thomson outcrop area in the valley of the St. Louis River. Note that the individual beds show a relatively consistent thickness over the entire outcrop area.

Table 2 – Mineralogic composition of selected Thomson Formation samples as estimated from 500 point counts per thin section.

Sample Number	Framework Constituents							Matrix Constituents				Values Recalculated to 100%						Average Grain Size in mm.
	Qtz.	Plag.	K-spar	Qtzite. & Chert	Gst. & Basalt	Granite	*Slate	Chlo & Musc.	Qtz. & Feld.	Calcite	Access	Qtz.	Feld.	Rock Frag.	Qtz.	Feld.	Matrix	
1	5	2	-	-	-	-	-	74	-	18	2	71	29	-	6	3	91	.02
2	14	10	2	Tr	Tr	-	-	65	3	2	Tr	48	48	4	13	14	73	.16
3	4	7	Tr	-	-	-	-	79	6	3	Tr	62	42	-	10	8	82	.05
4	9	1	-	-	-	-	-	75	-	15	-	-	-	-	-	-	-	.02
5	15	11	4	Tr	-	-	-	64	3	1	-	54	45	1	19	16	65	.09
6	29	14	4	2	-	7	4	35	2	Tr	1	55	29	16	40	19	41	.65
7	32	5	Tr	2	Tr	3	2	36	1	Tr	1	59	28	13	39	20	41	.58
8	10	12	4	-	-	-	-	67	6	13	-	69	31	-	11	6	67	.04
9	13	14	2	-	-	-	-	48	10	12	Tr	58	42	-	26	19	55	.08
10	14	13	3	-	-	-	-	63	4	1	Tr	53	47	-	18	17	65	.15
11	28	20	5	2	Tr	Tr	-	35	5	3	1	53	42	5	34	27	39	.14
12	40	26	5	2	-	Tr	-	14	6	3	3	57	39	4	51	34	15	.09
13	22	13	4	-	Tr	-	-	48	2	9	2	58	42	-	27	20	53	.07
14	13	20	3	Tr	-	Tr	-	55	5	Tr	Tr	42	53	5	19	24	57	.21
15	18	12	5	Tr	-	Tr	-	51	5	2	1	57	42	1	25	19	56	.08
16	15	10	4	Tr	-	Tr	Tr	53	12	3	Tr	52	48	-	25	22	43	.14
17	12	15	5	-	-	-	-	47	9	9	2	48	51	1	21	23	56	.08
18	19	14	6	Tr	Tr	Tr	-	52	4	2	Tr	50	46	4	24	22	54	.23
19	23	18	5	1	Tr	Tr	Tr	45	3	2	Tr	51	43	6	29	24	47	.38
20	12	12	3	Tr	-	-	-	58	8	5	1	86	13	1	21	16	63	.08
21	44	17	4	3	Tr	1	2	18	6	2	1	63	30	7	47	25	28	.57
22	35	16	5	1	-	2	-	33	Tr	2	Tr	58	34	8	40	24	36	.53
M-3509	39	20	8	2	2	Tr	-	21	3	Tr	Tr	56	35	9	48	30	22	.66
M-55010	16	13	4	Tr	-	-	-	47	14	3	Tr	62	36	2	31	18	51	.14
M-55070	10	16	4	-	-	-	1	46	14	7	Tr	55	45	-	27	22	51	.18

* Originally mudstone clasts of intraformational origin

Tr equals less than one percent

both oligoclase and andesine also are present. Orthoclase and microcline occur as subangular or subrounded grains. Perthitic lamellae in potassium feldspar and inclusions of quartz in both the potassium feldspar and plagioclase are common. Almost all the feldspar grains are dusty and highly sericitized and are replaced along their boundaries by muscovite and/or calcite.

Several types of rock fragments are present in small amounts, and increase in number as grain-size increases (tbl. 2). They are chiefly chert, quartzite, and "granitic" rocks, and include minor amounts of schist, greenstone, and basalt. There is almost a complete gradation between grains classified as quartz and grains classified as chert or quartzite rock fragments. Rock fragments classified as "granitic" consist of both monocrystalline and polycrystalline quartz and sodic plagioclase, or more rarely, quartz and potassium feldspar. It appears that much of the quartz and plagioclase that occurs as individual detrital grains was derived from the same source as the "granitic" rock fragments. The schist fragments are composed of elongate, angular quartz grains joined by straight boundaries, and subordinate amounts of elongate chlorite or muscovite. The basalt and greenstone fragments are small and well-rounded, and consist of a dark green chloritic and/or epidotic groundmass with small lath-like crystals of highly altered feldspar. Rounded grains composed of microcrystalline aggregates of chlorite with interstitial magnetite also are present.

Angular fragments of slate and siltstone, similar to the interbedded slates and siltstones and probably derived from them, also are present, especially in the coarse-grained beds. Commonly these slate and siltstone fragments have been partially recrystallized and tend to merge into the matrix of the graywacke, but they can be recognized readily in thin section because they are nearly opaque as a result of the presence of finely divided pyrite and carbonaceous material.

Matrix constituents-- finer than 0.03 mm in diameter-- make up from 15 to 75 percent of the total volume of the samples studied. The matrix is a microcrystalline aggregate of recrystallized chlorite, muscovite, quartz, plagioclase, and authigenic calcite with trace amounts of pyrite and accessory minerals. Commonly, it is not possible to distinguish between fine-grained feldspar and quartz, and therefore they were counted together in the matrix analysis (tbl. 2). The layered silicates have several modes of occurrence, each reflecting different modes of origin. The most common are lacy patches of pale green or colorless chlorite and intergrown muscovite. Where the individual minerals can be resolved, chlorite is generally many times more abundant than muscovite. Both chlorite and muscovite replace the edges of framework grains, and apparently were derived through recrystallization of an original clayey matrix. The matrix also may have been derived in part from the diagenetic alteration of unstable rock and mineral fragments, as suggested by Cummins (1962) for some graywackes. Some of the smaller feldspar grains are almost completely altered to muscovite, and their grain

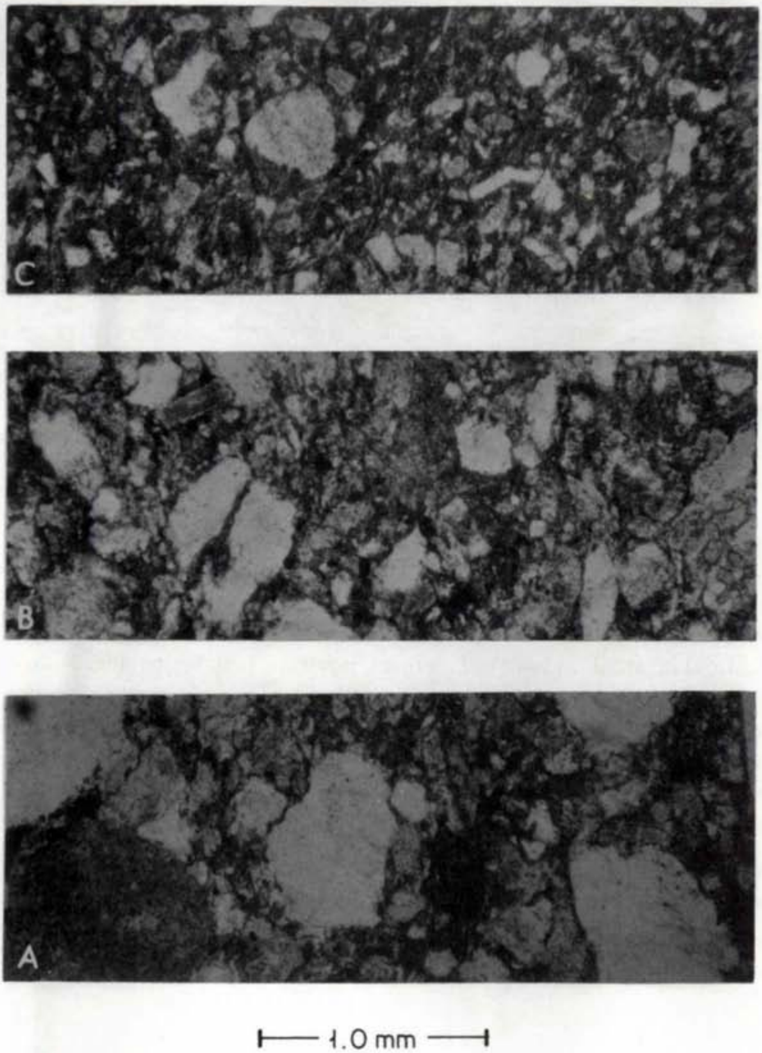

Figure 5 – Photomicrographs of representative graywackes from the Thomson Formation. Note the typical graywacke texture of framework grains in a matrix of finer-grained material.

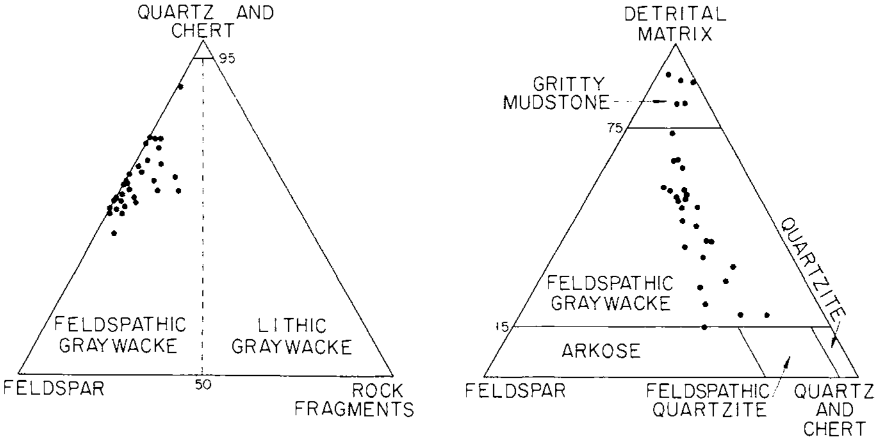

Figure 6 – Summary of the mineralogic composition of the Thomson Formation (Triangles after Pettijohn, 1957a).

boundaries are nearly obliterated. Large individual grains of either muscovite or chlorite also are present and either cut across framework grains or occur as interstitial material. In both occurrences, however, they are parallel to an incipient cleavage direction that lies at an angle to the bedding, suggesting a metamorphic origin. Authigenic calcite is present in all the samples, and occurs as micrograins or as larger aggregates of small subhedral grains which preferentially replace the detrital matrix.

Accessory minerals constitute less than three percent of the samples studied. Pyrite is most common, and occurs as euhedral grains as much as 0.05 mm in diameter; these grains are commonly rimmed or totally replaced by hematite. Other accessory minerals identified in thin sections include apatite, sphene, zoisite, zircon, and garnet.

Siltstone

Macroscopic character

Siltstone, a fine-grained equivalent of the graywacke, comprises 25 to 43 percent of the measured sections (tbl. 1). It differs from typical slate in containing more quartz, in being more massive and lighter in color, and in having a less well-developed cleavage. In general, most siltstone beds are neither as thick nor as massive as the graywacke beds. Individual beds range in thickness from less than one inch to more than six feet, and 83 percent are less than one foot thick (fig. 3).

Microscopic character

The siltstones are similar in composition to the graywackes, but contain no rock fragments and less feldspar. The silt-sized grains are nearly always angular, and are cemented by muscovite and chlorite and, in part, by authigenic calcite (fig. 7). Most of the siltstones are laminated, and have layers rich in quartz and plagioclase that alternate with layers rich in micas. The mica flakes and elongate quartz and feldspar grains have a strong orientation parallel to the internal horizontal or cross-lamination; this is modified through the development of some layered silicates parallel to a poorly developed tectonic cleavage.

Slates

Macroscopic character

Dark greenish-gray or black slate comprises 23 to 31 percent of the measured sections (tbl. 1). It is the dominant lithology in some parts of the formation, and thicknesses of as much as 500 feet have been reported (Schwartz, 1942). Individual slate "beds" (comprised of laminations) range in thickness from less than one inch to more than 60 feet. The slate is readily distinguishable from siltstone and graywacke in outcrops because it has a darker color and a well-developed cleavage.

Microscopic character

The slate samples that were studied contain as much as 20 percent fine silt-sized quartz and feldspar in a matrix of fine muscovite, chlorite, quartz, opaque organic matter, pyrite, and authigenic calcite. In the thicker-bedded slate units the silt-sized detritus generally occurs as randomly distributed grains, whereas in laminated beds it is concentrated in laminae less than a millimeter thick. The micaceous minerals have a preferred orientation parallel to bedding or, more commonly, parallel to the well-developed cleavage.

Concretions

Carbonate concretions are abundant and characterize the entire formation (Schwartz, 1942; Weiblen, 1964), occurring in approximately 20 percent of the beds in the measured sections (fig. 8). Many concretions are in zones parallel to bedding, and thus are a valuable guide to the attitude of the bedding, but others are randomly scattered throughout thick beds. The concretions range in size from "knots" less than one inch in diameter to irregular masses three feet long. Concretions in individual zones commonly are similar in size, but radically different sizes have been observed in zones only a few feet apart. Some zones continue along the entire length of outcrops, whereas others continue for less than 10 feet.

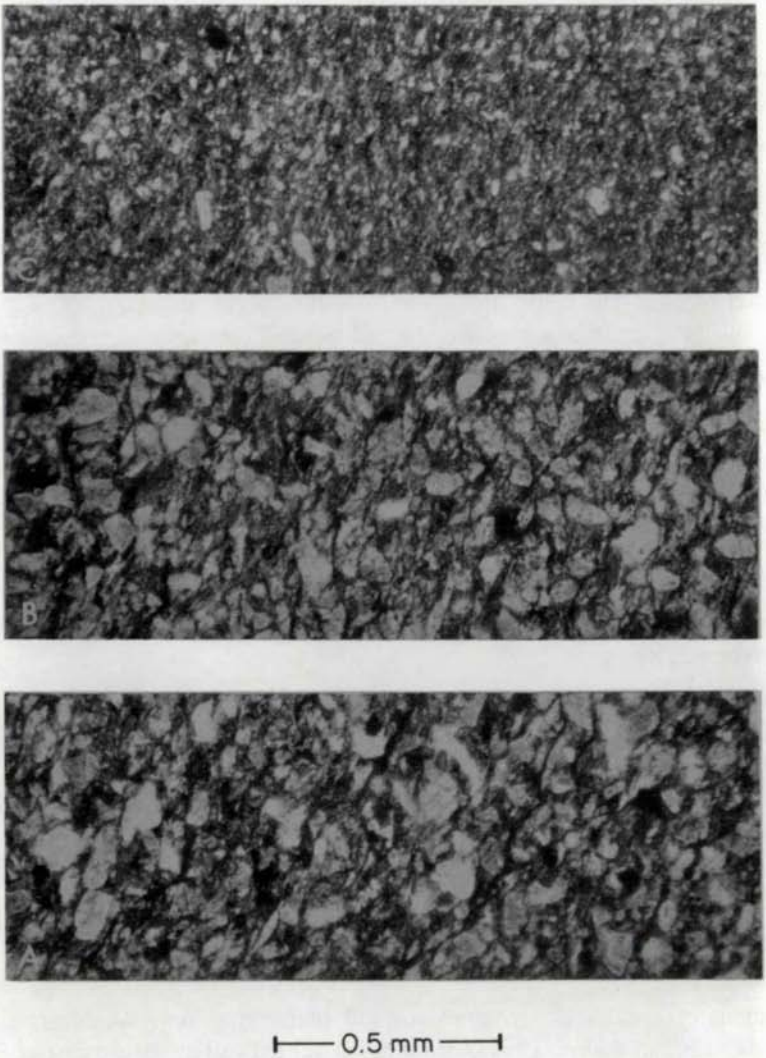

Figure 7 – Photomicrographs of representative siltstones from the Thomson Formation. Note the textural similarity to the sandstones in Figure 5 and the crudely developed foliation.

Figure 8 – Internal bedding features observed in the Thomson Formation. Note wavy cross-bedding sets, laminations, and "ball structures." The cavity near hammer formed by the weathering of a concretion.

Weiblen (1964) recognized two types of concretions: (1) those in graywacke beds that contain varying amounts of carbonate and have a bedding generally continuous with that of the enclosing rock; and (2) those in siltstone and slate that consist of two structurally distinct parts -- an inner core of slaty material having bedding that may be discordant with the enclosing rock, and an outer rim consisting of cone-in-cone structures composed of recrystallized carbonate and quartz.

Probably the concretions are diagenetic, and formed after deposition of the enclosing sediments. However, their present ellipsoidal shapes reflect deformation during tectonism. Concretions in graywacke have undergone little rotation, whereas some of those in the fine-grained rocks have been rotated and flattened parallel to the direction of cleavage. Extensive recrystallization has occurred in pressure shadows resulting from rotation. Although the concretions are useful in detailing the deformational history of the rocks, they are of little value in correlating specific beds from exposure to exposure.

SEDIMENTARY STRUCTURES

Several sedimentary structures, in addition to bedding, are well-preserved in the Thomson Formation.

Cross-bedding

Cross-bedding is common in the siltstone beds and in the uppermost parts of graywacke beds (fig. 8). It occurs as small-scale sets generally less than four inches thick. The sets are generally trough-like and wavy, but there is generally a preferred direction of dip within each set.

Graded Bedding and Associated Internal Bedding Features

Of 156 graywacke beds analyzed in the two measured sections, 88 percent contain visible grading in the outcrop. In addition, 27 percent of 177 siltstone beds studied also are graded, and a microscopic study of them might well indicate additional graded beds. In both the sandstones and the siltstones, a clayey matrix--now recrystallized-- is disseminated throughout, indicating deposition by a waning suspension current such as a turbidity current.

The graded graywackes contain internal bedding features considered indicative of "turbidite" deposition *(e.g.,* Kuenen, 1964). Bouma (1962) noted a definite order in these features and defined the "ideal" bed. Such features within the Thomson graywacke beds are compared with his "ideal" bed in Figure 9.

Laminated Bedding

Laminations ranging in thickness from one-eighth of an inch to one inch are common and well preserved in the siltstones, as well as in the upper parts of graywacke beds, as illustrated in Figure 10. They also are present in the slate intervals, but are considerably obscured by cleavage.

Sole Marks

Sole marks are obscure because cleavage in the interbedded slates causes irregular surfaces at many graywacke-slate interfaces. The thicker and more massive graywacke beds, however, commonly have better preserved soles; most sole marks were observed on beds 12 to 18 inches thick and two were observed on beds 48 inches thick.

Flute casts (Crowell, 1955) were noted on 17 graywacke soles, groove casts (Kuenen, 1957) on 26 graywacke soles, and finer "striation marks" on two soles. Most flute casts were only a few inches long and had low relief.

"Pseudo-sole marks," which generally resemble groove casts but in some cases resemble flute casts, apparently result from the weathering and abrasion--especially during flood stage of the St. Louis River-- of slaty cleavage-bedding plane intersections on exposed soles in the river channels (fig. 11). Many such

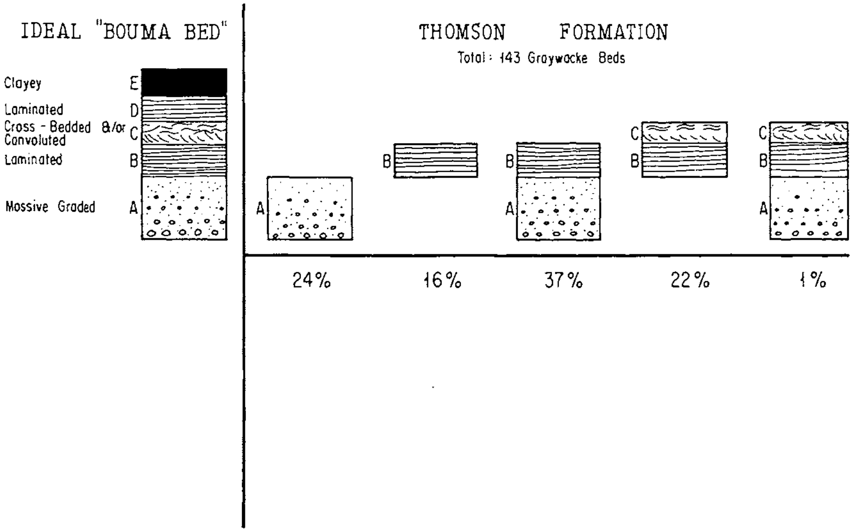

Figure 9 – Abundance and types of internal bedding features observed in graywacke beds of the Thomson Formation. The ideal "Bouma Bed" is after Bouma (1962).

"pseudo-sole marks" observable in the area are parallel to cleavage and can thereby be distinguished from genuine structures of sedimentary origin which trend at angles of 10°-40° to the cleavage.

Miscellaneous Structures

"Loaded soles" and flame structures are common in graywacke beds, with the underlying slate beds penetrating the soles of the overlying graywacke beds (fig. 10). Evidently irregularities on the bottoms of unconsolidated sandstone beds were deformed somewhat by the weight of the beds themselves.

"Ball structures" were noted near or at the bases of four graywacke beds and eight siltstone beds (fig. 8). They appear to have resulted from loading, perhaps associated also with post-depositional movement of unconsolidated beds.

Post-depositional slumping and thickening was observed within a 30-foot long segment of one graywacke bed which elsewhere is 14 inches thick. Slate blocks as much as three feet long are present near the middle of the bed, and are cut by highly contorted graywacke sandstone dikes that are from half an inch to six inches thick. The bed is not disrupted east and west of this zone. Small sandstone dikes were noted in other beds as well.

Figure 10 – Typical upper laminated part of a graded graywacke bed and flame structures in the basal part of the overlying graded graywacke bed. Note the contrast in grain-size of the two beds.

Large slate chips are common, especially in the upper parts of graywacke beds, and apparently were torn off the muddy basin floor by the depositing currents and then incorporated into the graywacke beds. Other evidence of penecontemporaneous erosion also was observed.

Definite ripple marks were not observed, but pseudo-ripple marks are common. Evidently they resulted from abrasion and weathering of cleavage surfaces, and unless scrutinized carefully can be mistaken for true sedimentary structures.

PALEOCURRENT ANALYSIS

The orientations of cross-bedding and sole marks were measured wherever observed to obtain a statistical representation of the paleocurrent pattern of the formation. Only one observation per bed was made in order to give each reading equal weight.

Figure 11 – "Pseudo-sole marks" resembling flute casts. Note the parallelism of the marks and the cleavage in the underlying slate bed, indicating a related origin.

The cross-bedding measurements were corrected for tectonic folding about horizontal axes by means of a computer program, whereas measurements of sole marks were rotated in the field with a leveling device. No corrections were made for plunge because the plunges are generally gentle, with a maximum angle of 20 degrees. McBride (1962, p. 77) noted that in folds plunging from five to 20 degrees, most azimuthal errors in cross-bedding directions "...introduced by neglecting the plunge are probably less than 10 degrees, although they may reach as high as 30 degrees..."

The dip azimuth directions of cross-bedding show a consistent direction of current flow from north to south (fig. 12a). The vector mean dip direction was calculated and found to be 172 degrees, using the trigonometric function described by Potter and Pettijohn (1963, p. 264). To ascertain the scatter of the dip azimuths, the magnitude of the mean vector in percent also was calculated (Potter and Pettijohn, 1963, p. 264) and determined to be 73 percent. (This value will be zero percent where the distribution is completely random and 100 percent where all vectors have identical azimuths.)

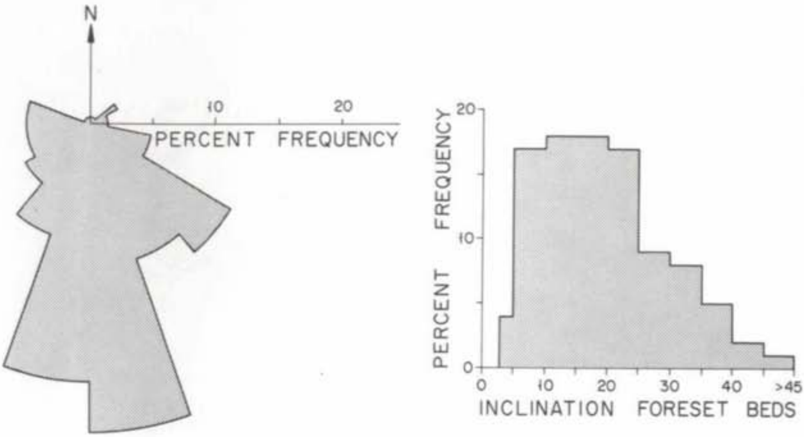

Figure 12 – Rose diagram and histogram summarizing orientation and inclination of 201 cross-bedded units in the Thomson Formation.

The corrected inclinations of the cross-beds range from four to 50 degrees and average 23 degrees (fig. 12b). Some inclinations are too low and others too high for the angle of repose of sediments in water; both post-depositional soft-sediment slumping and tectonic deformation may be responsible for these anomalous values.

The directions of current flow indicated by the 17 flute casts are scattered (fig. 13). If considered by themselves, they are bimodal in distribution and indicate current flows in both westerly and southeasterly directions. This bimodality however, may be the result of a sparsity of data, inasmuch as the general spread of the observations is not inconsistent with the distribution pattern exhibited by the cross-bedding.

Most of the 26 measured grooves and the two "striated soles" trend east-west-- an average of 98 or 278 degrees-- and cluster within 30 degrees of their mean direction (fig. 13). The marked similarity in cleavage trend-- plus or minus 10 degrees of an 85 to 265 degree value according to Wright and others (1970) -- and sole mark trend suggests that we may have mistaken some pseudo-groove casts for true sole marks. However, the good agreement between the measured flute casts and the "least suspect" groove casts suggests that they are indeed sedimentational and not tectonic structures.

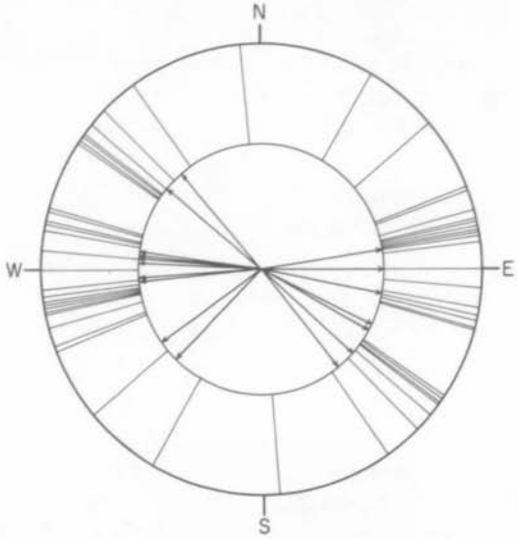

Figure 13 –Orientation of 17 flute casts (inner circles) and 26 groove casts (outer circle) in the Thomson Formation.

Eight graywacke beds were observed that contained both marks on the soles and cross-bedding in the upper finer-grained parts of the beds. In each bed, the two types of paleocurrent indicators are oriented at high angles to one another (fig. 14).

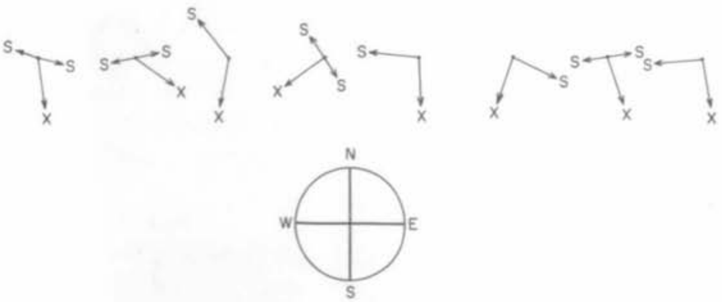

Figure 14 –Angular discrepancies between orientation of cross-bedding (x) and orientation of sole marks (s) on eight graywacke beds of the Thomson Formation.

PROVENANCE AND SEDIMENTATION

Several sedimentation models could be formulated for the Thomson Formation, as was done, for example, by deVries Klein (1966) for Mississippian units in the Ouachitas. However, because the area of study is small and stratigraphic relationships with other correlative units in the region are not definite, it seems more appropriate at this time to concentrate upon the simplest model which can be constructed from our data.

The excellent preservation of the laminated black muds -- now slates -- indicates that they accumulated slowly in quiet water below wave base, possibly in deep water, and were not subsequently reworked. Deposition of this material was periodically interrupted by the deposition of the silt and sand beds by currents entering the area.

The prevalent grading of the graywackes and the siltstones strongly suggests that turbidity currents were the active mechanisms of transport and deposition. The other sedimentary structures present, and the lack of large-scale cross-bedding which would be indicative of "normal" currents in shallow water, are compatible with this suggestion. The fact that over two-thirds of the graywacke beds contain a massive graded part (fig. 9) shows that strong turbidity currents repeatedly reached this part of the basin. The remaining one-third of the graywacke beds are composed of only laminated and/or small-scale cross-bedded parts (fig. 9), indicating that they represent the "tails," "noses," or "edges" of the deposits of individual turbidity currents.

Several lines of evidence suggest that the graywacke sandstones and the siltstones had similar sources and origins: (1) In general, both rock types contain the same mineral components but different relative amounts because of differences in grain size between the two types; (2) many beds were difficult to classify as graywacke sandstones versus siltstones because they are on the sand-silt textural boundary; (3) grading is common in the graywackes and fairly common in the siltstones; (4) similarities of internal bedding structures such as laminations, cross-laminations, and convolutions in the two rock types suggest that individual siltstone beds like the fine-grained graywackes, are simply finer-grained lateral equivalents of graywackes, constituting the "tails," "noses," or "edges" of thicker graywacke lenses; (5) cross-bedding dip azimuths in the upper parts of the eight graywacke beds having sole marks (fig. 13) agree with those of the 201 cross-beds that were measured in both siltstones and graywackes.

If we assume that the sole marks used as paleocurrent indicators are indeed sedimentological in origin, our model must then explain the difference in current trends as given by the cross-bedding and by the sole marks, and the reason for the same difference in paleocurrent indicators within the eight graywacke beds.

Studies in areas of younger rocks indicate that small-scale cross-bedding in the upper parts of graded beds commonly gives approximately the same paleocurrent directions as sole marks of the same beds; examples have been described by Johnson (1968) in the Mississippian Stanley Group of the Ouachitas and by Ojakangas (1968) in the Cretaceous of California. In many examples, however, individual turbidite sedimentation units are not always the result of a single uni-directional density current into an otherwise stagnant environment (cf. Dott, 1963, p. 127). Inasmuch as sole marks probably result from erosion at the beginning of a spasmodic incursion of a high-energy current, and cross-bedding may result from deposition toward the end of that event, examples of angular discrepancies between sole marks and cross-strata are not uncommon in turbidite deposition (Kelling, 1964; Jipa, 1968). Thus the relationship of cross-bedding trending at nearly right angles to the sole marks is not unique to the Thomson Formation.

Whether the same turbidity currents were responsible for the scouring and grooving which preceded deposition, as well as for the deposition itself, or whether the sole marks were carved by other "normal" bottom currents, is not really critical to our interpretation. Of importance here, however, is the difficulty in determining which of the two trends resulted from currents moving down a paleoslope. Neither structure gives definitive information on a paleoslope trend, and sedimentary structures such as slump fold axes which might be indicative of the paleoslope orientation were not observed. Fortunately, Morey's (1967b) study of the Rove Formation (fig. 15) and the regional paleogeographical picture outlined below provide us with indirect evidence which suggests that the cross-bedding rather than the sole marks was formed by currents moving down a paleoslope.

Paleogeographic, stratigraphic, and mineralogic considerations, some of which are presented below, indicate that the Thomson Formation, the Virginia Formation, and the Rove Formation probably are correlative, and probably represent deposition in different parts of the same Middle Precambrian sedimentary basin (fig. 15). The Virginia and Rove Formations are located just south of exposed older Lower Precambrian igneous and metamorphic rocks that probably had a pre-Middle Precambrian northeastward-striking regional tectonic trend like that observed today. The north shore of this Middle Precambrian basin apparently paralleled this tectonic trend, and was north of the present Virginia outcrop belt; however, its exact location is unknown because of subsequent erosion of the Middle Precambrian rocks. Therefore the Thomson Formation was deposited at least 60 miles farther from the shoreline than was the Virginia Formation, if the two units are indeed closely correlative.

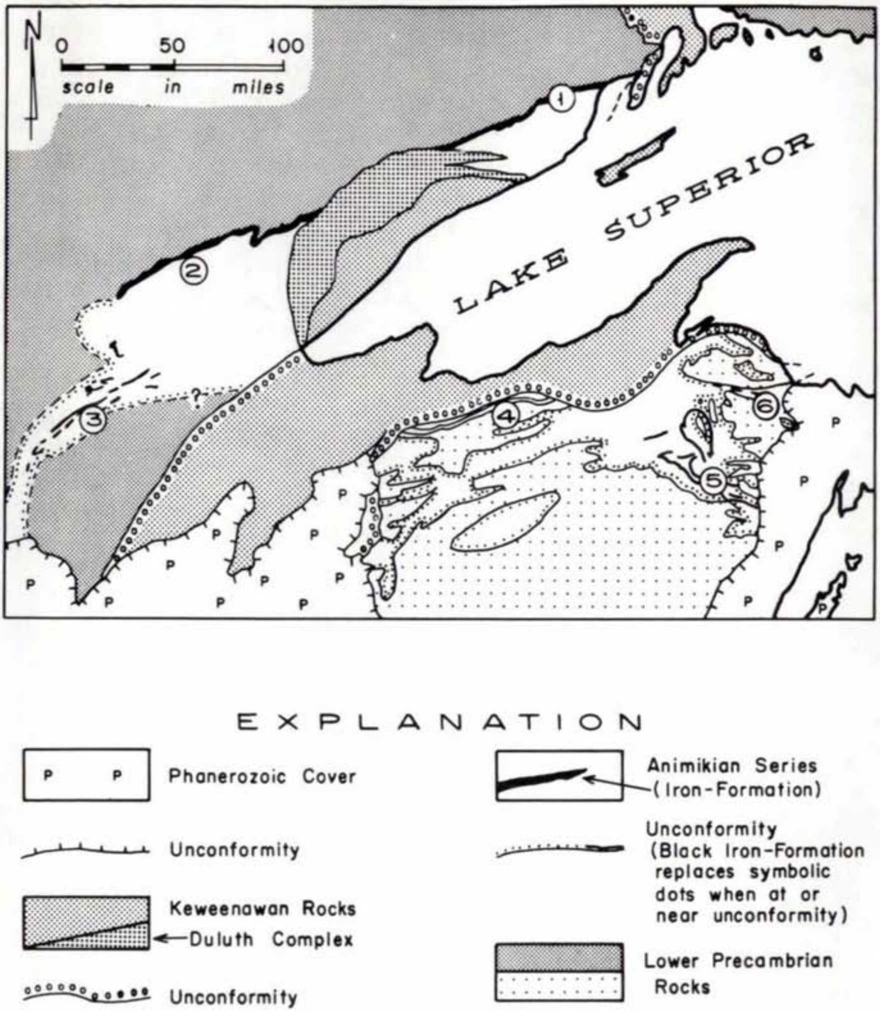

Figure 15 – Regional geologic map of the Lake Superior region (after Trendall, 1968) showing location of correlative (?) Middle Precambrian formations discussed in text.

In the Rove Formation, both small-scale cross-bedding and sole marks were made by south-southeastward-flowing currents which probably were moving nearly perpendicular to the inferred northeast-trending shoreline (Morey, 1967b; 1969). However, Morey (1967b) noted ripple marks on the tops of some beds that also contain sole marks. The ripples were inferred to be formed by currents flowing toward the southwest, apparently sub-parallel to the shoreline, the basin axis, and the strike of the paleoslope. Such ripples were not noted in the Thomson Formation, perhaps because the Thomson may have been deposited further from shore than was the Rove. If the Thomson Formation in the Carlton-Cloquet area is representative of the entire formation, and if the Thomson Formation is closely related in age and origin to the Rove Formation, it can be tentatively inferred that the cross-bedding in the Thomson Formation was probably also caused by currents flowing down the paleoslope, perpendicular to the shoreline, as was the case for the Rove Formation. If so, then the sole marks in the Thomson must have been eroded by currents that were moving parallel to the shoreline, the basin axis, and the strike of the paleoslope, and which may have been either "normal" bottom currents or turbidity currents that were diverted from a southerly direction to easterly and westerly directions. This diversion could have resulted from submarine topography or simply from depositional irregularities on the basin floor. Fanning out of the currents over a gently sloping paleoslope axial part of the basin could also explain the spread in the azimuths of the sole marks examined.

The paleocurrent indicators suggest a northerly source for the detritus, and the area north of the Middle Precambrian outcrop belt contains a variety of Lower Precambrian rocks of suitable composition and age to have supplied all the sediment. The detrital minerals of the Thomson Formation cannot be attributed definitely to certain source rocks because detailed mineralogic studies of the possible source rocks have not yet been done. However, some general statements can be made. Most of the sand grains are plagioclase and quartz, apparently derived from a plutonic terrane. The dominance of plagioclase over potassium feldspar strongly implies rocks of a granodioritic rather than a granitic composition. The Giants Range batholith which lies just north of the Mesabi range, was described by Allison (1925) as being dominantly granite and quartz monzonite, but recent work by Green and others (1966), Hanson (1964), and Griffin and Morey (1969) indicates that granodiorites are dominant in the eastern part of the batholith. A review of 22 chemical analyses (Ruotsala and Tufford, 1965) shows that the Lower Precambrian plutonic rocks have a K_2O/Na_2O ratio of 0.73, a value considered indicative of granodiorite (Daly, 1933), and available modal analyses show that these rocks generally contain sodic plagioclase in excess of potassium feldspar. Furthermore, the volcanic and sedimentary rocks of the

Lower Precambrian "Ely Greenstone" and "Knife Lake" units contain much plagioclase and very little potassium feldspar.

Chert, quartzite, schist, greenstone, and basalt, which occur in minor amounts in the Thomson Formation, also are common rock types in the Lower Precambrian terrane of northeastern Minnesota.

BROADER STRATIGRAPHIC RELATIONSHIPS

Apparently the Thomson, Rove, and Virginia Formations were deposited in the northern (miogeosynclinal?) part of an elongate southeastward-trending basin that extended from Minnesota into Wisconsin and Michigan (Goldich and others, 1961, p. 6). The configuration of the basin probably was controlled by a pre-existing northeastward-trending regional structure (Van Hise and Leith, 1911, p. 623) and resultant topography. As previously stated, the present Middle Precambrian outcrop belt in northern Minnesota coincides with the exposed southern edge of the Lower Precambrian complex, and the north shore of the Middle Precambrian "sea" apparently was about parallel to this feature. White (1954, p. 43) suggested that the western shoreline was located somewhat west of the present western limits of the Middle Precambrian exposures on the Cuyuna Range. The basin extended to the east beyond the Thunder Bay district in Ontario (Goodwin, 1956). In Wisconsin, the stratigraphic sequence of Middle Precambrian rocks is similar to that in Minnesota (Aldrich, 1929), and in northern Michigan a eugeosynclinal (?) accumulation of graywackes, slates, and volcanics is now exposed (James, 1958). The basin thus appears to have been at least 250 miles long and 150 miles wide, and perhaps open to the sea along its southern margin (fig. 15).

Little is known about the sedimentologic aspects of these Middle Precambrian rocks; Morey's (1967b; 1969) study of the Rove Formation and this study of the Thomson Formation are the only relatively thorough studies to date. The Virginia Formation is poorly exposed and has not been studied in detail; however, Pfleider and others (1968) have pointed out that the stratigraphic succession in the Virginia Formation is very similar to that described from the Rove Formation.

The Middle Precambrian Rabbit Lake Formation of the Cuyuna district, tentatively correlated with the Thomson, Rove, and Virginia Formations, was described by Schmidt (1963) as a "deep-water" argillite, but little else is known. In Wisconsin, Nilsen (1965) described several quartzite units intercalated within the Michigamme Slate, which is considered to be equivalent -- at least in part-- to the Rove-Virginia-Rabbit Lake Formations in Minnesota, but little is known about the Michigamme Slate itself. Nilsen (1965, p. 815) reported that "...thin sections of typical graywackes of the Michigamme Slate invariably indicate a quartz-rich composition..."

To summarize our knowledge of these Middle Precambrian formations, including the Thomson, the sedimentary model concept (Pryor, 1960; Potter and Pettijohn, 1963) can be used (tbl. 3). The arrangement of the sedimentary fill, the sedimentary structures, and the paleocurrent patterns are very similar in the Thomson and Rove Formations. It is also noteworthy that the Thomson Formation contains the same mineral components in about the same proportions as the Rove Formation (fig. 16). These results are consistent with the paleocurrent pattern of Middle Precambrian quartzites in Michigan (Nilsen, 1965, p. 816, fig. 9), and imply, as Pettijohn (1957b) has pointed out, that a terrane to the north and northwest of the Lake Superior area was the primary source of the Middle Precambrian sands in the Lake Superior region.

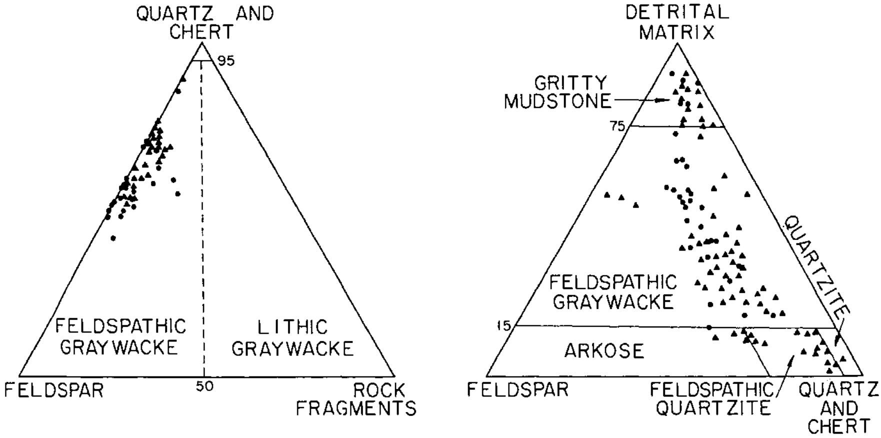

Figure 16 – Summary of the mineralogic composition of the Thomson Formation (dots) and the Rove Formation (triangles). (Triangles after Pettijohn, 1957a).

Table 3 – Sedimentary models for Thomson Formation and other formations of Middle Precambrian Age.

References Attribute	Thomson Formation (this paper)	Rove Formation (Morey, 1969)	Virginia Formation (Pfleider & others, 1968; White, 1954)	Rabbit Lake Formation (Schmidt, 1963)	Michigamme Slate (James, 1958; Nilsen, 1965)
Basin Geometry	Basin elongated east-west parallel with tectonic strike; regional paleoslope dips toward south; loci of maximum accumulation unknown.	Basin elongated east-west parallel with tectonic strike; paleoslope dips toward the south; loci of maximum accumulation probably to the south.	Basin elongated east-west parallel with tectonic strike; paleoslope probably dips toward the south; loci of maximum accumulation probably to the south.	Basin probably elongated east-west parallel with tectonic strike; shoreline north-south with paleoslope dipping to the east; loci of maximum accumulation probably to the east.	Basin elongated east-west parallel with tectonic strike; paleoslope unknown; loci of maximum accumulation unknown.
Directional Structures	Chiefly small-scale cross-stratification; the dip azimuth (mean 176°) indicates the paleoslope and is normal to the depositional strike; flute and groove casts indicate southward-trending currents but have a wide scatter.	Small-scale cross-stratification, flute and groove casts; all (mean 170°) indicate paleoslope and are normal to depositional strike; ripple marks indicate southward-flowing longshore currents.	Cross-stratification, but direction unknown.	Unknown.	Mostly unknown, cross-stratification indicates current flow to the southeast.
Lithic Fill	Interbedded, graded feldspathic graywacke, siltstone and slate, abundant carbonate concretions.	Interbedded graded feldspathic graywacke siltstone and argillite, abundant carbonate concretions, chert lenses, especially near base; siltstone and graywacke more abundant upward in section, minor quartzite in upper 700 feet.	Interbedded graded graywacke, siltstone and slate, abundant carbonate concretions & chert lenses near base, siltstone and graywacke more abundant upward in section.	Interbedded graywacke, siltstone and slate, slate apparently most abundant; lava flows(?) locally near base; interbedded lenses of iron-formation.	Interbedded graded quartzose and feldspathic graywacke and slate; scattered concretions and local quartzite units.
Thickness	At least 3,000 feet and perhaps as much as 20,000 feet.	0-to at least 3,100 feet.	0-to at least 3,000 feet.	At least 2,000 feet.	Minimum of about 5,000 feet to a possible maximum of about 11,000 feet.
Arrangement	Unknown.	Sand-shale ratio increases upward; marginal facies removed by pre-Keweenawan erosion.	Sand-shale ratio increases upward; marginal facies removed by pre-Keweenawan erosion.	Unknown.	Unknown.
Tectonic Setting	Unknown; probably miogeosynclinal – moderately negative.	Miogeosynclinal – moderately negative.	Miogeosynclinal – moderately negative.	Unknown.	Strongly negative – abundant associated volcanic rocks, etc.

CONCLUSIONS

We conclude that sediments of the Thomson Formation were derived in large part from a Lower Precambrian, largely plutonic terrane, located to the north. The original muds were deposited by a slow raining down of suspended clay particles. Turbidity currents probably transported the silt and sand to this part of the basin down a southward-dipping paleoslope. "Normal" bottom currents may have operated in the area, but it is not likely that they reworked the commonly graded sediment. The Thomson Formation is particularly similar to the Rove Formation of northeastern Minnesota, and generally similar to other formations of Middle Precambrian age in the Lake Superior region, supporting Irving's (1883) original conclusion of a Middle Precambrian age.

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