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STRATIGRAPHY AND PETROLOGY OF THE TYPE FOND DU LAC FORMATION DULUTH, MINNESOTA

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ABSTRACT

The Fond du Lac Formation of Upper Keweenawan (Precambrian) age is exposed along the St. Louis River near Duluth, Minnesota. It is inferred to be more than 800 feet thick in this area, but only 300 feet are exposed.

The formation consists predominantly of lenticular beds of red sandstone and siltstone and interbedded shale, but conglomerate beds containing clasts of vein quartz, basalt, felsite, chert, and quartzite are common. Physically isolated exposures of quartz-pebble conglomerate previously assigned to the Lower Keweenawan are reassigned to the Fond du Lac Formation because the conglomerate (1) grades into sandstone and shale that are similar in lithology to definite Fond du Lac strata, and (2) it contains heavy minerals identical to those found in the Fond du Lac sandstones.

The sandstone of the Fond du Lac Formation is arkosic or subarkosic, consisting of 36-68 percent quartz, 5-29 percent feldspar, 1-10 percent rock fragments, 1-15 percent matrix material composed of quartz, illite, chlorite, and rare kaolinite and biotite, and 1-20 percent cement of hematite, calcite, quartz and dolomite. Heavy minerals of the Fond du Lac Formation are leucoxene aggregates, apatite, tourmaline, zircon, magnetite-ilmenite, and garnet. The siltstone and shale, although fine-grained, are mineralogically equivalent to the sandstone.

Analysis of cross-bedding and other sedimentary directional indicators imply that the formation was derived from a terrane consisting of igneous, high-grade metamorphic, and sedimentary rocks that probably was situated to the west of the Fond du Lac basin of deposition.

Although the basal quartz-pebble conglomerate was deposited on an irregular surface during a transgressive sea in early Fond du Lac time, most of the formation was deposited by fluvial-deltaic processes, as indicated by the presence of filled channels, intraformational fragments, mud cracks, ripple marks, rain imprints, and extensive large- and small-scale cross-bedding.

INTRODUCTION

The Lake Superior region during Keweenawan time was the site of an accumulation of more than 20, 000 feet of clastic sediments which were later warped into a broad syncline now underlying most of Lake Superior. The majority of exposures of these rocks in Minnesota and Wisconsin are found along the south shore of Lake Superior. In Wisconsin, the upper 2, 000 feet of the sequence consists of interbedded, red feldspathic sandstone and micaceous shale known as the Bayfield Group (Thwaites, 1912). Correlative rocks are exposed in Minnesota at several localities and drilling and magnetic information indicates that red beds occur in a narrow belt in eastern Minnesota between Duluth and southeastern Minnesota, where they are overlain by Paleozoic rocks (Sims and Zietz, 1967). The red sandstones and shales in Minnesota are referred to as the Fond du Lac Formation (Upham, 1884) where exposed at the surface, and as the "Red Clastic Series" (Hall, Meinzer, and Fuller, 1911) when encountered in the subsurface beneath the Paleozoic rocks.

Although the Bayfield Group in Michigan and Wisconsin is well described (Hamblin, 1958, 1961, 1965; Thwaites, 1912), very little is known about its counterpart in Minnesota. The Fond du Lac Formation, therefore, was studied in detail at its type locality in order to interpret its northwestern facies in the Keweenawan basin.

Geologic Setting

The most complete exposures of the Fond du Lac Formation are found at Fond du Lac, a suburb of Duluth, Minnesota. The formation is exposed almost wholly in the valley floor of the St. Louis River and several of its tributaries, where it is overlain by unconsolidated Pleistocene clay and fine sand. Typical red sandstone and shale of the formation are exposed a short distance downstream from a well-exposed quartz-pebble conglomerate outcrop on Little River, in section 1, T. 48 N., R. 16 W., and the formation is more or less continuously exposed along the St. Louis River from the mouth of Little River to Fond du Lac (plate 1).

The oldest formation exposed in the area studied is the Middle Precambrian Thomson Formation (table 1), a thick sequence of alternating graywacke and slate beds that were folded about 1.7 billion years ago (Goldich and others, 1961, p. 117-120). It is cut by many irregular veins of white quartz, and is intruded by dikes and sill-like bodies of Middle Keweenawan diabasic gabbro. An angular unconformity, well exposed in section 10, T. 48 N., R. 15 W., and in section 2, T. 48 N., R. 16 W., separates the Thomson Formation from overlying beds of

Table 1--*Stratigraphic succession in the Fond du Lac Area (after Goldich and others, 1961, p. 5)*

Era	Major Sequence		Formation	Lithology	Age (millions of years)
Upper Precambrian	Keweenawan		Fond du Lac Formation	Sandstone and shale	
			Unconformity (?)		
		North Shore Volcanic Group	Undivided	Dikes and sills of diabasic gabbro	1,100
			Disconformity		
			Puckwunge Sandstone (missing in Fond du Lac Area)		
			Unconformity		
Middle Precambrian	Penokean intrusive rocks				1,700
		Animikie Group	Thomson Formation	Graywacke and slate	

quartz-pebble conglomerate.

The age of the quartz-pebble conglomerate above the unconformity has been a problem. Winchell (1889, p. 567) excluded it from the Fond du Lac Formation and correlated it with what is now known as the Puckwunge Sandstone, assigned to the Lower Keweenawan. His correlation was based on a similarity in structural position; i.e., inferred Puckwunge Sandstone rests on Thomson Formation several miles north of the area of plate 1; therefore, the quartz-pebble conglomerate that lies on slate must also be Puckwunge. Winchell believed that the quartz-pebble conglomerate is separated from the overlying Fond du Lac Formation by another unconformity, although he recognized that evidence for such an unconformity was poor and unconvincing.

Grout and others (1951) also considered the quartz-pebble conglomerate to be of Lower Keweenawan Age, whereas the Fond du Lac Formation was assigned to the Upper Keweenawan. They suggested, however, that (p. 1059) "...quite possibly a fault passes between the...outcrops...of quartz-pebble conglomerate and the Fond du Lac Formation in section 1, T. 48 N., R. 16 W., and that...the Upper Keweenawan is in contact with the Lower Keweenawan along the fault plane..." As evidence for the presence of a fault they cited a drill hole, at the dam on the St. Louis River in section 6, T. 48 N., R. 15 W., which penetrated 102 feet of alternating red shale and sandstone without reaching the quartz-pebble conglomerate or the Thomson Formation. Although several small normal faults occur in the area, there is no evidence for a fault between the two outcrops of the magnitude postulated by Grout and others.

The gross distribution of rock types (plate 1) indicates that the conglomerate and overlying red sandstone are conformable, and, in fact, Thwaites (1912, p. 70) concluded that "...there is a complete gradation between ..." them. It will be shown later that such a gradation is real, and that the quartz-pebble conglomerate should be considered as basal Fond du Lac Formation.

Type Section

Although Winchell (1889, p. 567) denoted the rocks "...exposed on both banks of the St. Louis River from Fond du Lac westward..." as the Fond du Lac type section, he did not completely describe them. Thwaites (1912, p. 69) described a stratigraphic sequence exposed along the St. Louis River, but water later ponded by a dam now covers much of these rocks. It was necessary to measure and describe the remaining good exposures along the river. These exposures were tied together into a composite stratigraphic section (appendix) by an alidade survey because a lack of key beds makes it virtually impossible to correlate from one exposure to another.

In addition to the type section, another fairly complete sequence is exposed about one-half mile northeast along Mission Creek. Even though it was not possible to correlate the two sequences precisely, the Mission Creek section is probably equivalent to the upper part of the St. Louis River section.

Neither the top of the formation nor the overlying Hinckley Sandstone is exposed near the type locality. Approximately 300 feet of the Fond du Lac Formation are exposed along the St. Louis River, although the total thickness along the river probably exceeds 800 feet. Correlative rocks in southeastern Minnesota may be as much as 2,000 feet thick (Kirwin, 1963, M.S. Thesis, University of Minnesota).

Rock Types

Several distinct rock types are recognizable in the Fond du Lac Formation. Lenses of conglomerate of several compositions occur at the base with alternating layers of fine arkosic sandstone and red micaceous shale. The upper part of the exposed sequence consists mostly of lenticular sandstone--with shale-pebble conglomerate common at many horizon levels--and interbedded shale.

The basal 60 feet of the formation is a conglomerate that consists predominantly of pebbles and cobbles up to six inches in diameter. Pebbles of vein quartz predominate, and there are minor amounts of chert, quartzite, graywacke, and slate. The matrix is mostly a coarse grit of angular quartz and feldspar, with some clay-sized matrix material and dolomite cement. Pyrite and marcasite concretions and individual grains are common in the matrix; locally they have been altered to limonite.

The conglomerate grades upward into a sequence of interbedded light greenish gray to dark reddish brown sandstone and mudstone typical of the Fond du Lac Formation. The sandstone is medium-bedded, whereas the mudstone is either fissile or massive. Within the gradational zone, which is several feet thick, the size of the conglomeratic clasts becomes progressively smaller and the amount of sand-size material increases; there is no distinct break between the quartz-pebble conglomerate and sandstone beds that are similar to recognizable Fond du Lac Formation. Because of this gradational contact, the quartz-pebble conglomerate is assigned to the Fond du Lac Formation.

Most of the formation consists of compact dense sandstone and siltstone interbedded with fissile shale. Sandstone beds are mostly lenticular in shape and range in thickness from one to eight feet. Shale units are more uniform in thickness, with individual units being as much as 18 feet thick.

The sandstone and shale are predominantly very dusky red to dark reddish brown, but streaks and mottles of white, light greenish gray, and pinkish gray are also common. In general, the fine-grained beds are the most intense red and have the least amount of mottling when compared with coarse-grained rocks which are lighter in color. Most of the abrupt color changes are at bedding planes separating units of differing grain size and sorting, or along joint and fracture planes.

Many extraformational conglomerate beds are intercalcated with the sandstone and shale. The most prominent of such conglomerates gradationally overlies the basal quartz-pebble conglomerate in section 1, T. 48 N., R. 16 W., and consists of fine-grained, reddish brown sandstone that contains pebbles of highly altered basalt and basalt porphyry. The matrix is similar to the sandstones associated with the basal quartz-pebble conglomerate and to that of the overlying rocks. Identical conglomerates also occur stratigraphically higher in the formation where they make up a small part of the sequence.

Intraformational conglomerates composed of pebbles of reddish brown shale are common near the base of many of the sandstone beds. The clasts range in size from less than one-half to more than six inches in greatest dimension. Most of the pebbles are irregular in shape and show little effect of abrasion. Generally, they comprise thin beds or lenses, but many isolated "floating pebbles" are scattered throughout most of the sandstone units.

Sandstone concretions cemented by calcite are also common. They are egg-shaped and are oriented parallel to the bedding. The contact between the concretions and the sandstone matrix is sharp, and the bedding is interrupted and bent around the concretions; apparently the concretions formed before compaction was complete.

SEDIMENTARY STRUCTURES

Medium- to large-scale cross-bedding is the most abundant primary sedimentary structure in the Fond du Lac Formation. It is predominantly of the trough-type (McKee and Weir, 1953), in which each set of cross-strata forms a wide, shallow, concave-upward channel that is U-shaped in plan view and wedge- or lens-shaped in longitudinal section. These structures are generally 3-6 feet wide, 1-2 feet deep, and 5-10 feet long. Small scale cross-bedding, with foreset beds 3-6 inches long, also is present but not abundant. Small-scale cross beds are similar in shape to the typical festoon-type described by Knight (1929), in which the individual cross-stratum has an elongate ellipsoidal shape in plan view. In many exposures the large scale trough-like cross-bedding occurs in channels that are cut into previously deposited sediments. The small scale cross-bedding, however, is associated with horizontal bedding and appears to have formed as bed load structures.

The azimuth of both the large and small scale cross-bedding was measured at all outcrops. Because in trough-type cross-bedding only one direction, the axial plane, parallels the current flow, and because it is unlikely that all the measured azimuths of foreset beds parallel that direction, most cross-bedding azimuths deviate from the true direction. The results, however, (see figure 1), when corrected for regional dip, indicate a predominantly eastward current direction.

The fan-shaped unimodal current-rose of cross-bedding azimuths is similar to those of other fluvial sediments (Potter, 1955, Fig. 7; Pryor, 1960, Fig. 13; and Yeakel, 1962, Figs. 7, 10 and 12). It should be pointed out, however, that some nonfluvial deposits may have similar distributions of dip azimuths (McKee, 1940, p. 813).

The azimuths of other current-direction indicators such as grain lineations, channel axes, ripple marks, and flute casts also were measured. All results are consistent with an eastward current movement.

Also, ripple marks, mud cracks, and rain imprints are present and well preserved, indicating that the water was shallow and subject to periods of alternating drying and wetting.

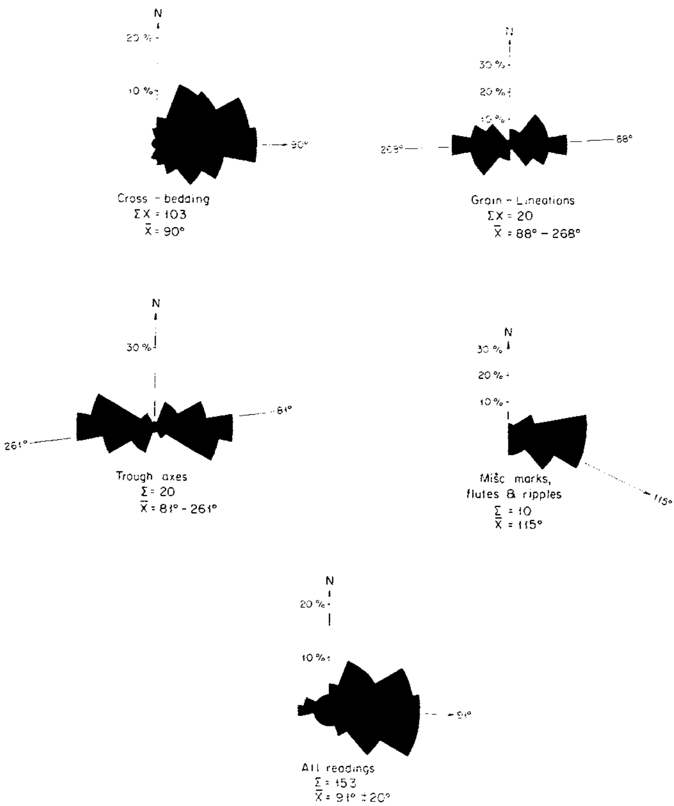


Figure 1--Summary of paleocurrent data

PETROLOGY

Sandstone

Fine- and medium-grained sandstones are the most abundant rock in the Fond du Lac Formation. Coarse siltstone and very fine, coarse, and very coarse sandstone also are present. The thickness of a sandstone bed in a general way is directly proportional to its median grain-size; thin beds are very fine-grained and thick beds are coarse-grained.

Most of the sandstone is well cemented, compact, and impervious. Grain size analyses were performed on seventeen friable samples (table 2); most of the samples are fine- to medium-grained and fairly well sorted, and their cumulative curves are skewed to the fine side.

The mineralogic composition of the sandstone was studied in 19 thin sections. One hundred points were counted on each section to determine relative amounts of framework grains, cement, and matrix; additional observations were then made on each section until 100 framework grains were classified. The relative abundance of grains, cement, and matrix of the samples and the composition of the framework grains are summarized in fig. 2 and table 3.

Chemical cement, except quartz, ranges from one to twenty percent and averages 10 percent. Varied amounts of quartz overgrowths are present in all samples studied, but many could not be accurately distinguished from the nuclei; all quartz was recorded as a framework mineral. Calcite and hematite are the major non-siliceous cementing minerals; dolomite is a minor cement except in a few conglomerate samples, where it has partially replaced calcite. Hematite occurs as thin coatings on quartz and feldspar grains, as stain on clay minerals and rock fragments, and as interstitial void fillings.

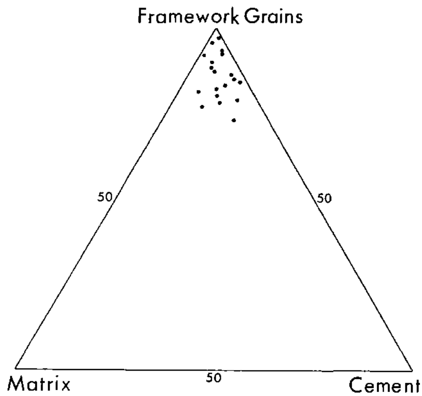
Matrix material--detritus less than 0. 03 mm. --constitutes one to 15 percent and averages nine percent of the sandstones studied. X-ray diffraction shows that the matrix is composed of quartz, illite, chlorite, and rare kaolinite and biotite.

Framework grains, in order of decreasing abundance are: quartz, feldspar, rock fragments of sedimentary, igneous, and metamorphic rock types, muscovite, and biotite. Fond du Lac sandstones can be classified mostly as arkoses or subarkoses according to McBride's classification of clastic rocks (1963), which has end members of quartz (including quartzite and chert), feldspar, and rock fragments. The

Table 2--*Grain size analyses of selected sandstones*

Sample (1) number	Median dia. (mm)	1st Quartile (mm)	3rd Quartile (mm)	Sorting	Skewness
Q-1 - - - -	0.55	0.20	1.11	2.57	0.71
Q-2 - - - -	0.94	0.40	1.68	2.06	0.76
F-1 - - - -	0.20	0.12	0.29	1.59	0.86
F-2 - - - -	0.16	0.08	0.26	1.50	0.80
F-3 - - - -	0.24	0.14	0.56	1.94	1.42
F-4 - - - -	0.18	0.08	0.28	1.89	0.62
F-5 - - - -	0.19	0.13	0.33	1.34	0.82
F-6 - - - -	0.17	0.10	0.31	1.77	0.03
F-7 - - - -	0.19	0.14	0.27	1.37	1.04
F-8 - - - -	0.20	0.13	0.32	1.56	1.01
F-9 - - - -	0.13	0.08	0.25	1.77	1.05
F-10 - - -	0.21	0.14	0.35	1.61	1.08
F-11 - - -	0.20	0.11	0.24	1.41	0.69
F-12 - - -	0.20	0.12	0.26	1.47	0.78
F-13 - - -	0.28	0.17	0.24	1.58	0.91
F-14 - - -	0.18	0.10	0.46	1.56	0.74
F-15 - - -	0.31	0.19	0.25	1.55	0.87

(1) Q samples are sandstones associated with quartz-pebble conglomerate; F samples are from Fond du Lac Formation.



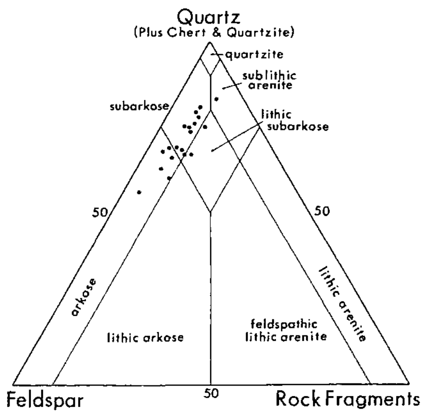


Figure 2--Textural and compositional diagrams of the sandstones of the Fond du Lac Formation.

Table 3--*Modal analyses of selected Fond du Lac sandstones*

Sample Number	Framework grains					Matrix			Cement		Accessory		
	Quartz	Ortho-clase	Plagio-clase	Micro-cline	Rock Frag-ments (2)	Chlorite	Muscovite	Biotite	Calcite	Hematite	Opaque ores	Leucoxene aggregates	Other (3)
M-15,201 . . .	42	19	3	1	9	3	12	Tr	1	12	---	4	3
M-15,202 . . .	54	13	4	2	11	Tr	6	---	4	1	Tr	5	---
M-15,203 . . .	45	11	2	3	8	2	7	---	2	7	9	5	---
M-15,204 . . .	60	11	4	2	11	3	3	---	1	1	1	1	2
M-15,205 . . .	36	25	3	2	11	Tr	7	2	1	9	Tr	Tr	2
M-15,206 . . .	58	14	2	Tr	10	4	3	---	5	Tr	2	2	---
M-15,207 . . .	46	6	3	1	18	1	3	---	16	Tr	Tr	3	1
M-15,208 . . .	56	5	3	3	18	2	2	---	9	3	2	6	1
M-15,209 . . .	54	12	2	---	13	---	2	---	13	Tr	---	4	---
M-15,210 . . .	49	18	3	Tr	12	1	4	---	Tr	11	---	Tr	1
M-15,211 . . .	46	20	2	Tr	10	4	8	2	4	1	Tr	2	1
M-15,212 . . .	56	2	2	1	8	3	12	2	5	2	2	3	2
M-15,213 . . .	59	17	1	Tr	10	Tr	5	---	Tr	6	1	Tr	3
M-15,214 . . .	60	3	4	7	---	1	20	---	1	3	1	---	---
M-15,215 . . .	50	15	3	---	5	2	4	Tr	1	15	Tr	4	Tr
M-15,216 . . .	68	10	Tr	---	17	1	2	Tr	Tr	---	---	Tr	2
M-15,217 . . .	51	17	Tr	Tr	18	1	1	---	Tr	4	1	3	2
M-15,218 . . .	56	20	4	2	13	Tr	Tr	---	---	2	---	1	1
M-15,219 . . .	42	14	Tr	Tr	18	2	2	Tr	2	11	3	6	---

(1) Samples on file with the Minnesota Geological Survey
(2) including intraformational fragments
(3) including "heavy" minerals

rocks are arkose or subgraywacke, according to Pettijohn's classification (1957, p. 293), depending on the feldspar-rock fragment ratio.

Quartz comprises 36-68 percent of the samples studied, and averages 52 percent. Angular to sub-rounded quartz grains having strong undulatory extinction are predominant, although well-rounded grains and other varieties are not uncommon. Many samples also contain composite grains of quartz, implying possible derivation from a metamorphic or igneous terrane.

Feldspar content ranges from 5 to 29 percent and averages 17 percent. Some grains are unaltered but most are partly altered to kaolinite or sericite; therefore, accurate counts of feldspar types could not be made. Orthoclase is estimated to be the most abundant type, although twinned and untwinned albite-oligioclase and microcline are locally abundant. Some detrital grains that have well rounded highly sericitized cores have overgrowths of weakly sericitized feldspar, which in turn is surrounded by abraded overgrowths of clear feldspar, implying more than one cycle of authigenic growth and therefore more than one cycle of deposition.

Rock fragments, including both sedimentary and igneous-metamorphic derivatives, are common constituents of samples studied, averaging 10 percent. Fragments derived from rocks older than the Fond du Lac Formation include basalt, felsite, iron-formation, schist, chert, and quartzite. Chert and quartzite grains are the most abundant constituents (averaging slightly more than half of the above mentioned rock-types), but iron-formation was abundant in one sample. Sedimentary rock fragments similar to rocks of the Fond du Lac Formation are considered to be of intraformational origin, although some may have been derived from older Keweenawan red beds. Mudstone and shale are the most common types; siltstone and sandstone are present in many samples.

Heavy minerals in the Fond du Lac Formation occur in small placer deposits that probably developed in local current-eddies. They were described by Tyler and others (1940, p. 1511) and are, in order of decreasing abundance: leucoxene aggregates, apatite, tourmaline, zircon, opaque ores including magnetite and ilmenite, and garnet.

Mudstone

Mudstone, as used here, is a general term for clastic rocks that contain more than 75 percent fine silt and clay. These rocks in the Fond du Lac Formation have either a laminated or a massive appearance. Many mudstones are fissile, and therefore properly can be called shales, but many others lack fissility. The presence or absence of parting planes is a function of amount and distribution of the silt-size fraction; fissile and laminated rocks contain small amounts of silt, whereas structureless units are very silty, and the silt-size grains are generally randomly distributed. In laminated beds, silt is concentrated in discontinuous layers less than a millimeter thick.

Clay minerals constitute between 75 and 95 percent of the mudstones. X-ray diffraction studies show that the clay is predominantly illite and chlorite, with minor amounts of kaolinite and mixed layer montmorillonite-illite. Most of the silt-size grains are quartz and feldspar; rock fragments were not observed. Hematite appears to be the most common cementing material, but calcite locally cements some of the structureless beds.

Conglomerate

The sand-size matrix of the conglomerate beds is similar mineralogically to the sandstone in the formation. The matrix can be classified as a lithic arkose (McBride, 1963) or as a subgraywacke (Pettijohn, 1957), for it contains more sand-size rock fragments than do non-conglomeratic sandstones. Most sand-size rock fragments are chert or fine-grained quartzite, but slate grains are common in the matrix of the basal quartz-pebble conglomerate.

The mineralogy of the granule to boulder fraction, however, differs considerably from sample to sample. The lithologic character of the pebbles, along with size and shape data are summarized in table 4.

Heavy minerals separated from eight samples of the quartz-pebble conglomerate are summarized in table 5. They are very similar both in kind and relative abundance to the heavy mineral suite of the Fond du Lac sandstones described by Tyler and others (1940, p. 1511).

Table 4 --*Pebble counts, size, sphericity, and roundness of conglomeratic units in the Fond du Lac Formation*

Sample number	No. of pebbles	Lithology by percent										Average max. dia. (mm)	Average (1) sphericity	Average (2) roundness
		vein quartz	basalt	basalt porp.	iron-form. & chert	felsite	felsite porp.	gabbro	shale	sandstone	slate			
Q-1 - - -	100	88	-	-	12	-	-	-	-	-	-	14	0.53	0.37
Q-2 - - -	100	93	-	-	6	-	-	-	-	-	1	84	0.63	0.40
F-6 - - -	100	39	-	1	6	-	-	5	1	22	1	33	0.65	0.40
F-7 - - -	100	41	-	1	8	-	-	4	1	18	1	39	0.58	0.35
Q-3 - - -	23	56	-	-	13	-	-	-	-	8	17	19	0.43	0.41
F-8 - - -	25	55	-	-	15	-	-	-	-	6	19	23	0.42	0.43
Q-4 - - -	100	80	-	-	7	-	-	-	-	-	13	89	0.60	0.50
Q-5 - - -	100	87	-	-	8	-	-	-	-	-	4	70	0.65	0.30
F-9 - - -	100	27	-	-	-	1	8	-	64	-	-	20	0.47	0.45
F-10 - -	100	20	-	-	-	2	20	-	58	-	-	52	0.54	0.50

Q 1-5 quartz-pebble conglomerate; F 1-10 "other" conglomerate in the formation.
(1) Determined by alignment diagram method (Krumblein and Pettijohn, 1938, p. 293).
(2) Visually estimated from charts prepared by Powers (1933, p. 117-119).

Table 5--*Heavy minerals separated from the quartz-pebble conglomerate*

Sample no.	Wt. percent heavy mineral		Relative abundance* heavy minerals before acid treatment				Percentage distribution accessory minerals after acid treatment					
	before HCL	after HCL	carbonate	leucoxene	accessories	pyrite	apatite	garnet	zircon	tourmaline	opaques	other (?)
Q-1	1.2	0.8	A	C	A	P	26	7	21	16	30	-
Q-2	0.8	0.4	A	P	P	C	26	6	24	16	22	6
Q-3	1.0	0.6	P	P	A	C	30	2	18	4	40	2
Q-4	3.6	2.4	F	P	P	A	17	3	9	10	55	6
Q-5	1.8	1.5	A	C	P	F	16	3	10	10	55	6
Q-6	4.2	4.0	P	C	A	A	20	5	12	15	45	3
Q-7	3.6	2.3	C	C	A	F	18	7	5	10	58	2
Q-8	2.1	1.6	C	C	P	F	15	5	5	--	75	-

* P 0-15%, C 15-30%, A 30-50%, F >50%

Provenance

The mineralogic composition of the Fond du Lac rocks indicates a complex source area consisting of volcanic, high-grade metamorphic, igneous, and sedimentary rocks, as shown in figure 3.

Abundant angular to sub-angular clasts of felsic and basic extrusive rocks undoubtedly were derived from a nearby source--the Middle Keweenawan extrusive rocks now exposed around the Fond du Lac area. The more resistant, well rounded fragments of sand- and granule-sized quartzite, chert, and iron-formation, however, indicate that Middle Precambrian or older rocks located somewhat distant from the depositional site also supplied material to the basin.

The predominance of potash feldspar over plagioclase indicates that much of the Fond du Lac sediments were derived from a granitic or gneissic terrane. The fact that the feldspar consists both of fresh and altered varieties implies that it was derived from both fresh and weathered material or that the altered feldspar was re-cycled from an older sedimentary source. The latter possibility is substantiated in part by the presence of grains with abraded overgrowths. It may be that much of the Fond du Lac material was derived from an older sedimentary source that originally was derived from a granitic or gneissic terrane.

A source area consisting of several rock types is also indicated by the heavy mineral suite. Tyler and others (1940) demonstrated that the most abundant heavy minerals, such as leucoxene and opaque ores, were derived from basic igneous rocks. Zircon, garnet, tourmaline, and apatite, on the other hand,probably were derived from granitic or high-grade metamorphic rocks, although the first three minerals may have been derived wholly or in part from Keweenawan sandstones older than the Fond du Lac.

Paleo-current data summarized in figure 1 indicates an easterly current-movement. This direction is approximately perpendicular to the generalized form lines of the Keweenawan basin based on inferred stratigraphic thicknesses (Irving, 1883; as cited in Hamblin, 1965). The data therefore appears to reflect a paleo-slope to the east, or towards the basin, during Fond du Lac time. This picture is consistent with the depositional model suggested by Hamblin (1961; 1965) for other parts of the Keweenawan basin. It follows, therefore, that the source area was located west of Fond du Lac in what is now central Minnesota.

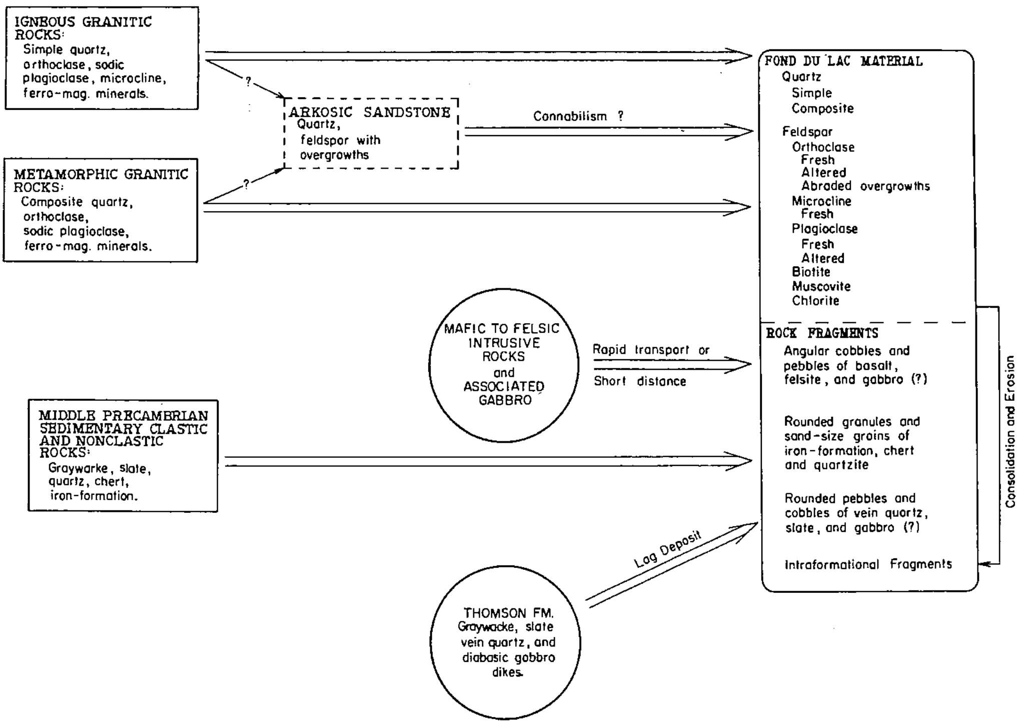


Figure 3--Summary of various sources of Fond du Lac mineralogy (Circles = local source; rectangle = distant source; width of line proportional to amount contributed)

SUMMARY AND CONCLUSIONS

Because of its physical isolation, it is difficult to correlate the Fond du Lac Formation with equivalent formations of the Lake Superior region. Tyler and others (1940, p. 1470) concluded, on the basis of heavy minerals, that the Fond du Lac Formation is equivalent to the Bayfield Group in Wisconsin. Data obtained from the study of the limited exposures near Fond du Lac do not contradict this correlation. Equivalents of the Oronto Group, which underlies the Bayfield Group in Wisconsin, are not known in the Fond du Lac area. Either the Oronto was not deposited or it was removed prior to deposition of the Fond du Lac. Its absence, in either case, indicates a long period of erosion or non-deposition prior to Fond du Lac time, features that are strikingly apparent in the Fond du Lac area. The surface on which the Fond du Lac sediments were deposited was very irregular; the unconformity between the underlying Thomson Formation and the overlying Fond du Lac Formation is exposed at about 900 feet above sea level in the Fond du Lac area, but several miles to the north the Thomson Formation crops out at 1100 or more feet above sea level. Winchell (1889) first pointed out that the basal quartz-pebble conglomerate of the Fond du Lac Formation is variable in thickness because it fills low spots on an irregular surface developed on the Thomson Formation. He noted at one place that the conglomerate was more than 75 feet thick, but more commonly it averages 25 to 50 feet.

The composition of the basal quartz-pebble conglomerate is simple, with more than 95 percent of the clasts being either vein quartz, quartzite, or chert. Most of the clasts are spherical and well rounded, and the conglomerate is nearly everywhere well sorted. Vigorous erosion, prior to and during deposition, destroyed much of the less resistant slate and graywacke of the Thomson Formation and left behind a lag deposit of more resistant material that was incorporated into the conglomerate. These above features indicate that the conglomerate was deposited on a surface of moderate to rugged relief in either stream valleys or in a shallow transgressing body of water.

The major part of the Fond du Lac Formation that is stratigraphically above the basal quartz-pebble conglomerate is thought to have been deposited by fluvial-deltaic processes. Several sedimentary and lithologic attributes favor deposition by fluvial-deltaic processes. Although none of the following features in itself is sufficient grounds for unique interpretation, collectively they are consistent with the thesis that the environment was fluvial-deltaic: (1) sharp erosional basal contacts which channel-cut parts of the underlying strata, (2) an upward change in sedimentation units from thick-bedded, coarse-grained, locally conglomeratic sandstone at the base to thinly bedded, fine-grained sandstone and siltstone at the top, (3) common cut- and -fill structures, (4) poor sorting and bimodal size distribution of conglomerate within the sandstones, and (5) rapid lateral changes in both thickness and lithology.

The lateral extent of the sandstones suggest that more than one stream was operative during the deposition of a single sandstone. Each sandstone was probably deposited by a series of alluviating streams which meandered across a broad deltaic plain. The laminated shales were probably deposited in lakes or on flood plains. The presence of associated mud cracks, ripple marks, and rain imprints collectively suggest that the water was shallow and that the sediments were subjected to alternating periods of wetting and drying. This interpretation is consistent with that of Thwaites (1912) and Hamblin (1958, 1961) for equivalent rocks in Wisconsin and Michigan.

The red color of the Fond du Lac rocks is imparted by a hematitic coating on the surface of sand and silt-size quartz and feldspar grains, by disseminated hematite-stained clay, by what appears to be partially altered chlorite, biotite, and rock fragments, and by small grains of hematite. On some detrital grains the hematitic coating is variable in thickness, and other adjacent grains may not be coated with hematite at points of contact. The coatings on still other grains is about the same thickness on all parts of grains. It seems likely, therefore, that hematite formed in place sometime after deposition and prior to complete lithification.

Miller and Folk (1955), in a study of certain redbeds, suggested that a large part of the iron that now occurs as hematite originated from the destruction of iron-bearing primary silicate minerals. A similar mechanism may be used to explain the source of the iron in the Fond du Lac Formation. Magnetite-ilmenite is an abundant heavy mineral in the Fond du Lac Formation. There is ample evidence to indicate that these minerals were derived, at least in part, from an igneous source that consisted of both granitic and basaltic rocks. Such a source would also have contained large amounts of other iron-bearing minerals such as pyroxene, hornblende, and biotite, but these minerals are either absent or rarely found in Fond du Lac sediments. Inasmuch as these silicate minerals are unstable in an oxidizing environment, they would have been destroyed before or soon after burial; iron from them would therefore be available for the formation of hematite. The magnetite-ilmenite persisted because it is destroyed only in a reducing environment. Thus, no special set of conditions are required either in the source area or at the site of deposition to explain the source of the iron. All that is required is a source for the original iron-bearing minerals and their transportation to an oxidizing environment at the depositional site.

It is more difficult to determine when the alteration of the original iron-bearing minerals and the subsequent oxidation of the released iron took place. Miller and Folk (1955, p. 344) stated that "...hornblende and pyroxene...are largely destroyed by surficial weathering before they reach the site of deposition..." This implies that the iron was transported in solution to the depositional site where it was oxidized. However, Robb (1949, p. 102) described a redbed occurrence in which iron, which subsequently was oxidized to form hematite, was released from an alteration product of detrital biotite sometime after deposition. Walker (1967) also described the alteration of detrital hornblende to an authigenic clay from which iron was released by continuous intrastratal leaching. These data suggest that authigenic clay formed from the original iron-silicate mineral is a source of iron in the hematite pigment, particularly in the matrix. The association of hematite staining with both rock fragments and biotite suggests that this may also have been an important process in the formation of red pigments in the Fond du Lac Formation.

It follows from the above discussion that post-depositional-diagenetic processes caused the original red color. However, numerous gray-green spots and zones in which the iron is present in a reduced state, and which range in size from small spots to entire beds, also occur in the formation. Gray-green zones are more common in the sandy beds within the strata, as a result of surface leaching by ground water; other smaller, spherical spots poor in ferric iron may be the result of the oxidation of local accumulations of organic matter (Hamblin, 1958).

In summary, the Fond du Lac Formation in its type area is considered to be a fan-shaped wedge of clastic material that was deposited in a shallow, oxidizing, deltaic environment by a system of streams emerging from a western highland and dispersing material to the east and southeast.

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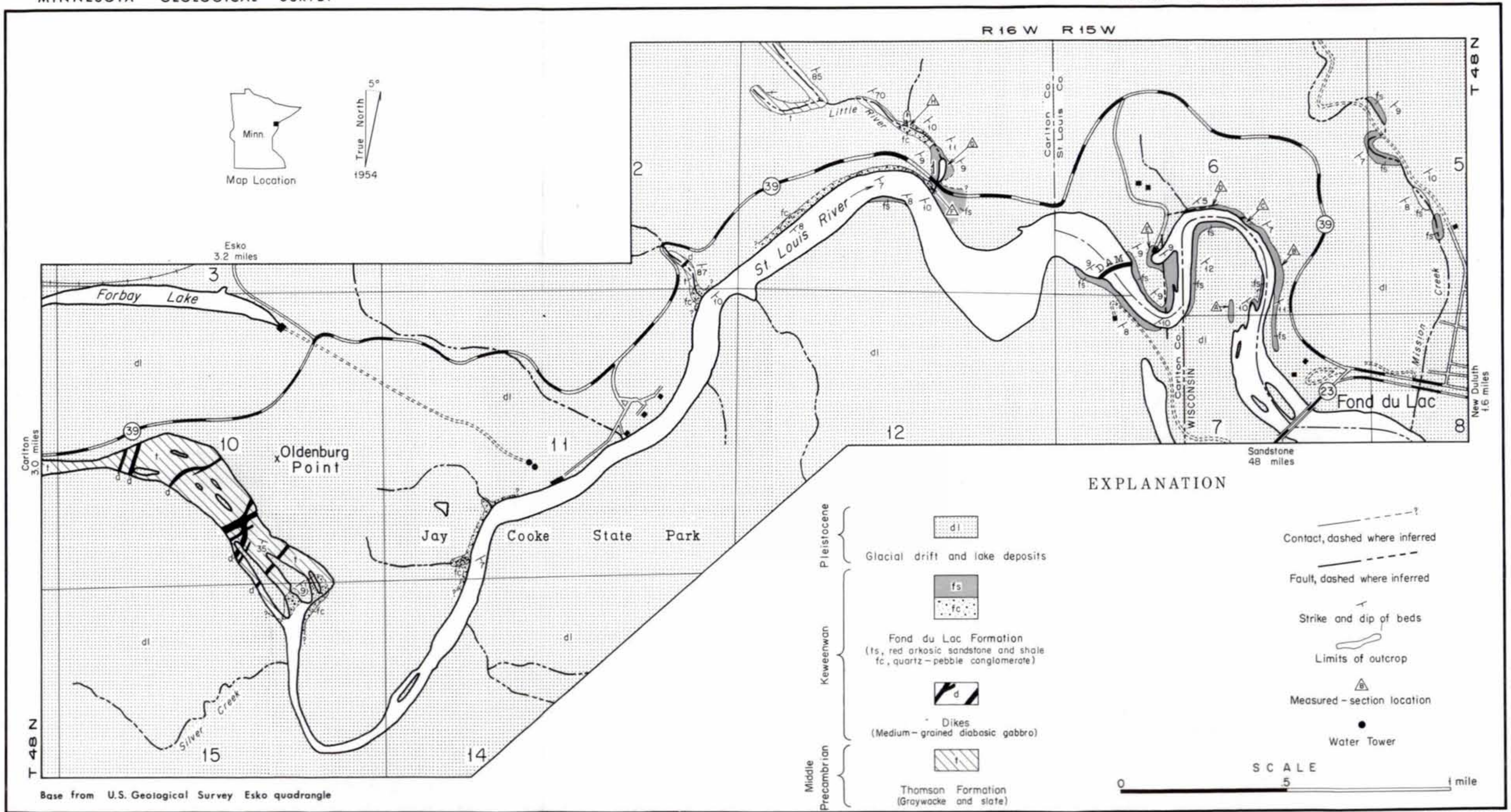

Geology by G.B. Morey, 1958 and 1965

Geology of the Fond du Lac Area, near Duluth, Minnesota

APPENDIX
Measured Sections

The St. Louis River composite section consists of eight parts, lettered A through H on Plate 1.

Part A

	Feet	Inches
Pleistocene:		
56. Glacial drift: red silt		
Upper Keweenawan: Fond du Lac Formation:		
55. Sandstone, fine-grained, dark reddish brown (10R3/4), structureless, but has some wedges of thin beds, cross-bedding. Unit contains vugs of clay up to 1 inch in diameter	4	6
54. Shale, grades upward to fine sandstone, greenish gray (5G6/1) grading upward to pale red (10R6/2), thin-bedded, mica common on parting planes	1	10
53. Sandstone, fine-grained, dark reddish brown (10R3/4), medium-bedded with cross-bedding, unit very irregular in thickness	1	6
52. Conglomerate. Pebbles of milky quartz and felsite porphyry up to 4 inches in diameter, flat pebbles of red shale up to 5 inches in diameter. Matrix coarse-grained, light greenish gray (5G8/1). Unit structureless, but wavy and irregular	1	6
51. Sandstone and shale, sandstone, medium-grained, white (ON9) grading to reddish brown (10R3/4), interbedded with medium greenish-gray (5G6/1) shale with abundant mica	2	7

	Feet	Inches
50. Sandstone, medium-grained, dark reddish brown (10R3/4) with some light greenish gray (5G8/1) clay galls, thin-bedded, some cross-bedding. Unit has concretions up to 5 inches in diameter of same lithology. Top of unit irregular - -	7	6
49. Sandstone, same as unit 50 without concretions -	21	0
48. Sandstone, same as unit 50 but structureless to locally cross-bedded. Unit has brown and green clay near base similar to that found in unit 47 - - - - - - - - - - - -	7	6
47. Shale, very dusky red (10R2/2), abundant mica, contact with unit 48 very wavy- -	0	2
46. Sandstone, medium-grained, light greenish gray (5G8/1), medium-bedded with cross-bedding - - - - - - - - - - - - - - - -	3	6
45. Covered -	80	0

Part B

	Feet	Inches
44. Sandstone, medium-grained, banded dark reddish brown (10R3/4) and light greenish gray (5GY8/1), unit structureless to cross-bedded. Bedding in middle of unit highly contorted. Unit contains clay lenses and clay galls up to 3 inches in diameter - - - - - - - - - - - - - - - - - -	14	0
43. Sandstone, medium-grained, banded light greenish gray (5GY8/1) and dark reddish brown (10R3/4), thin-bedded, parting planes contain abundant mica- - - - -	0	8

	Feet	Inches
42. Sandstone, same as unit 44. Unit contains clay lenses up to 1 inch in length, and quartz and red shale pebbles up to 1/2 inch in diameter	7	10
41. Sandstone, medium-grained, very dusky red (10R2/2) with light greenish gray (5GY8/1) patches up to 1/2 inch in diameter. Unit cross-bedded	2	8
40. Sandstone, medium-grained, gray (ON8), medium-bedded, passing gradationally upward to a thinly laminated, dark reddish brown (10R3/4) shale	0	6
39. Siltstone, same as unit 41, interbedded with light greenish gray (5G8/1) sandstone, very thick-bedded with cross bedding	8	0
38. Sandstone, medium-grained, banded light greenish gray (5GY8/1) and dark reddish brown (10R3/4), thin-bedded	2	6
37. Sandstone and shale, sandstone medium-grained, well cemented, pale red (5R6/2), medium-bedded, shale dark reddish brown (10R3/4), laminated	0	6
36. Siltstone, same as unit 41 with clay lenses 1/8 inch thick and 2 inches long	6	0
35. Covered	115	0

Part C

	Feet	Inches
34. Sandstone, fine-grained, dark reddish brown (10R3/4), thin-bedded	6	0

	Feet	Inches
33. Sandstone, fine-grained, gray (ON8), thick-bedded and shows cross-bedding, clay galls and mica common on parting planes. Unit contains quartz pebbles up to 1/4 inch in diameter	10	0
32. Shale, dark reddish brown (10R3/4) with medium greenish gray (5G5/1) patches, fissile	4	4
31. Sandstone, same as unit 33	1	0
30. Sandstone, conglomeratic. Matrix medium-grained, very dusky red (10R2/2). Unit contains clay galls and mica on parting planes. Pebbles of vein quartz and felsite porphyry up to 1 inch in diameter common	0	8
29. Sandstone, same as unit 33	10	7
28. Covered	100	0

Part D

	Feet	Inches
27. Sandstone, fine-grained, gray (ON8), thick-bedded, cross-bedded, contains clay lenses; cuts unit 26	7	8
26. Shale, dark reddish brown, (10R3/4) with medium greenish gray (5G5/1) silty patches, fissile	20	0
25. Sandstone, fine-grained, dark reddish brown (10R3/4), medium-bedded with cross-bedding	3	0
24. Covered	30	0

Part E

	Feet	Inches
23. Sandstone, fine-grained, banded greenish gray (5G6/1) and pale red (5R6/2), unit mostly very thick-bedded with cross-bedding, locally thin-bedded. Unit contains mica on parting planes and on contact with unit 22 - - - - - - - - - - - - - - - - -	35	0
22. Shale, silty, very fine-grained, dark reddish brown (10R3/4), thin-bedded to fissile. Local stringers of light greenish-gray silt. Mica common on parting planes - - - - - - - - - - - - - - - - - -	2	1
21. Sandstone, fine- to medium-grained, medium greenish gray (5G5/1) to dark reddish brown (10R3/4), structureless - - - -	1	0
20. Shale, same as unit 22. There is a gradational contact through 3 feet between this unit and the overlying sandstone - - - - - - -	21	8
19. Sandstone, very fine-grained, medium greenish gray (5G5/1), thin-bedded and has cross-bedding - - - - - - - - - - - - - - -	6	0
18. Sandstone, fine-grained, dark reddish brown (10R3/4), unit thin-bedded and has cross-bedding -	9	5
17. Clay, dark reddish brown (10R3/4), silty, irregular -	0	1
16. Sandstone, medium-grained, very dusky red (10R2/2), medium-bedded and highly cross-bedded. Unit contains very thin, irregular clay stringers - - - - - - - - - - - -	11	0
15. Covered by water reservoir - - - - - - - - - -	280	0

Part F

		Feet	Inches
14.	Sandstone, conglomeratic, coarse-grained, dark reddish brown (10R3/4), medium-bedded. Unit contain one half inch diameter pebbles of basalt, felsite and chert randomly scattered throughout the sandstone	5	0
13.	Covered	20	0
12.	Sandstone, medium-grained, very light-gray (ON8) to pinkish gray (5YR8/1), medium-bedded	3	4
11.	Sandstone, fine-grained, dark reddish brown (10R3/4), thin-bedded and with mica on parting planes	1	9
10.	Sandstone, conglomeratic, coarse-grained, dark reddish brown (10R3/4), medium-bedded. Unit contains small quartz, chert, and basalt pebbles up to one inch in diameter	3	0
9.	Conglomerate, gradational bedding by grain size, but otherwise structureless. Basalt, felsite, quartz and chert pebbles up to 3 inches in diameter grading to 1 inch near top of unit. Matrix granular, dark reddish brown (10R3/4)	20	10
8.	Covered	30	0

Part H

	Feet	Inches

Quartz pebble conglomerate:

	Feet	Inches
7. Sandstone, fine-grained, dark reddish brown (10R3/4), laminated to thin-bedded, passing to medium-bedded near top of unit. Muscovite common on bedding planes - - - - - - - - - - - - - - - - -	4	3
6. Shale, sandy near top, greenish gray (5GY6/1), thin-bedded passing to laminated near top. Some muscovite on bedding planes - - - - - - - - - - - - - -	4	2
5. Shale, conglomeratic, well rounded milky quartz pebbles 1/2 inch in diameter grading to none near top. Matrix medium-grained, greenish gray (5G7/1), thin-bedded -	1	7
4. Conglomerate, milky quartz pebbles 1/2 inch in diameter. Matrix coarse-grained, greenish gray (5G6/1), feldspathic with thin shale lenses 1/2 to 3/4 inch in length- -	0	5
3. Conglomerate, coarse-grained with well rounded quartz pebbles up to 4 inches in diameter. Matrix light greenish gray (5GY8/1) with some rust brown staining, medium-bedded. Unit also contains grains of pyrite and marcasite - - - - - - - -	10	2
Total Exposed Thickness - - - - - - - - - -	305	3
Middle Precambrian:		
2. Covered -	20	0
Thomson Formation:		
1. Slate, light grayish black, fine-grained? - -	?	