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The Geology of the Middle Precambrian Rove Formation in northeastern Minnesota

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THE GEOLOGY OF THE MIDDLE PRECAMBRIAN ROVE FORMATION IN NORTHEASTERN MINNESOTA

by

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THE GEOLOGY OF THE MIDDLE PRECAMBRIAN ROVE FORMATION IN NORTHEASTERN MINNESOTA

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ABSTRACT

The Middle Precambrian Rove Formation, the upper part of the Animikie Group, is estimated to be at least 3,200 feet thick and is exposed between northwestern Cook County, Minnesota and the Thunder Bay district, Ontario. It is a sequence of graywacke, argillite, locally abundant intraformational conglomerate, quartzite, and carbonate rocks. The formation was deposited some time between 2.0 b.y. and 1.7 b.y. ago in a northeast-trending basin, the configuration of which probably was controlled by a pre-existing structural grain.

Detailed mapping in the 7 1/2-minute South Lake quadrangle combined with a field and laboratory study of approximately 150 other scattered stratigraphic sections provide a basis for the recognition of three informal lithic units. From oldest to youngest these are: (1) lower argillite, 400 feet thick; (2) transitional beds of interbedded argillite and graywacke, 70 to 100 feet thick; and (3) thin-bedded graywacke, as much as 2,700 feet thick.

It is concluded that the argillite and associated graywacke-sandstone and graywacke-siltstone units were deposited in moderately deep, quiet water. Repeated graywacke sedimentation units indicate sediment transport and deposition by turbidity currents. A sedimentation unit reconstructed from composite sections consists of (1) a basal conglomeratic graywacke, (2) a structureless unit that grades indistinctly into (3) a graded graywacke that is overlain by (4) a laminated graywacke, which may be modified by (5) small-scale cross-bedding, or (6) contorted bedding. Any one or several of these may be absent, but the unit is always overlain by (7) an argillite.

Post-depositional soft-sediment structures such as load casts, flame structures, clastic dikes, bed pull-aparts, overfolds, and microfaults indicate rapid deposition of Rove sediments, active bottom currents, and post-depositional deformation, implying a significant paleoslope.

A detailed analysis of paleocurrent directional indicators such as groove casts, flute casts, dendritic ridges, and cross-bedding shows that the turbidity currents had a southerly trend about perpendicular to the axis of the Rove basin. However, ripple marks, winnowed lag deposits at the tops of many graywacke beds, and possibly some festoon-type cross-bedding show that the turbidities were later modified by bottom currents that trended southwesterly or parallel to the axis of the basin.

The heavy minerals of the Rove are characterized by epidote-group minerals, apatite, sphene, and tourmaline, and are typical of older Precambrian igneous rocks now exposed north of the present Rove outcrop area.

Thin-section and X-ray analyses of 200 samples show that the graywackes consist of angular, poorly sorted grains of clastic quartz and plagioclase (An_{10}-An_{25}) embedded in an argillaceous matrix that now consists of quartz, chlorite, and muscovite. The fine-grained, fissile argillite and mudstone have the same mineralogy and microtextures as the graywacke.

Erosion subsequent to pre-Keweenawan tilting removed an unknown amount of the formation prior to the deposition of Lower Keweenawan sedimentary rocks. The intrusion of Middle Keweenawan mafic igneous rocks caused local metamorphism of the Rove Formation to a variety of mineral assemblages now assigned to the pyroxene- and hornblende-hornfels facies, but the remainder of the formation is essentially unmetamorphosed.

INTRODUCTION

The Middle Precambrian Rove Formation, about 3,200 feet thick, is exposed in northeastern Minnesota and adjoining Canada. It consists of a basal dark gray to black argillite that passes upward into a thick sequence of interbedded graywacke, siltstone, and argillite. This study of the formation was undertaken to determine insofar as possible the manner and environment of its deposition. Special emphasis was given in the study to (1) arrangement and type of lithic fill, (2) basin geometry, (3) current activity, and (4) tectonic setting.

Location and Scope of Study

The Rove Formation is exposed between a point 10 miles west of Gunflint Lake in Minnesota to the Thunder Bay district, Ontario (fig. 1). The outcrop belt is bordered on the north by the slightly older Gunflint Iron-formation and on the south by much younger rocks of Keweenawan age. Eastward the formation is covered by Lake Superior.

The study was conducted in two phases. The first, detailed mapping of the formation and associated rocks in the South Lake quadrangle, Minnesota, was completed during three months in the summer of 1962. The second phase, a more generalized stratigraphic study of the Rove in Minnesota and Canada, was completed during four months in the summer and fall of 1963. Selected exposures, many of which are accessible only by canoe, were described and measured in a field. Beds six inches thick or less were measured to the nearest inch, whereas thicker beds were measured to the nearest tenth of a foot. The orientation of all directional features was measured at each exposure. An attempt to obtain a uniform density of observation points was limited by the distribution of suitable outcrops. Large rock samples were taken in order to study bedding-types, internal sedimentary structures, and sole marks by thin-section, polished and etched surfaces, and radiographs (Hamblin, 1962). Point counts of selected thin-sections were made to determine compositions and rock types. In addition, qualitative X-ray analyses of approximately 50 fine-grained argillite samples were made.

Acknowledgments

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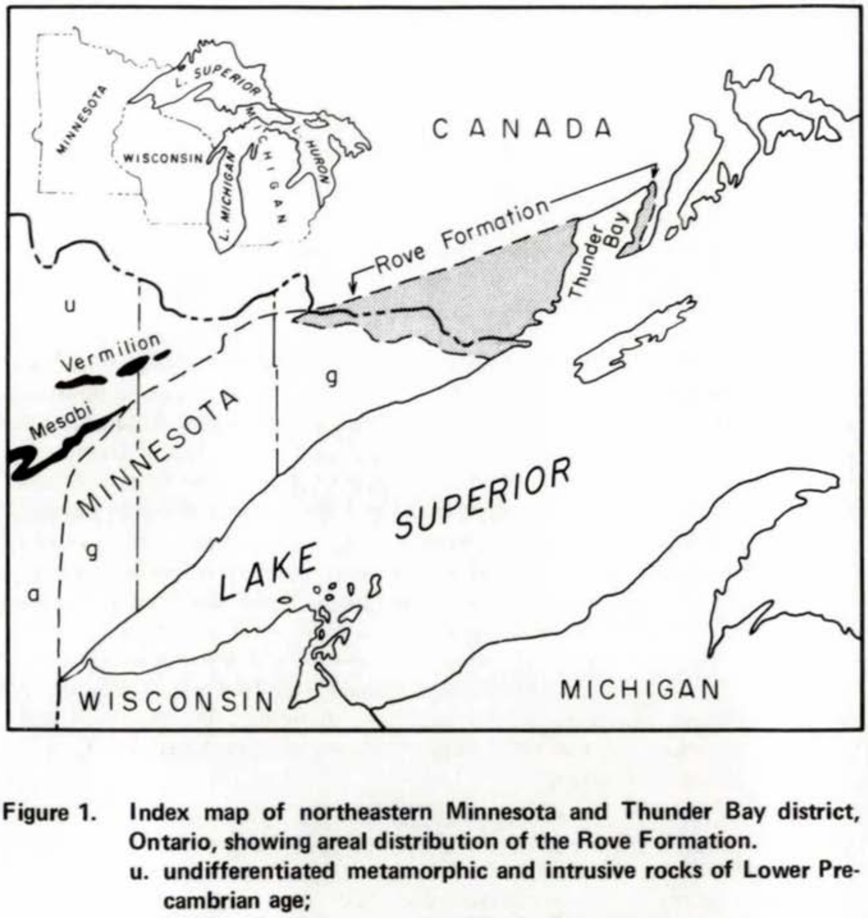


Figure 1. Index map of northeastern Minnesota and Thunder Bay district, Ontario, showing areal distribution of the Rove Formation.

- u. undifferentiated metamorphic and intrusive rocks of Lower Precambrian age;
- a. argillites and graywackes of Middle Precambrian age;
- g. gabbroic and volcanic rocks of Upper Precambrian age (Keweenawan); solid black, iron-formation.

Regional Geology

The stratigraphy of the rocks in northeastern Minnesota and the adjoining Thunder Bay district, Ontario was described previously by Tanton (1931), Grout and Schwartz (1933), Grout and others (1959), and Goldich and others (1961). The chronologic and stratigraphic sequence of rocks in this area is summarized in Table 1. Figure 2 is a generalized geologic map of northern Cook County, Minnesota. Maps of Tanton (1931), Moorhouse (1960), and Goodwin (1960) show the geology of adjoining areas in Canada.

The Lower Precambrian rocks in Cook County consist of an older dominantly volcanic succession and a younger sedimentary succession that are separated by a period of igneous intrusion (table 1). The oldest unit is the Ely Greenstone, a group of basic to andesitic volcanic rocks that was highly altered by various metamorphic processes. It was intruded in the northwestern part of the area of this report (fig. 2) by the Saganaga Granite, which consists of granodiorites, syenites, and granites. The Knife Lake Group, a thick succession of interbedded slates, feldspathic and lithic graywackes, conglomerates, and lesser amounts of igneous flows and tuffs (Gruner, 1941), unconformably overlies both the Ely Greenstone and the Saganaga Granite in this region.

All the above-mentioned rocks were intruded by massive granites, granodiorites, and diorites during the Algoman orogeny at about 2.5 billion years ago (Goldich and others, 1961, p. 68). In the area of Figure 2, this event is recorded in the structural complexity and metamorphism of the Knife Lake and older rocks.

Middle Precambrian rocks unconformably overlie the rocks of Early Precambrian age. Lawson (1930) considered the hiatus represented by this unconformity to be one of the most profound in the geologic record and suggested the name Eparchean Interval. The Animikie Group, which consists of three conformable formations, comprises the entire Middle Precambrian in northeastern Minnesota. The basal Pokegama Quartzite is a thin unit, ranging from several inches to about 10 feet thick, composed of interbedded conglomerate and quartzite. The Gunflint Iron-formation, about 330 feet thick, gradationally overlies the Pokegama Quartzite, or rests on Lower Precambrian rocks where the quartzite is absent. A radiometric age of the Gunflint – approximately 2.0 billion years (Hurley and others, 1962) – places the formation in the middle part of the Middle Precambrian. The Upper Limestone Member defines the uppermost part of the Gunflint Iron-formation, and separates the iron-rich rocks below from the argillite and graywacke of the Rove Formation above. The Rove Formation, insofar as can be determined, marks the end of the Middle Precambrian in northeastern Minnesota, but equivalent rocks elsewhere in the state were involved in a period of folding and metamorphism at about 1.7 billion years ago (Goldich and others, 1961, p. 117). This event, termed the Penokean orogeny by Goldich and others (1961), is represented in northeastern Minnesota by a period of erosion that removed an unknown amount of Middle Precambrian rock.

A small angular unconformity separates Middle and Upper Precambrian rocks in northeastern Minnesota and on Sibley Peninsula, Canada (Moorhouse, 1960). The Late Precambrian (Keweenawan) was dominantly a time of igneous activity that followed a short period of sedimentation. The Lower Keweenawan consists of a series of conglomerates, sandstones, limestones, and cherts called the Sibley Series in Canada and the Puckwunge Formation in Minnesota. These

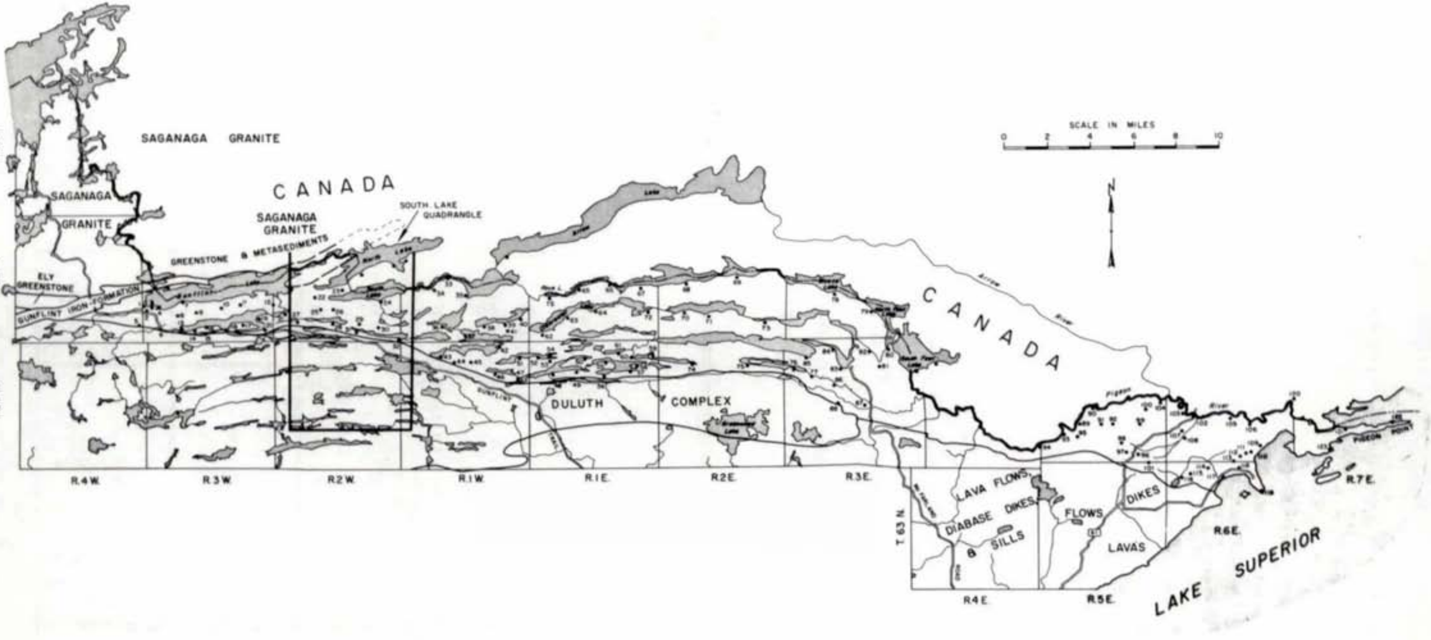


Figure 2. Generalized geologic map of northern Cook County, Minnesota (modified after Grout and others, 1959). The location of measured stratigraphic sections of the Rove Formation discussed in this report are shown by the black dots.

Table 1. Stratigraphic succession and geochronology of the Precambrian rocks in Cook County, Minnesota and Thunder Bay district, Ontario (modified from Goldich and others, 1961, p. 5; Tanton, 1931, p. 18; and Marsden, 1956, p. 23).

MINNESOTA					ONTARIO		
Era	Period - System	Major Sequence	Formation	Intrusive Rocks	Major Sequene	Formation	Intrusive Rocks
(1.1 b.y.) Late Precambrian	Keweenawan	North Shore Volcanic Grp	undivided	Duluth Complex Logan Intrusives	Kaministikwan	Osler Series	Logan Intrusives
		— — disconformity ? — —		— — — —		— disconformity —	— — — — — —
			Puckwunge			Sibley Series	
		unconformity					
(1.7 b.y.) Middle Precambrian	Huronian (?)	Animikie Grp	Rave Gunflint Pokegama		Animikie Grp.	Rove Gunflint Kakabeka	
		unconformity			unconformity		
(2.5 b.y.) Early Precambrian	Timiskamian	Knife Lake Grp.	undivided	"Algoman" Granites		"unnamed" conglomerate	Batholitic Intrusives (II)
		unconformity			unconformity		
	Ontarian	Keewatin Grp.	Ely Greenstone	Saganaga Granite	Schist Complex	undivided	Batholitic Intrusives (I)

formations range in thickness from a feather edge to about 500 feet. Middle Keweenawan basalts, rhyolites, and lesser amounts of tuff, shale, conglomerate, and agglomerate, which constitute the North Shore Volcanic Group, are at least 17,548 feet thick (Grout and others, 1959) and conformably overlie the Lower Keweenawan. Abundant tabular igneous rocks, called the Logan Intrusives, cut all of the older rocks in the area. Sill-like bodies are common in the northern and western part of the area included in Figure 2, but dikes are predominant to the southeast, around Grand Portage and Pigeon Point, Minnesota. The Duluth Complex, the youngest Precambrian rock in northeastern Minnesota intruded 1.15±.15 billion years ago, (Silver and others, 1963, p. 107) truncates the Animikian and older Keweenawan rocks. Gabbro is the most important rock type, although varieties of other rock types are locally prominent (Grout and others, 1959).

Structural Geology

The Lake Superior Syncline, the youngest major tectonic feature of northeastern Minnesota, is an elongate structural depression trending northeast-southwest. It formed at approximately the same time as the Middle Keweenawan igneous activity, and was superposed slightly to the north of the locus of the Penokean orogeny. It separates the Middle Precambrian rocks of northeastern Minnesota from those in Wisconsin and Michigan. The Rove Formation and associated rocks define the north limb of this structural basin, and dip gently 10° - 15° S. except near faults and igneous intrusives where the beds are distorted or disturbed (e.g. near the Duluth Complex, there is a fairly regular increase in dip to a maximum of 60°).

The structural relationships in this area are further complicated by the many tabular, concordant Logan Intrusives in the Rove Formation. The structure of the South Lake area (fig. 3) is typical of most of the area of Figure 2. Many of the smaller dikes and sills merge along strike into a single large body, which may again split into several smaller dikes or sills. Because such branching results in isolated, elongate "islands" of sedimentary rock between igneous masses, it is difficult to trace any stratigraphic horizon or marker-bed in the Rove Formation over any great distance. A few faults with small throw have been noted at several Minnesota localities; however, many faults have been reported in Canada (Moorhouse, 1960; Goodwin, 1960) near the hinge-line on the north edge of the Lake Superior Syncline. Where these faults cut both the Rove Formation and the sills, it is possible to determine the amount of throw, but it is difficult to recognize their presence at all where they displace only the Rove Formation.

Minor folds exist in narrow zones near intrusives, where it is likely that the sedimentary rocks were folded under stresses associated with intrusion of the Logan intrusives. There are several broad, open anticlines and synclines in the valley of Stump River (sec. 10, T. 64 N., R. 3 E.). However, such structures appear to be exceptional.

Rock Nomenclature

Seventeen sandstone classifications were proposed in the geological literature of North America between 1940 and 1960 (Klein, 1963, p. 555). Because there is no general agreement on terminology, it is necessary to define the rock names used in this report.

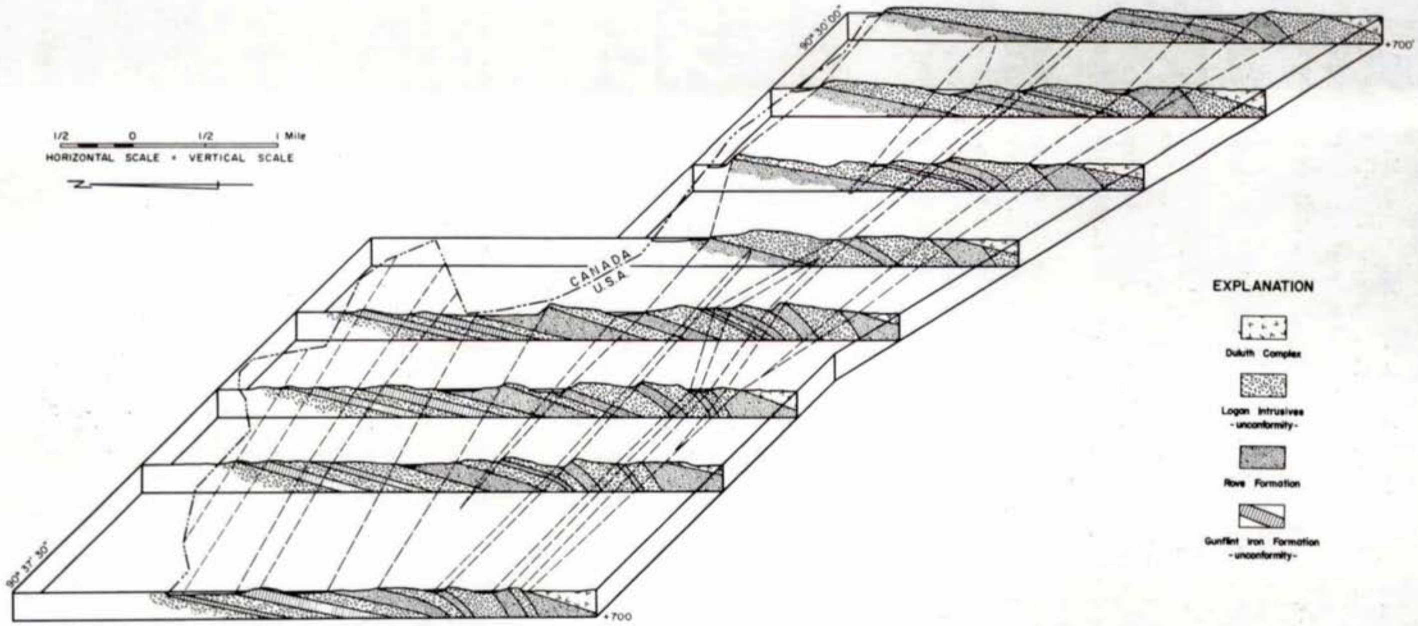


Figure 3. Structural block diagram of part of the South Lake quadrangle, T. 64 and 65 N., R. 2 W.

The rocks of the Rove Formation consist of admixtures of four components listed here in order of decreasing abundance: (1) layer silicates, (2) quartz, (3) feldspar, and (4) rock fragments. One classification whose terminology is consistent with that of previous workers and that accounts for all possible combinations of these four end members was proposed by Pettijohn (1957, p. 292), as shown in Figure 4. The classification, as used here, is purely descriptive and implies no particular depositional conditions.

Argillite as used here is a mudstone or shale hardened by recrystallization (Grout, 1932, p. 269).

Graywacke refers to a rock characterized by (1) grains of detrital quartz and feldspar set in a prominent to predominant clay-size matrix which may have been converted to chlorite and muscovite during low-grade metamorphism, (2) dark color, (3) toughness and induration, (4) angular detrital components, and (5) rock fragments in minor to abundant quantities.

Feldspathic quartzite and orthoquartzite have more silt- and sand-size material than graywacke and a relatively smaller clay-size fraction. It is obvious that these rock types grade into each other and that one sedimentary unit may therefore contain several lithologic types not easily divisible in the field. Where possible, nomenclatural errors caused by such gradations were later corrected by the study of thin-sections.

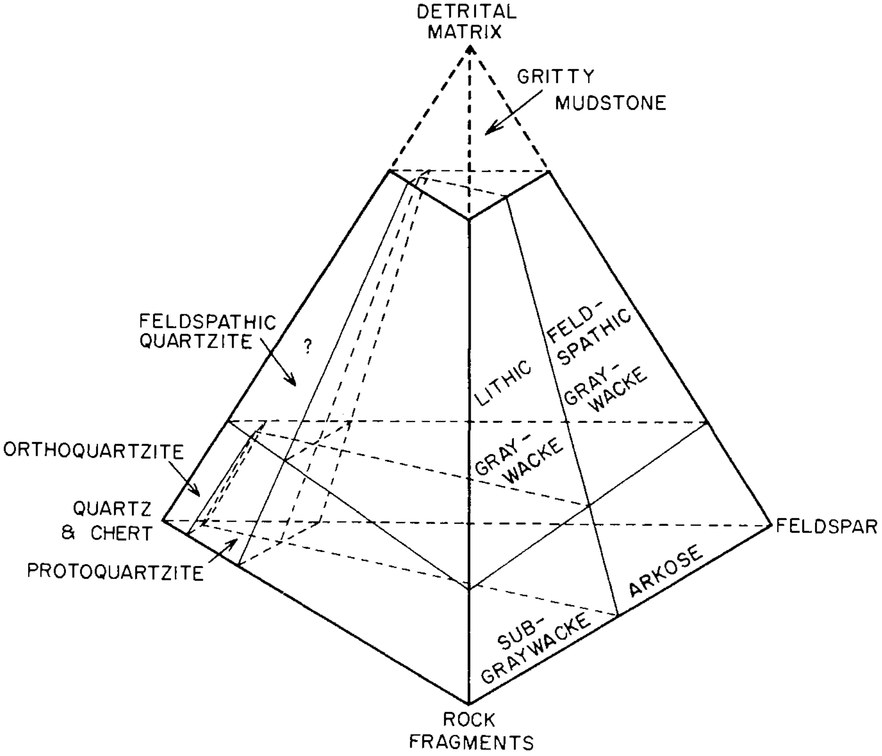


Figure 4. Sedimentary rock classification (after Pettijohn, 1957, p. 292).

STRATIGRAPHY

Introduction

Nomenclature and Correlation

Exposures of "slate", graywacke, and minor amounts of quartzite in northern Cook County, Minnesota were first described by Bell (1873, p. 93), who correlated them with rocks of the type Animikie around Thunder Bay, Ontario (Hunt, 1873). The term Animikie first was used in Minnesota for a formation with three members (Grant, 1899): (1) a basal "taconite member", (2) a middle "black-slate member", and (3) an "upper graywacke-slate member", which was correlative with similar rocks exposed on the Mesabi range in north-central Minnesota (Irving, 1883). Clements (1903) raised the Animikie to group status and named the intermediate and upper members the Rove Slate. Because much of the formation is argillite rather than slate and contains graywacke and quartzite, the name was changed by Grout and Schwartz (1933, p. 3) to Rove Formation.

The age of the Animikie Group has long been a problem. Logan (1863) believed that the type Animikian rocks were correlatives of rocks beneath the Huronian type section (Murray, 1857) on the north shore of Lake Huron. Irving (1883), however, equated the Animikie directly with the original Huronian, and the U.S. Geological Survey (Van Hise and Clements, 1901; Van Hise and Leith, 1911; and Clements, 1903) accepted this correlation.

However, because A. Winchell (1890) and Allan (1920) recognized two major unconformities in the Huronian of Wisconsin, Leith and others (1935) placed each formation of the Animikie Group in Minnesota in a different time unit, despite the lack of evidence indicating the presence of unconformities.

Because of the nomenclatural confusion, Allan (1920) suggested that the term Animikie be dropped. However, Grout and others (1951) and James (1958) advocated dropping the term Huronian for these rocks because the Animikie rocks, especially in Minnesota, clearly are correlative with the original Animikie locality and not with the Huronian type locality.

The Animikie Group comprises the entire Middle Precambrian in Minnesota, the duration of which was 800 million years (Goldich and others, 1961). However, James (1958) complicated the nomenclature by introducing the term Animikie Series to include all of the Middle Precambrian rocks in the Menominee district, Michigan. The two terms are not equivalent. The Animikie Group is correlative with only the middle part of the Animikie Series of James (1958).

Type Section

A type section has never been described for the Rove Formation; however, Clements (1903) specified the south shore of Rove Lake as the type area. Consequently, an exposure within the type area, located 800 feet south and 100 feet west of the northeast meander corner of sec. 29, T. 65 N., R. 1 E., Cook County, Minnesota is here designated as the type section. It is noted as "TS" on Figure 2. The measured section is given in Table 2 (dry, fresh rock color designations are after Goddard, Rock Color Chart, 1963 printing).

Table 2. Type section of the Rove Formation.

		Unit No.		Thickness in feet
		47	Covered	Varies
Keweenawan	LOGAN INTRUSIVES	46	Gabbro, diabasic, greenish-black (5G2/1), fine- to medium-grained; composed of plagioclase and pyroxene with minor magnetite-ilmenite and pyrite. Top not exposed.	40.0
		45	Basalt, black (N1), fine-grained; slightly porphyritic with phenocrysts of glassy-appearing plagioclase 1/16" in length; appears dense and breaks with a conchoidal fracture.	0.2
Animikie	ROVE FORMATION (TYPE SECTION)		ROVE FORMATION (ANIMIKIE) TYPE SECTION	
		44	Hornfels, grayish-black (N2), fine-grained, structureless; no megascopically visible grains except pyrite.	0.5
		43	Graywacke, grayish-black (N2), thin-bedded, fine-grained; some angular plagioclase visible; minor pyrite.	3.0
		42	Graywacke, medium dark gray (N4), thick-bedded, fine- to medium-grained; graded.	4.0
		41	Argillite, black (N1), fissile, very fine-grained; minor pyrite or pyrrhotite.	0.1
		40	Graywacke, light gray (N7), structureless, medium-grained; unit grades into unit 41.	1.0
		39	Graywacke, medium dark-gray (N4), thin-bedded, fine-grained; unit contains some argillaceous partings 1/16" thick.	0.4
		38	Argillite, black (N1), thin-bedded, fine-grained; minor pyrite.	0.3
		37	Graywacke, medium dark gray (N4), structureless medium- to coarse-grained; visible quartz and chlorite with minor plagioclase.	0.7
		36	Argillite, black (N1), fissile, very fine-grained; unit contains some thin silty laminations and is poorly graded.	0.4
		35	Graywacke, grayish-black (N2), structureless, medium-grained; irregular top and bottom; sole marks; muscovite common on parting planes; minor pyrite.	2.5
		34	Graywacke, grayish-black (N2), thin-bedded to fissile, very fine-grained.	2.5
		33	Graywacke, medium dark gray (N4), thin-bedded, fine-grained; cross-bedded.	0.3
		32	Graywacke, black (N1), thick-bedded, fine-grained; unit contains some thin argillaceous partings.	6.0
		31	Graywacke, dark gray (N3), thick-bedded, fine-grained; composite; graded.	1.0
		30	Graywacke, dark gray (N3), thin-bedded, very fine- to fine-grained; graded.	0.5
		29	Graywacke, dark gray (N3), thick-bedded, medium-grained; unit very irregular.	0.8
		28	Graywacke, black (N1), thin-bedded, fine-grained.	1.0
		27	Graywacke, black (N1), fine- to medium-grained, graded; unit grades into unit 28.	4.0
		26	Graywacke, medium gray (N5), thin-bedded, fine-grained.	1.5
		25	Graywacke, black (N1), very fine- to coarse-grained; graded; unit has a very irregular sole.	6.0

Table 2 (Continued)

		Unit No.		Thickness in feet
Animikie	ROVE FORMATION (TYPE SECTION)	24	Argillite, black (N1), fissile, fine-grained; unit very irregular.	0.1
		23	Graywacke, medium gray (N5), thin- to medium-bedded, fine-grained; graded; pyrite common, limonite stains on parting planes.	2.0
		22	Graywacke, dark gray (N3), fissile, very fine-grained; graded laminae.	0.3
		21	Graywacke, medium gray (N5), structureless, fine- to medium-grained; upper 1/2 to one inch is quartzite.	3.0
		19	Argillite, black (N1), fissile, very fine-grained; unit very irregular.	0.1
		18	Graywacke, black (N1), thin-bedded, fine-grained; graded.	0.4
		17	Graywacke, black (N1), massive, fine-grained, graded; unit grades into unit 18.	1.5
		16	Graywacke, black (N1), thin-bedded, fine-grained, graded; grades into argillite, black (N1), fissile, very fine-grained.	0.5
		15	Graywacke, dark gray (N3), structureless, fine-grained.	2.0
		14	Argillite, black (N1), thin-bedded, very fine-grained; graded into thin laminae.	0.5
		13	Graywacke, medium dark gray (N4), thick-bedded, fine-grained; graded.	2.0
		12	Argillite, black (N1), thin-bedded, very fine-grained.	0.3
		11	Graywacke, medium dark gray (N4), thick-bedded, medium- to coarse-grained; graded; visible quartz, plagioclase, and muscovite.	1.0
		10	Argillite, black (N1), fissile, very fine- to fine-grained; graded laminae.	1.0
		9	Graywacke, medium dark gray (N4), structureless, fine- to medium-grained; visible quartz, plagioclase, biotite, magnetite; top of unit quartzite, medium light-gray (N6), fine-grained, moderately sorted.	7.5
		8	Graywacke, black (N1), thin-bedded, fine-grained.	0.5
		7	Quartzite, pinkish gray (5YR8/1), structureless, medium- to coarse-grained; moderately well sorted.	2.0
		6	Graywacke, medium dark gray (N4), thin-bedded to fissile, fine-grained; graded.	0.3
		5	Graywacke, black (N1), thin-bedded, fine-grained; graded.	0.1
		4	Graywacke, dark gray (N3), thick-bedded; fine- to medium-grained; graded; unit very wavy and irregular.	1.0
		3	Graywacke, black (N1), thin-bedded, fine-grained; in part argillaceous.	2.0
		2	Graywacke, black (N1), medium-bedded, fine-grained, graded; some visible plagioclase, quartz and pyrite. Bottom of unit not exposed.	4.0
		1	Covered	Undetermined.
			Total exposed thickness of Rove Formation	70.1

Thickness

Although it is not possible to observe the entire Rove Formation at a single locality some data can be cited that establish limits on its thickness.

The formation thins rapidly north and east of Fort William, Ontario, Canada. On Sibley Peninsula, 800 feet of Rove are exposed above lake level, but 20 miles northeast at Pass Lake the Rove is but 130 feet thick. Four miles north of Pass Lake, the formation is 20 feet thick. The thinning has been attributed to pre-Keweenawan erosion.

Near Fort William the formation crops out 800 feet above Lake Superior, and about 3 miles to the southeast a drill hole penetrated 1,280 feet of the formation below lake level (Tanton, 1931, p. 36). Therefore, the total thickness in this area is presumably more than 1,280 feet; it may be more than 2,000 feet, but the section may be repeated because of faulting (Moorhouse, 1960).

Goodwin (1960, p. 44) reported that in the vicinity of Arrow Lake, Canada, the Rove is " . . . several thousand feet . . . " thick. My detailed structural and stratigraphic studies in the South Lake area south-west of Arrow Lake, indicate that in this area the sedimentary rocks are about 1,900 feet thick.

Determination of thickness is complicated by the many Keweenawan sills and dikes. No evidence is now available indicating how much, if any, Rove Formation was removed by assimilation during the intrusion of these rocks. If, however, dilation is assumed and the sills are graphically removed, the total thickness is calculated as 3,200 feet. This value is undoubtedly excessive because of the probable presence of thin, undetected sills in covered portions of the outcrop area. In addition, any estimate of a thickness represents only a minimum because an unknown amount was removed prior to Keweenawan time.

A scarcity of extensive, continuous exposures makes it impossible to construct more than a general picture of Rove stratigraphy. The exposed sections, which were measured in detail, represent only a small part of the formation. Small, limited outcrops with only a few or no key beds (or zones) make it virtually impossible to correlate from exposure to exposure. Moreover, differences between successive beds in most of the formation are so slight that only the most favorable conditions of exposure permit one to establish the stratigraphy in detail.

Approximately 150 incomplete sections were measured and described. Of these, 120 are located in Minnesota (fig. 2).

A longitudinal stratigraphic section with the sills removed was reconstructed by projecting measured sections up dip onto an imaginary vertical plane that parallels the map contact between the Gunflint and Rove Formations. The sections so projected fall into their general stratigraphic position relative to an arbitrarily straightened base line representing the top of the Gunflint Formation (fig. 5). The short, black lines on the figure represent the measured sections that were projected onto a vertical plane. Three informal lithologic units are recognizable, but exposures are too discontinuous to reveal all the details of their relationships. Although the succession is reasonably well established, the thickness of units in the upper part of the formation is not known definitely. Most outcrops are so small that only one lithologic type is exposed, but where exposures showing several lithologic units can be found, the contact is generally graditional, making distinction difficult. The three units from bottom to top are: (1) lower argillite, (2) transition sequence, and (3) thin-bedded graywacke. It should be emphasized that none of the rock types are restricted to any one unit. The distinction between units is therefore based on the predominant lithologic type and on variations in other features such as bedding characteristics.

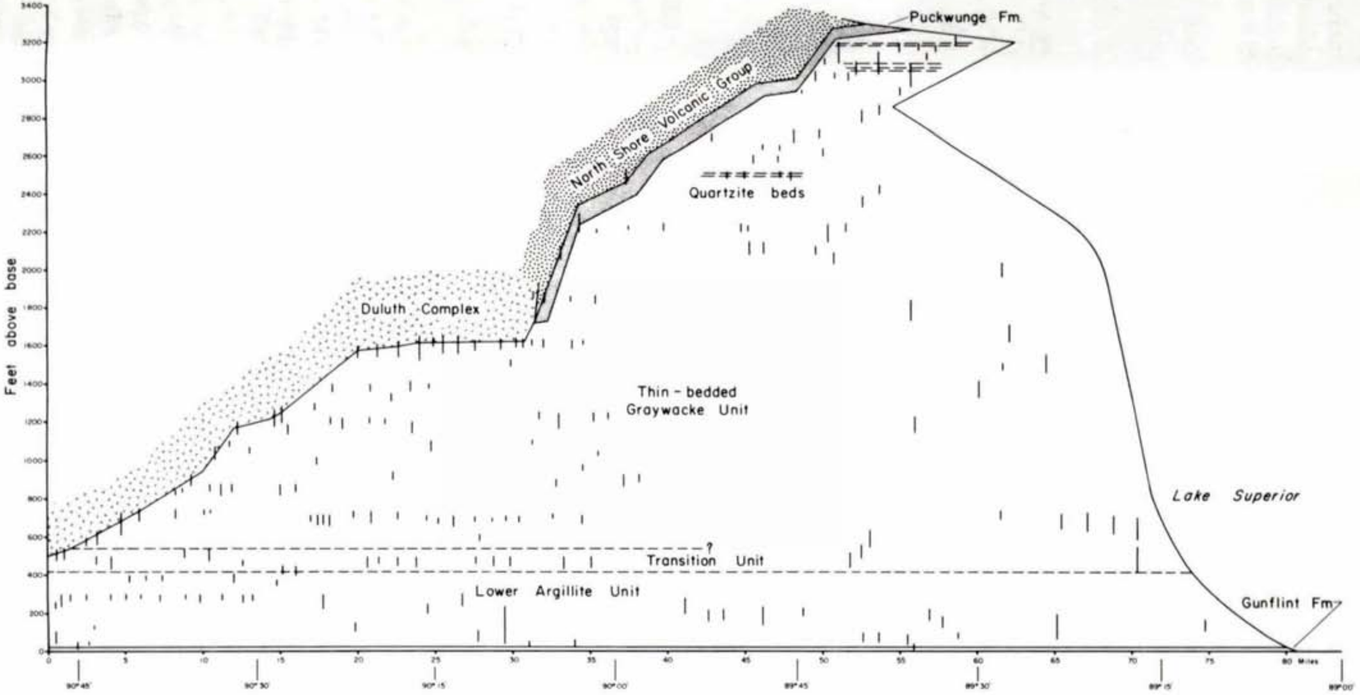


Figure 5. **Composite longitudinal section of the Rove Formation, Cook County, Minnesota.**

Lower Argillite Unit

Definition, Distribution, and Thickness

The lower argillite unit is exposed in a narrow belt along the north edge of the main outcrop area. It was first recognized by Grant (1899), who termed it the " . . . middle black-slate member of the Animikie Formation . . . " Grout and Schwartz (1933) did not consider this unit to be recognizable over a wide area and therefore eliminated its formal status. However, because their work was confined to Minnesota, and because the basal unit is exposed mainly in Canada, they were unable to trace it very far and confirm its presence.

Although both the top and bottom of the unit are gradational, and nowhere is it completely exposed, stratigraphic information from the South Lake quadrangle indicates that the unit is approximately 400-500 feet thick. It thickens slightly to the west and thins slightly to the east in Canada.

The unit includes the black fissile argillites that conformably and gradationally overlie the Upper Limestone Member of the Gunflint Iron-formation and which grade into thicker and coarser-grained graywacke beds of the overlying transitional unit. It is well exposed at many localities (e.g. localities 1, 22, 23, and 33; fig. 2) in Minnesota. The unit is also well exposed in Canada at Mink Mountain, Sun Mountain, Stanley Hill, Slate River, and Sibley Penninsula.

Lithologic Character

The argillites are predominantly black (N1) to grayish black (N2). Some beds on Sibley Peninsula, however, are brown (5YR2/2), green (5G2/1), or red (10R2/2). Generally these are thin and unimportant, but Tanton (1931, p. 37) reported a red argillite bed 20 feet thick. In addition to the fine grain-size of the argillite, the black color is imparted by finely divided carbonaceous material and pyrite. Apparently the red color is due to the oxidation state of the iron and the green to chlorite. The argillities characteristically have remarkably regular fissility parallel to the bedding, which is best observed on slightly weathered surfaces (fig. 6). The lower argillite unit is composed of three predominant rock types, each having a characteristic kind of bedding: (1) light gray, graded, argillaceous siltstone – including some very fine-grained graywackes – that mostly has a bedding characterized by paper-thin laminae; less commonly argillaceous siltsone occurs in beds as much as two feet thick, some having small-scale cross-stratification in the upper part; (2) dark gray, silty argillite, mostly thinly laminated but having a few beds about three feet thick; (3) black, carbonaceous, thin-bedded argillite, most beds being less than one inch thick. These three types generally occur in a definite order as follows: a lower silty bed is overlain by silty argillite and this in turn by a carbonaceous layer, though one or more may be absent. Inasmuch as siltstone and very fine-grained graywacke are almost completely absent in the lower part of the unit, the rock generally is composed of alternately bedded dark gray and black argillite. However, stratigraphically higher beds are thicker and contain more silt-sized particles.

One of the few known exposures of coarse-grained graywacke near the base of the unit is in a road cut along the Canadian National Railroad on Sibley Peninsula. Large, angular flakes of white, detrital muscovite cemented by carbonate are randomly oriented in a medium-grained matrix of quartz, feldspar, and muscovite.

Limestones

Limestone lenses and irregular beds of various thicknesses and configurations are common in the lower part of the unit (fig. 6). They are at most three feet thick and range from black (N1) to light gray (N7). Some beds are very pure and others contain large amounts of argillaceous material; the darker colors indicate a higher content of insoluble residue.

Concretions

Calcareous concretions as much as 10 feet in diameter also characterize the lower part of the unit (fig. 7). They have been described briefly by Logan (1863, p. 69), Tanton (1931, p. 40), and Grout and Schwartz (1933, p. 20). Moorhouse (1963, p. 43) also figured and described many occurrences. They are well exposed in a quarry along Pass Lake Road on Sibley Peninsula and in cliffs along the banks of the Slate River in Canada. They are irregularly spaced within individual beds. In some exposures they are separated from one another by many feet; in others, they are closely packed or intergrown composite forms of two or more simple types.

The bedding of the adjacent argillite can be traced through the concretions, indicating that they grew by the concentration of carbonate minerals in local areas. Near the top and bottom of a concretion the argillite beds are bent, indicating that the carbonate was precipitated prior to compaction of the argillite and that the bedding was later molded around the structure, and to a lesser extent, that the concentration of carbonate was accompanied by an increase in volume and consequently a dilation of the argillite.

The concretions are generally shaped like oblate spheroids, curling stones, or discs somewhat thicker in the middle than at the edges (fig. 7). They generally have smooth surfaces, but some are ribbed with raised structures that join along the rim. Most are fairly symmetrical about a plane perpendicular to their short axis, but some are flatter on either their upper or lower surfaces.

The carbonate – either calcite or dolomite – is very fine-grained, but a few large crystals are present. There is a proportional relationship between the size of the clastic particles and the size of the individual carbonate grains, implying that the original porosity of the argillite controlled the growth of the calcite.

Finely disseminated pyrite is common in the silt-rich layers within the concretions. It also occurs as thin, badly fractured beds, or as egg-shaped nodules up to three inches in diameter which grew in place as evidenced by the fact that argillaceous laminae can be traced through and around them.

Cone-in-cone structure is common at the borders of many concretions. The cones are either calcite or dolomite in which the structure is accentuated by thin layers of clay.

Septarian structures or contraction cracks have been reported in some concretions (Tanton, 1931, p. 42), but none were observed in this study.

Transition Unit

Definition, Distribution, and Thickness

The transition unit is a sequence of interbedded argillites and graywackes in which the graywackes become thicker and more abundant upward. As the name implies, it is transitional between fissile argillites below and graywackes above. The Rove type section was described from this unit. Other excellent sections are exposed in Minnesota along the shores of Mountain and Clearwater

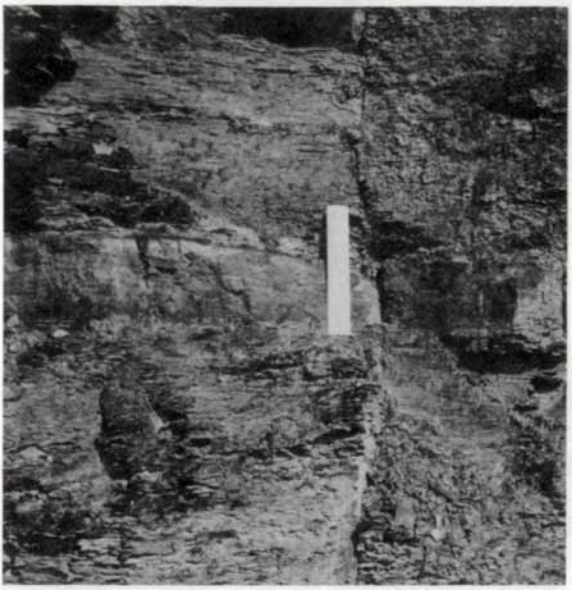


Figure 6. Typical bedding and limestone lenses in the lower argillite unit. The ruler is six inches long. Quarry on Pass Lake Road, Sibley Peninsula, Ontario.

Figure 7. Typical carbonate concretion. Ribs along the margin consist of cone-in-cone structures. The hammer provides the scale. Quarry on Pass Lake Road, Sibley Peninsula, Ontario.

Lakes near the International Boundary. The base of the unit is defined as that place where thick graywacke beds become more abundant than argillite beds, and its top is marked by a relative change from argillite to argillaceous siltstone.

The thickness of the unit differs from place to place because of its gradational character. Approximately 60 feet is exposed near Gunflint Lake, where the unit is truncated by the Duluth Complex. It is 90 feet thick in the South Lake quadrangle, but farther east it is about 100 feet thick. The unit has not been traced for any distance eastward into Canada.

The unit is characterized by an even and regular stratification. Individual beds appear to be slightly undulatory and fairly constant in thickness. Contacts between beds are quite distinct.

Lithologic Character

The graywackes are mostly thin- to medium-bedded. They do not possess fissility parallel to bedding, and the texture of each bed, either in whole or in part, is much coarser-grained than that of the argillite. Graywacke beds range in thickness from less than six inches to more than 10 feet. Most of the graywackes are dark gray (N3) or medium dark gray (N4). They are composed of angular clastic quartz and feldspar in a matrix of muscovite and chlorite.

Many of the thick beds in this unit are composed of graywacke which is overlain by feldspathic quartzite. The feldspathic quartzite is transitional with the graywacke, and is of variable thickness. The top of the bed is irregular and rarely grades into the overlying bed. The quartzite appears to be a lag deposit formed by the winnowing of clay-size material by bottom currents.

Argillite beds ranging in thickness from less than two inches to more than 10 feet are interbedded with the graywackes. The argillite is similar to that in the lower argillite unit except for: (1) a general increase in the size and amount of the quartz-feldspar fraction with a corresponding development of thicker beds and, (2) a lighter color imparted by the presence of more silt-size detritus and a relative lack of graphitic or carbonaceous material.

Thin-bedded Graywacke Unit

Definition, Distribution and Thickness

The thin-bedded graywacke unit is exposed throughout the outcrop area of the formation. It is about 100 feet thick near Gunflint Lake, where it is truncated by the Duluth Complex, but thickens eastward to a maximum of about 2,700 feet. Among the best exposures in Minnesota are those at localities 16, 17, 28, 48, 49, 102, 103, and 117 (fig. 2). Easily accessible exposures also are found in the vicinity of Port Arthur-Fort William, Canada at Mt. McKay, Mt. Goffrey, Mt. McRay, and Mt. McQuaig.

The unit consists of fine-to-medium-grained, light gray (N7) to dark gray (N3) graywacke interbedded with thin to thick beds of silty argillite and argillaceous siltstone. The graywackes contain many features indicative of a turbidite deposit. They are: (1) pronounced lateral continuity of individual beds, (2) sharp-bottom contacts and gradational tops, (3) generally well-defined internal structures, and (4) sole markings showing consistent directional characteristics.

The upper 700 feet of the unit is characterized by the presence of thin to thick quartzitic sandstone beds. They are particularly well-exposed near Grand Portage Bay and at High Falls (localities 117 and120, fig. 2) near the International Border.

Lithologic Character

The predominant rock type of this unit is graywacke as in the transitional unit, but many subtle differences in bedding, grain size, and sedimentary structures serve to distinguish it from the underlying beds.

Individual graywacke beds generally are thin, ranging from less than one to five feet, as shown in Figures 8 and 9. The basal part of each unit is typically structureless. The sole of each bed is sharp and rarely is marked by a thin intraformational conglomerate. The conglomeratic pebbles are mostly angular fragments of fine-grained, argillaceous material derived from a rock-type like that of the underlying bed. Most of the fragments are only a few inches in diameter, but Tanton (1931, p. 39) reported boulders having diameters of as much as three feet at one locality. These large boulders are slightly rounded and have a bedding that is only slightly askew, implying that they have not been moved very far. The matrix consists of fine- to coarse-grained, angular fragments of quartz and plagioclase floating in an intergrowth of muscovite and chlorite. Directly overlying the structureless parts of the bed are graded rocks, which reflect a decrease in the amount and size of the sand- or silt-size detritus. Generally, the uppermost part of the bed is thinly laminated and sharply truncated by the massive base of a repeated sequence. The exposure at McFarland Lake (fig. 2, locality 83) typically exhibits such a cyclic repetition.

Cross-bedding, clastic dikes, bed pull-aparts, load casts, and various sole marks are other sedimentary structures that have been observed.

The quartzites, in the upper part of the unit, are more-or-less feldspathic, and generally gray (N7), white (N9), or pinkish gray (5YR8/1). They occur in thick beds that for the most part have sharp soles and tops, but several units grade into overlying argillite. The thicker quartzites form topographic ridges like those formed by dikes and sills, in contrast to the argillites and graywackes which form depressions. These quartzites differ from those in the underlying unit by being thicker, much coarser-grained, lighter in color, and noticeably vitreous. Many were originally white but took on other colors during cementation or metamorphism.

Many quartzites are structureless, but others have curved bedding surfaces with a peculiar parting that vaguely suggests cross-bedding.

Typically, the quartzites are medium- to coarse-grained, well sorted, and somewhat graded. Many of the original grains were angular, and others were rounded, but all grains have been modified by secondary overgrowths and recrystallization to a sutured, interlocking mosaic texture. The original grains are recognizable as ghosts because they contain many minute inclusions not present in the overgrowths.

Concretions

Calcite concretions that range in diameter from less than one-half to more than two feet are common in the upper parts of certain quartzite beds. They are composed of fine-grained, rhombohedral grains of calcite having well developed cone-in-cone structures. Upon weathering they generally form small depressions surrounded by slightly higher rims of iron oxide.

Dolomite concretions with well-developed cone-in-cone structures occur at several levels in thinly laminated rocks. However, they are neither as large nor as consistently confined to any one horizon as are those in the lower argillite unit.

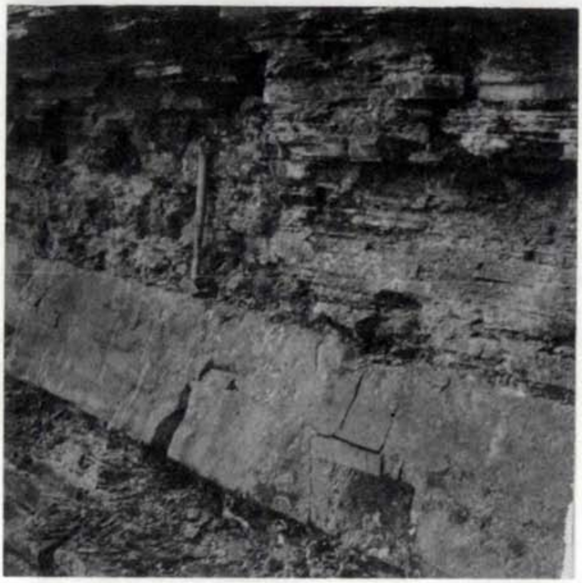


Figure 8. Graywacke sedimentation unit interlayered with argillite and argillaceous siltstone. Thin-bedded graywacke unit. Clearwater Lake, section 27, T. 65 N., R. 1 E.

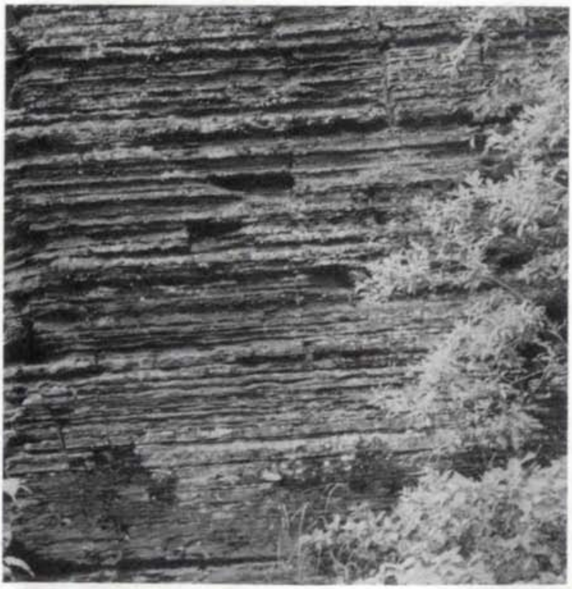


Figure 9. Typical exposure of the thin-bedded graywacke unit, showing successive alternations of fine-grained, graded graywacke and argillaceous siltstone. Pigeon River at the Tunnel, section 19, T. 64 N., R. 6 E.

SEDIMENTARY STRUCTURES

A variety of sedimentary structures are found in the Rove Formation. Because most of the structures summarized in Table 3 have not been recognized previously, and because they represent the key to a depositional interpretation, they are described here in the approximate order of their importance.

Internal Bedding Structures

The most distinctive feature of the Rove Formation is the thin intercalation of argillite and graywacke. This type of layering has a distinctive appearance in outcrop, particularly because the more resistant graywacke weathers in relief. Most graywacke beds are remarkably uniform in thickness over the several hundred feet lateral distance that they can be observed. Many of them have irregular but well-defined bases; only rarely do they grade into the overlying fine-grained units.

Table 3 – Sedimentary structures in the Rove Formation

Intrastratal Structures

1. Internal Bedding Structures
   A. Structureless Bedding
   B. Laminated Bedding
   C. Graded Bedding
      a. Simple
      b. Composite
   D. Cross-bedding
      a. Festoon
      b. Planar
   E. Complex Bedding
      a. Convolute Bedding
2. Post-depositional Soft-Sediment Deformation Structures
   A. Contorted Bedding (Slumping)
   B. Pull-aparts
   C. Clastic Dikes
   D. Flame Structures
   E. Overfolds
   F. Load Pockets
   G. Micro-faults
3. Grain Lineations

Interstratal Structures

1. Sole Marks
   A. Groove Casts
   B. Flute Casts
   C. Dendritic Ridges
2. Ripple Marks

Graywacke beds rarely exceed five feet in thickness and most are less than 12 inches thick; invariably they are graded and laminated. In contrast, the very fine-grained argillites have variable bedding characteristics; in the lower part of the formation they occur in beds up to 30 feet thick, whereas in the upper part they vary from thin laminae to beds several feet or more thick.

In describing the bedding of the Rove, it is convenient to make the distinction between a bed and a sedimentation unit. The term bed, as used here, is a layer of essentially the same lithology or structure separated from a layer of different lithology or structure above and below by bedding surfaces. Otto (1938, p. 575) introduced and defined the term "sedimentation unit" as a "... thickness of sediment which was deposited under essentially constant physical conditions." Jopling, however, (1964, p. 165-172) pointed out that many "sedimentation units", while the result of a single depositional episode, are deposited under varying rather than constant physical conditions, and the latter context is preferred in this paper. A single graywacke bed, with its associated structures, represents an environment considerably different from that of the underlying and overlying argillite. Typically, an individual sedimentation unit contains several kinds of internal bedding structures. Those most commonly seen include graded bedding, laminated bedding, cross-bedding, convolute bedding, and structureless bedding. At many localities, only graded or structureless bedding is visible on fresh surfaces. Slight weathering enhances internal structures, but intense weathering tends to obscure them. Moreover, low grade metamorphism preserves structures, but higher grade metamorphism tends to obliterate them. The types of bedding structures present in the Rove Formation are discussed below.

Structureless Bedding

Structureless bedding refers to beds or parts of beds that have homogeneously distributed grains and an absence of visible internal structure. Close examination of beds that appear to be structureless commonly reveals faint laminae, especially when radiographs of thin slices are studied. Structureless bedding commonly passes upward without interruption into graded or laminated bedding.

Laminated Bedding

Laminae, alternately rich and poor in coarse detritus, are characteristic of the argillites and argillaceous siltstones, and are common in the upper parts of graded graywacke beds. Most of the laminae are less than one mm thick, but range from 0.03 to several mm thick. Laminae composed of coarse particles are thicker than those composed of fine grains. An example of laminated bedding is illustrated in Figure 10. All the laminae are parallel to observable bedding. They commonly can be traced through an entire exposure except where truncated by cross-bedding or, more rarely, by convolute or contorted bedding.

Graded Bedding

Graded bedding is a common internal bedding structure in the Rove Formation. The grading in sandstone units is expressed by a notable decrease in both size and amount of coarse detritus from bottom to top with a clay-sized fraction equally mixed throughout the unit. The coarsest fraction in most beds is fine sand. The lower part of a sandstone bed is sharply defined by a coarser texture and lighter color, which is especially noticeable on slightly weathered surfaces of well indurated rocks (fig. 11). The sandstone beds rarely grade into overlying argillite beds.

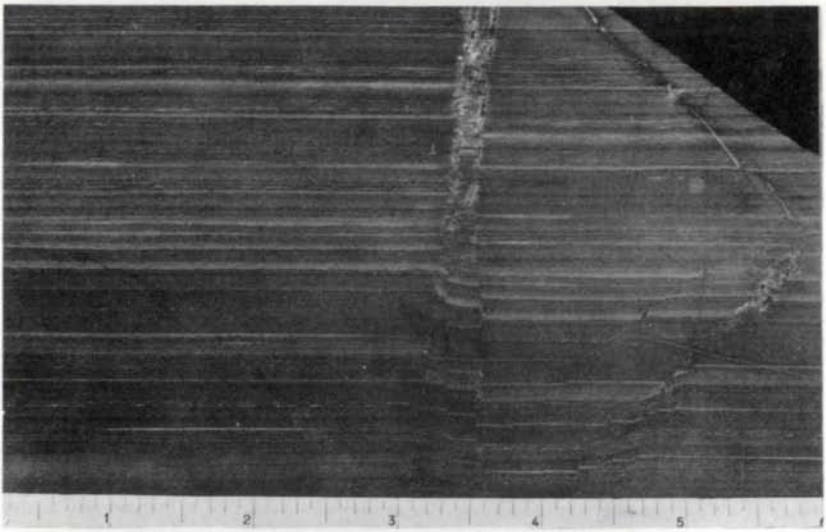


Figure 10. Polished slab of thinly laminated siltstone and argillite. Several mineralized micro-fault planes are visible. Section 35, T. 64 N., R. 6 E.

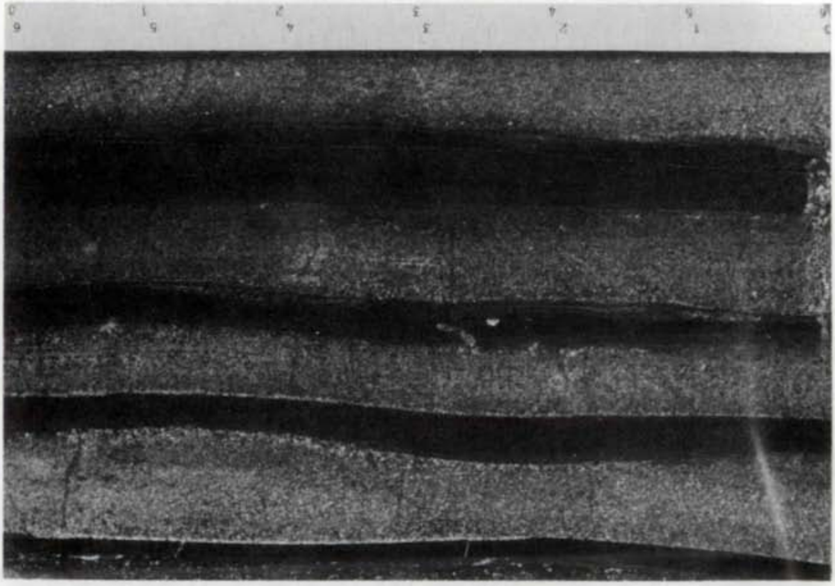


Figure 11. Polished slab of graded graywacke and interbedded argillite. Thin-bedded graywacke unit. Mt. Josephine area, section 34, T. 64 N., R. 6 E.

Most siltstones also are graded, but the gradation is visible only in thin-sections or polished sections. The siltstone beds have sharply defined lower contacts, but in contrast to the sandstones show less distinct upper contacts. Although the mean grain-size decreases upward, as in the graded sandstone, there is no decrease in amount of the silt-size fraction.

Differences in the appearance of grading in the Rove Formation result from various combinations of graded types. Delayed grading and interrupted grading (Walton, 1956, p. 263) are common, and composite or multiple graded units (Kuenen, 1953) in which individual graded units are repeated without intervening argillite layers occur in beds as much as three feet thick.

Cross-bedding

Cross-bedding in the Rove Formation may be defined as "... a kind of stratification in which the beds are deposited in varying directions to the original plane..." (Bouma, 1962, p. 137). Although there have been many attempts to classify types of cross-bedding and to devise appropriate terminology, confusion still exists concerning the nature and origin of the structure. Potter and Pettijohn (1963, p. 70) recognize only two basic types, both of which occur in the Rove Formation.

Festoon cross-bedding (Knight, 1929), the most common type, generally occurs in lenticular troughs that were cut into previous deposits. The axes of these troughs were parallel to the direction of current flow, and the troughs are filled by laminae that are concave upward (fig. 12). Troughs in the Rove Formation are generally less than five inches wide and range from less than one-half to more than one foot thick. Festoon cross-bedding occurs either alone or in combination with one or more of the other internal bedding structures described above.

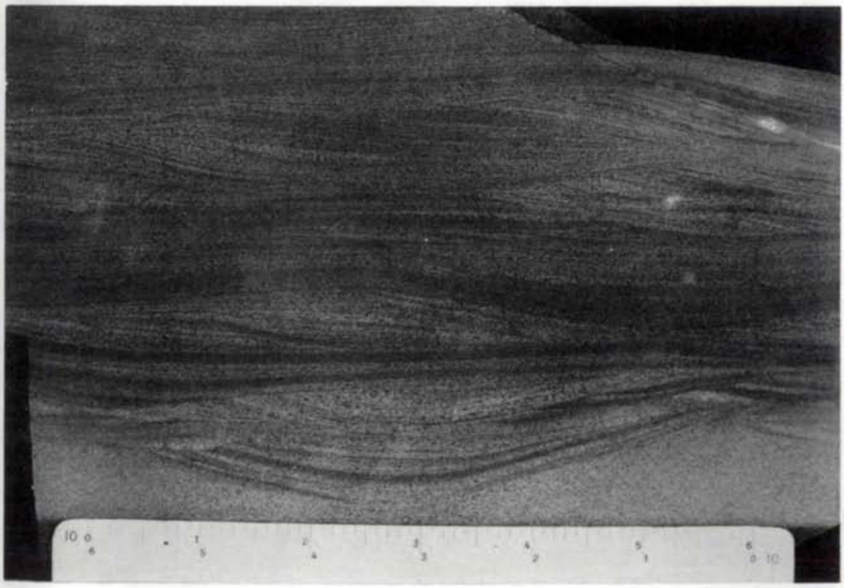


Figure 12. Polished slab showing cross-sectional view of cross-bedded sandstone. Note that the cross-laminae are cut into a layer characterized by structureless bedding. Mt. Rose, section 27, T. 63 N., R. 6 E.

Planar cross-bedding, a less common type, occurs in patchy layers of fine silt interbedded with thinly laminated argillaceous units. It is characterized by a series of parallel planes that meet the overlying and underlying beds at fairly high angles. Planar cross-bedding occurs in sets less than one inch thick and commonly in combination with other types of internal structures.

Cross-bedding with oversteepened fore-set laminae that dip as much as 50° is found in a few of the siltstones. The fore-set laminae, which are only a few inches thick, were steepened immediately after deposition, as shown by the fact that many are covered by undeformed laminae within the same sedimentation unit.

Convolute Bedding

Convolute bedding (Kuenen., 1953) or convoluted laminations (Haaf, 1956, p. 188) are present locally in some of the fine-grained rocks. In cross-section convolute bedding has a folded appearance, with the folds ranging from small sharp anticlines and broad rounded synclines to highly contorted folds that commonly are overturned. The deformed zone is confined to the top several inches of siltstone beds, and never extends into the overlying argillite beds, indicating a syndepositional origin for the structure. The absence of truncation serves to distinguish it from similar-looking slump structures that will be discussed later.

Internal Bedding Sequences

The various types of internal bedding structures described above occur within individual sedimentation units in all combinations, but in only certain permutations. An ideal sedimentation unit containing all of the internal bedding structures was not observed, but data obtained from many exposures permit the recognition of six sub-divisions, each characterized by a predominance of one of the described bedding types. An ideal sequence is:

(1) Intraformational conglomerate – a conglomeratic zone rarely occurs, but where present the clasts are enclosed in a structureless unit. The layer rests discordantly on the top of an interlayered argillite.

(2) Structureless layer – the bottom part of this layer commonly consists of ungraded heterogeneous sand-size detritus, which is transitional upward over a thin interval into an overlying graded layer.

(3) Graded layer – the most commonly observed layer in the Rove consists of fine sand-size detritus at the base that is transitional with the structureless layer. Graded beds may be single, delayed, interrupted, or composite. The grading is very distinct only where the material is not well sorted. Where the overlying units are missing, the upper part of this layer has been partially reworked in places into a moderately well-sorted sandstone whose grain-size ranges from fine-sand to silt.

(4) Laminated layer – the laminated layer is characterized by thin, parallel, alternately-bedded laminae of clay-size and silt-size material. Grading is present at some places. Where this layer is overlain by a cross-bedded unit, the contact is generally very sharp.

(5) Cross-bedded layer – this layer consists of a series of festoon-type cross-bedded units, mostly one-half to six inches thick. Where the overlying units are absent, its top is commonly ripple-marked, especially in the upper part of the formation.

(6) Layers with contorted bedding – contorted bedding, which was rarely observed, is a thin zone consisting of highly contorted laminae, much of which appears to be the result of slumping or a combination of slumping and other processes. It is overlain at most places by a thin layer of very finely laminated silt and argillaceous material.

Sedimentation units in the Rove Formation most commonly contain a combination of structureless bedding, graded bedding, and laminated layering. The combination of structureless, graded, and cross-bedded intervals also is common. Sedimentation units containing horizontal laminae and cross-bedding in addition to the above are fairly common, but units with intraformational conglomerates and contorted bedding are rare.

Post-depositional Soft-sediment Deformation Structures

Graywacke beds or sequences of interbedded graywacke and argillite that were deformed during post-depositional subaqueous movements are conspicuous at many localities. Most of the deformation involved internal shearing between particles and beds.

Tanton (1931, p. 39) was the first to recognize the presence of such structures in the Rove Formation, but because he did not discuss them in detail, they are described below.

Contorted Bedding

Apparently a few beds in the Rove Formation slipped on an underlying layer of very fine-grained argillaceous material; the movement produced a series of complex disharmonic folds with associated thrusts or nappe-like structures several inches thick. These structures are everywhere confined to argillites or siltstones, and many are associated with cross-bedding in which the foreset laminae are oversteepened and overturned. Commonly the contorted laminae are truncated, whereas the overlying layers are undeformed, indicating contortion and erosion prior to the deposition of the next layer.

Bed Pull-aparts

Natland and Keunen (1951) described structures similar to those in the Rove Formation in which thin layers of silty material appear to have been pulled apart by slumping. This has resulted in a thinning and "necking" of some layers with little apparent disturbance in the underlying units. Most of the layers are less than one-fourth inch thick and are associated with very fine-grained argillaceous material. They are visible only on the polished surfaces of cut slabs (fig. 13).

Clastic Dikes

Clastic dikes in the Rove Formation are structureless intrusions of fine-grained sandstone, mostly less than two inches wide and six inches long (fig. 13). Individual dikes are generally tabular or ellipsoidal in cross-section, and appear to have penetrated the containing rock by forceful injection from either above or below. Their source can be traced to thin sand units in places where there are many alternations of sandstone and argillite beds.

Load Pockets

Holland (1960) proposed the term load pockets for irregular pockets in the base of fine-grained graywackes overlying argillaceous material. Load pockets in the Rove Formation occur on the upper surfaces of argillite beds that apparently were plastic at the time of sand deposition. Deformation results in swellings that range from slight bulges to thick rounded masses and to highly irregular protuberances, all of which are one to three inches high. They also are common in areas of alternating argillite and graywacke.

Flame Structures

Structures consisting of a series of pointed tongues of argillite that project into overlying graywacke were termed flame structures by Walton (1956, p. 267). In the Rove Formation, they are small and tend to point in several directions, and are best seen in cross-sections of welded sandstone and argillite layers (fig. 13).

Overfolds

Overfold structures like those described by Crowell (1955) are found in the upper part of the Rove Formation. Overfolds are slump structures characterized by hook or ball-like masses of fine-grained material apparently formed from broken pieces of thin but relatively competent units deposited over fine-grained argillaceous material. They are never more than two inches in diameter and are commonly flattened parallel to bedding. On weathered surfaces they appear to be nodules, but faint structures implying rolling can be seen on polished slabs. They apparently formed prior to deposition and consolidation of the overlying beds because the sediments of these beds drape around the structure with little or no loss in thickness.

Microfaults

Small high-angle faults with displacements of less than six inches are common throughout much of the Rove Formation. They are conspicuous where they cut thinly laminated beds (fig. 10). Most faults are characterized by sharp planes which now contain sulfides. Most of the faults die out within sandstone beds, indicating that movement occurred before deposition of the overlying layer was completed.

Ripple Marks

Current ripple marks were first noted in the Rove Formation by Grout and Schwartz (1933, p. 15). They are preserved on the tops of a considerable number of beds, especially at localities 93 and 120 (fig. 2). The ripples are mainly lobate in form (fig. 14), although a few are straight-crested. They generally occur in sets less than six inches thick. Individual amplitudes are two inches or less and wave lengths range from four to six inches.

Sole Marks

Sole marks are surficial irregularities of sedimentary origin on the lower bedding planes of many sandstone beds. They were first interpreted in the Rove Formation as fossil tracks (Selwyn, 1890), but Tanton (1931) later correctly

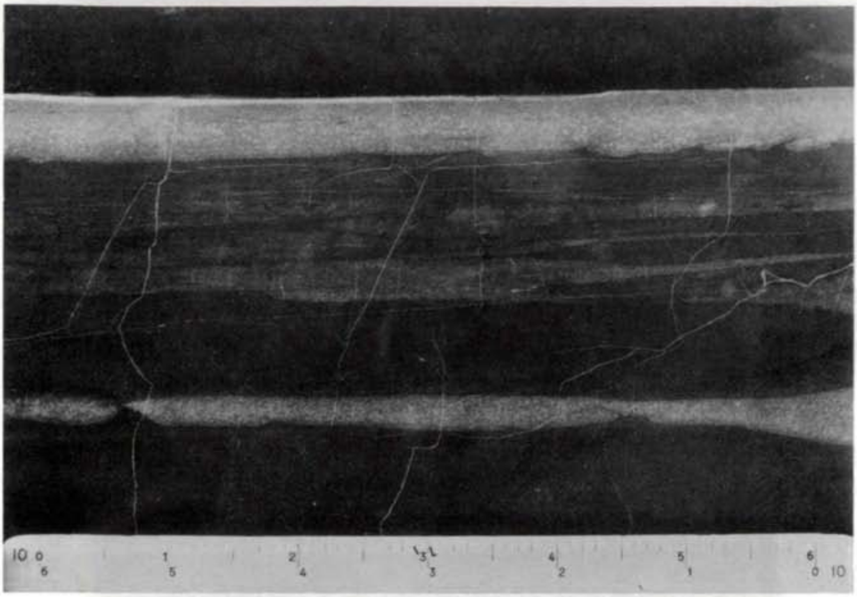


Figure 13. Polished slab showing a variety of post-depositional soft-sediment deformation structures. Note the flame structures at the base of the siltstone beds, the clastic dike in the lower right part of the picture, and the disturbed appearance of the thinly laminated bed in the center of the picture. Sample locality 29, Mayhew Lake, South Lake quadrangle.

Figure 14. Ripple-marked upper bedding surface in the upper part of the thin-bedded graywacke unit. The compass is oriented east-west. Sample locality 120, High Falls on the Pigeon River, Thunder Bay district, Ontario.

interpreted many of them as slump-related structures. Other structures, however, show strong directional trends in agreement with other current-produced features. The sole marks in the Rove Formation are discussed below roughly in the order of their abundance.

Groove Casts

Groove casts are linear ridges on the soles of many beds (Shrock, 1948, p. 163). They formed by the filling of grooves that were scoured on the surface of an underlying bed by moving debris. In the Rove Formation grooves range in size from faint, short ridges to smooth or ribbed forms more than three inches wide. A few soles are profusely covered with them, but most surfaces have only a few widely spaced grooves. Although groups of grooves differ in directions by as much as 40°, most of the grooves on a particular bedding plane are remarkably parallel.

The size range of the grooves implies that a wide variety of different sized objects were transported by the currents. While many kinds of scribing agents are suggested in the literature, nothing in the Rove Formation was found that can be certainly identified as a scribing tool. A few of the overlying sandstone beds contain small, intraformational fragments, apparently torn from the underlying layer, which may have scribed some of the grooves, but the large size of many grooves and the small size of the fragments precludes this mode of origin for all the grooves observed.

Flute Casts

Flute casts are elongate bulges on soles of beds that formed when depressions scoured into the underlying substratum by current action subsequently were filled with sand. Flutes and flute casts are present but relatively rare in the Rove Formation. Those observed have a wide variety of shapes, but the up-current end is characteristically rounder, narrower, and deeper than the down current end, which flares and merges with the surface of the bed. Most flutes are small, generally less than one-half inch deep, less than five inches long, and one-half to three inches wide (fig. 15). A wide variety of forms are present in the Rove Formation, but as in other similar deposits, they tend to be of the same shape, size, and distribution on a particular sole. Furthermore, flutes on any one surface in the Rove Formation tend to show a consistent orientation, with a deviation of less than 30°.

Dendritic Ridges

Surfaces that have a dendritic pattern of thin sharp ridges separated by broad flat-bottomed troughs are found in small patchy areas that never have an extent of more than several square feet. The ridges are most common on the interfaces between coarse and fine-grained rocks, where they are less than one-sixteenth of an inch high and one to two feet long.

Paleoenvironmental Interpretation

Sedimentary structures provide information on the manner in which the depositional medium applied energy to the clastic detritus. Unfortunately, most of the individual structures described above are not unique to a single sedimentary environment, but in the Rove Formation turbidity flow is suggested by a particular combination of structures.

Figure 15. Flutes on an upper bedding surface in the upper part of the thin-bedded graywacke unit. The scale is six inches long and is oriented north-south. Sample locality 120 on the Pigeon River, Thunder Bay district, Ontario.

The concept of turbidity flow was first developed by Daly (1936), and since that time a large amount of experimental evidence (Dzulynski and Walton, 1965) and data from recent turbidity-current deposits indicate that this is a plausible mechanism. Kuenen (1963, p. 9) summarized properties characteristic of modern deep sea turbidites that can be used to recognize similar deposits in ancient rocks. Included among these properties are: (1) graded bedding, (2) the admixture of clay to produce dark sands (graywackes), (3) convolute bedding, (4) current-rippled upper margins, (5) sole markings such as flute and groove casts, (6) shale intervals that separate sandstone layers, (7) normally sub-parallel current directions over wide areas and through thick sequences, and (8) the apparent widespread continuity of individual layers over large areas. Of course, not all the criteria observed in modern turbidites are applicable to the Rove Formation, but there is a close similarity between the structures in modern turbidites and those found in the Rove Formation.

Furthermore, Dott (1963, p. 118) concluded that the most diagnostic criterion of turbidity current deposition in unfossiliferous rocks is ". . . graded bedding through many successive units . . ." Graded bedding may also be formed by other processes such as in-place liquification (Terzaghi, 1956), burrowing of organisms (Rhoads and Stanley, 1965), and simple settling through any medium (Kuenen, 1953), but the presence of repeated graded sequences with remarkably even layering, combined with other structures indicative of current movement, strongly indicates deposition from a turbidity current.

Sequences of internal bedding structures in graywacke sedimentation units, described above, that are intercalated between argillite units indicates that each graywacke sedimentation unit was deposited by currents of continually decreasing velocity. Kuenen (1953) described similar sequences from the lower Paleozoic of west-central Wales and the Ventura Basin of California, which he concluded were turbidites. Bouma (1962) and McBride (1962) also described somewhat similar sequences from the Alps and the Martinsburg Formation in Pennsylvania, respectively, and attributed them to turbidity currents.

Thus, if what is known about turbidites elsewhere is applied to the Rove Formation, the following generalized history of a single Rove turbidity current can be outlined.

(1) The initial load was composed of sand, silt, and mud. Many modern marine turbidites develop from submarine slumps that originate at the mouths of rivers where large volumes of loose sediment accumulate. Many such slumps are triggered by earthquakes (Heezen and Ewing, 1952; 1955), but not all currents originate in areas of seismic instability. Heezen and others (1964) demonstrated that turbidity currents off the Congo River are triggered by peak-discharges of sediment-laden river water during flood stages.

(2) The current moved with a velocity sufficient to erode and drag portions of the weakly lithified bottom over which they flowed and fragments from the substratum were thereby incorporated in the current.

(3) At the same time, flutes were eroded into the substratum by hydrodynamic forces, grooves were cut by objects that scoured the bottom while being transported by the current, and dendritic ridges formed by the flowing of a sediment-saturated layer of water over a viscus mud layer. When compared to other turbidites, there is a lack of flutes and grooves in the Rove Formation, but this fact cannot be used as evidence against turbidity current deposition. Dzulynski and Sanders (1962, p. 87) stated that "... the absence of scour marks ... may indicate a slow current that was too weak to scour the bottom or a faster one in which a traction carpet was completely effective in shielding the bottom from turbulent eddies. The absence of tool marks ... may be due to one of three causes: weak currents, fully protective traction carpet, or absence of suitable tools."

(4) As long as the velocity of a current was constant or the sediment load was well sorted, a carpet of ungraded material was deposited to form a structureless layer (Kuenen, 1951, p. 29). As the current velocity decreased, the coarser-grained material settled out first. Because deposition from the mud-chocked current was too rapid to allow complete sorting, sand, silt, and clay were simultaneously deposited forming a layer with a constant clay-size content and coarser particles that are graded in a way outlined by Kuenen (1951, p. 28). Many graded units in the Rove Formation were deposited from a single current, but changes in current velocity and load modified the settling of material so that delayed or interrupted grading formed. In addition, many other graded units are composite, in that one graded layer is directly superposed on another. Kuenen (1953, p. 1056) suggested that pulses in an individual flow could commonly follow each other so that the nose of a later pulse closely followed the tail of an earlier one; each pulse deposited a graded layer that together produced a composite graded unit.

(5) A change from turbulent to laminar flow conditions and movement of fine-grained sediments by traction brought about the deposition of a laminated layer commonly associated with small-scale cross-bedding and rippling. Brush's

(1959) flume experiments showed that laminated layers formed when the current velocity exceeded that at which ripples can form, migrate and thus produce cross-laminae. Likewise, Simons and others (1961) observed sand ripples transitional to planar laminae with an increase in current velocity.

(6) The mud sub-strata buried by sand or silt yielded because of the overburden and produced a wide variety of compaction and soft-sediment deformation structures such as load-casts, flame structures, and clastic dikes.

(7) In most instances, enough fine mud was deposited by traction from the slowly moving tail of the current to fill in and smooth over ripple troughs to produce a bed with an even upper surface. For this reason, ripple marks are rare in most of the Rove Formation, but cross-laminae are fairly common.

However, turbidite currents were not the only currents active in the Rove basin of deposition, for several lines of evidence also can be cited that indicate possible reworking by bottom-flowing traction currents. First, many Rove beds have current ripple-marked tops that indicate current movement in a direction almost perpendicular to that indicated by sole marks on the same bed. While Sullwold (1960) showed that ripple marks are widespread in many turbidite sequences, the above data indicates that some turbidites in the Rove Formation were modified later by bottom currents not associated with the original turbidity current. Secondly, the presence of fairly well sorted lag deposits formed by the winnowing of clay-sized material from previously deposited poorly sorted sediments also implies the presence of non-turbidite associated bottom currents. In fact, Kuenen (1964, p. 16) suggested that the absence of winnowed deposits is good negative evidence for turbidite deposition.

Traditionally it has been assumed that the ocean floor where turbidity currents are operative today is free of bottom currents or is subjected to reworking by gently flowing bottom currents (Kuenen, 1964; Hubert, 1964). However, work by Volkmann (1962), Swallow and Worthington (1957, 1961), and Steele and others (1962) has demonstrated that the velocities of some bottom-scouring ocean currents commonly average 20-25 cm/sec. In fact, Steele and others (1962, p. 471) reported bottom current velocities of 50-60 cm/sec. If Hjulstrom's (1939) erosional curve is applied to ocean currents, the particle sizes that these ocean currents can erode can be extrapolated with little difficulty. The high velocity ocean currents reported by Steele and others (1962) are capable of eroding sand, silt, clay, and fine-gravel. The current velocities reported by Swallow and Worthington (1957, 1961) and Volkmann (1962) can erode coarse silt, sand, and granules. If these velocity data are plotted on Sundborg's (1956, p. 177) erosional curve, such currents also can erode clay (Hubert, 1964, p. 782).

The direction of flow of ocean currents also is noteworthy. Oceanographic data (Heezen and others, 1959, p. 50; Volkmann, 1962; Swallow and Worthington, 1957, 1961; Steele and others, 1962, p. 471, fig. 6; Darbyshire, 1964) have shown that bottom currents generally flow parallel to topographic trends rather than down-slope. Creger (1963), Stride (1963), and Allan (1963) have shown that, in shallow oceans, current systems also parallel topographic contours. Sverdrup and others (1942, p. 680) noted that non-wind-driven and non-wave-driven ocean currents normally flow parallel with topographic contours in the western North Atlantic Ocean.

Rippled sands also have been described from sea-floor sediments (Heezen and others, 1959; Heezen and Hollister, 1964). Rippled zones commonly are associated with turbidite sediments, particularly in the upper parts of such beds

(Bouma, 1962, p. 49). Originally attributed to the waning later stages of a single turbidity current by Natland and Kuenen (1951, p. 87), such ripples and associated micro-cross-laminae have been attributed more recently to the reworking action of ocean-bottom currents (Craig and Walton, 1962, p. 118; Dott, 1963, p. 119, 126; Hsu, 1964; Hubert, 1964). Hsu (1964) in particular, reviews many lines of evidence that confirm that even slow-moving ocean currents can produce rippled and cross-laminated zones in turbidites. Therefore, the presence and orientation of ripple marks and some micro-cross-laminated layers in the Rove Formation suggests that some of the original turbidite material was reworked by ocean currents that flowed parallel to the inferred strike of this part of the depositional basin. However, while there is some evidence for the reworking of deep-sea sands by "normal" currents, there is no evidence indicating that these currents are capable of depositing graded beds. Therefore, it is not likely that the bottom currents played a major role in the movement of sediment.

Analysis of Directional Structures

The orientation of all recognizable directional sedimentary structures was measured at each place they were exposed in order to obtain a regional pattern of sediment transport. Rove beds generally dip from 5° to 10°, and the markings are generally parallel to the dip direction. Potter and Pettijohn (1963, p. 116) have pointed out that the azimuth error from beds dipping less than 25° is negligible, and accordingly no correction was applied. In analyzing the data, the formation was divided into three arbitrary geographic areas as shown in Figure 16a which, from northwest to southeast, essentially represent successively younger parts of the formation. The orientation data from each area is presented graphically in Figure 16b to summarize the data for each structure.

Cross-bedding is a poor directional indicator because of the wide spread in the values of the directions obtained. The scatter may reflect two directions, one formed by turbidity currents and the other by bottom currents.

Flute and groove directions, on the other hand, have a much narrower range with a maximum spread of only 70°. The direction of the linear structures such as grooves can be inferred with a large degree of certainty from the direction indicated by the flutes that show both orientation and direction.

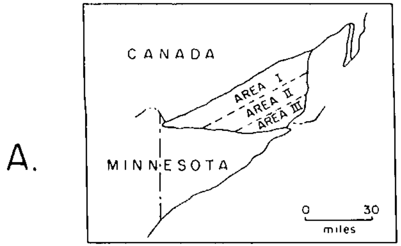
If, as it is assumed, the present northeast-trending outcrop belt is nearly parallel to the strike of the depositional basin, the bulk of the data indicates that sediments were introduced by turbidity currents flowing in a southerly direction, approximately perpendicular to the axis of the basin.

The orientation of a limited number of ripple marks and perhaps some of the cross-bedding indicates that the turbidites were modified by bottom currents that flowed in a southwesterly direction approximately parallel to the strike of the basin.

PETROGRAPHY

Gross Lithologic Character

Argillite is estimated to comprise 90 percent of the lower argillite unit and from 30 to 50 percent of the upper units in the Rove Formation. The argillite of the lower unit has a few carbonate interbeds near the base, whereas thin beds and laminae of graywacke and siltstone are thicker and more abundant upward.



a. Location map.

b. Summary diagrams of directional features measured in the Rove Formation. Outer circle shows groove costs (solid line), and flame casts (short dashed line); middle circle shows flute costs (solid line) and cross-bedding (short dashed line); inner circle shows ripple marks.

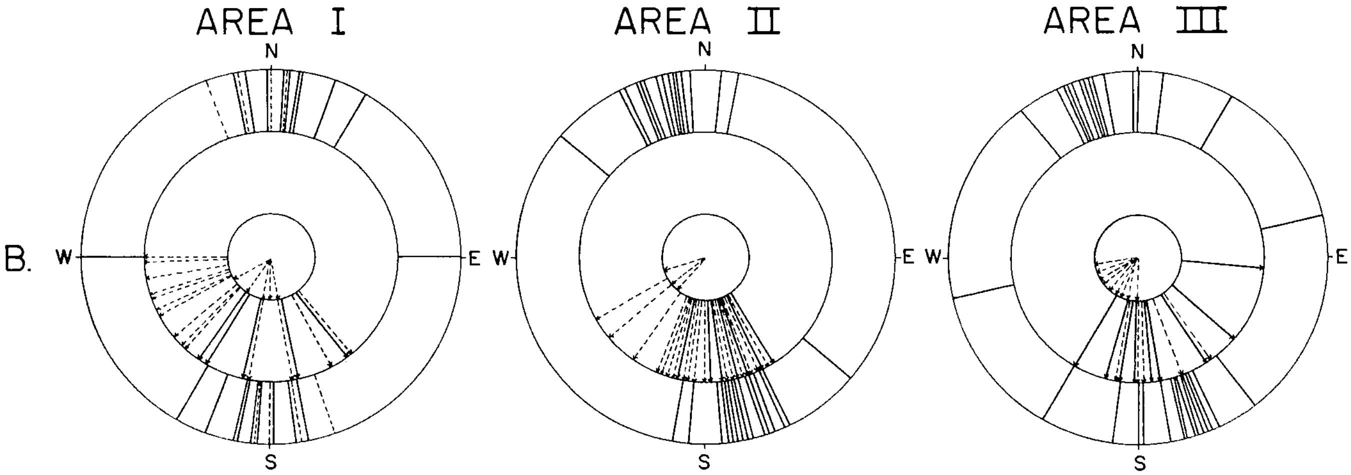


Figure 16. Analysis of directional structures.

Repeated alternations of argillite, siltstone, and even-bedded graywacke (40-80 percent) and minor quartzite (2-5 percent) characterize the upper units in the formation. Most of the rocks are similar in many aspects to flysch facies as the term is used by Dzulynski and Walton (1965, p. 3). Variegated argillite, limestone, dolomite, chert, conglomerate, and altered tuffaceous sediments make up a few percent of the formation. Most of the latter rock types are in the lower argillite unit. The petrography of these rocks is described in the following sections, and the detrital components are evaluated in terms of potential source rocks.

Chert

Chert is rare in the Rove Formation. It is confined to the bottom part of the lower argillite unit, and represents repetition of depositional conditions characteristic of the underlying Gunflint Iron-formation. The chert is generally black (N1) to dark gray (N3) and occurs in beds rarely more than several inches thick. It is never pure, but consists of dusty, brownish, fine-grained, recrystallized silica that has five to ten percent muscovite and chlorite in long shreds. A poorly expressed lamination within the chert is defined by a sub-parallel arrangement of mica grains. Pyrite and black opaque carbonaceous material are present in small patches strung out parallel to the lamination.

Conglomerate

Two types of conglomerate occur in the Rove Formation. The first type, of intraformational origin, is fairly common. Their origin is demonstrated by: (1) angular edges, (2) composition similar to that of the underlying unit, and (3) bent shapes that imply only weak lithification. This type of conglomerate commonly is found in thin, irregular lenses near the bottom of graywacke beds, but flat, rounded pebbles of argillaceous material also may occur some distance above the base of some beds. Most of the clasts are not more than several inches in diameter, but Tanton (1931, p. 38) reported boulders as much as three feet in diameter that are only slightly removed from their place of origin. Units that contain clasts have sharp irregular basal contacts. The upper surface of the underlying argillite commonly contains scattered depressions several inches deep. It appears that a current plucked out and broke up material from underlying unit; this material is now consolidated in the lower part of the overlying coarse-grained bed.

Conglomerates of the second type, which contain quartz and granite pebbles derived from outside the basin, were described by Grout and Schwartz (1933, p. 23) and Bayley (1893, p. 73) from local lenses near the top of the formation. They were not observed during this study.

Carbonate Rocks

Five types of carbonate rocks occur in the Rove Formation. They are: (1) a basal thin bed of micritic limestone that contains broken granules from the underlying iron-formation; (2) massive, black to dark gray, fine-grained micritic to dismicritic limestone and dolomite that occurs in the transition zone between the Gunflint and Rove Formation; (3) thin beds of light gray limestone interbedded with argillite; (4) small to large dark gray, concretionary structures; and (5) thin beds of black carbonate that contain altered tuffaceous material.

Although limestones are most abundant, the presence of different proportions of calcite and dolomite make it necessary to use the broad term carbonate rock, especially because it is often difficult to distinguish one from the other in the field.

The Upper Limestone Member of the Gunflint Iron-formation is transitional into the argillites of the Rove Formation to the extent that carbonate beds are interlayered with argillites and thin layers of chert. Accordingly, it is difficult to pick a consistent marker horizon between the two formations. The uppermost iron-formation is composed of a heterogeneous mixture of granules of varied compositions. The granules are fairly uniform in size, ranging from 0.5 to 1.0 mm in diameter. Generally they are oval, kidney-shaped, or slightly flattened. Where closely packed, their shape is somewhat distorted to accommodate each other, indicating that they very likely were in a plastic state when deposited.

A micro-conglomerate of broken granules overlies the granular beds of the iron-formation. Although the conglomerate layers are discontinuous, they are important in that they mark the end of the major period of chemical deposition. A similar conglomerate in the same stratigraphic position was reported from the Mesabi range by White (1954). The fragmented granules are angular to poorly rounded, and are cemented by a very light gray micritic limestone (Folk, 1959) in which 0.5 to 1.0 mm dolomite rhombs occur as "floating-grains". In addition $1M_d$ muscovite ("illite") and associated leucoxene occur in small rounded balls disseminated parallel to bedding laminae. Goodwin (1956, p. 592) suggested that similar material in the Gunflint Iron-formation is altered pyroclastic material.

Although definite pyroclastic material was not found in the Rove Formation, some data may indicate a continuation of volcanic activity into at least the beginning of Rove time. This evidence is found in a thin carbonate bed at Slate River, Ontario, which contains several curving interlocking wormy channels that resemble tuffaceous material figured in Rogers and Kerr (1942, p. 575). The channels are filled with a low index isotropic material that may be devitrified glass. Moorhouse (1963, p. 54 and pl. 10) described and figured similar material from a concretion at the same locality, and also cited a possible volcanic origin.

Thin beds of light to dark gray limestone and dolomite are interbedded with black slightly calcareous argillite throughout the basal 100 feet of the formation. Many beds are even and continuous over several hundred feet but others pinch and swell. Some beds also are nodular, whereas others are lens-like. Generally, the carbonate beds are structureless and have a micritic or dismicritic texture, but some exhibit thin laminae of silt-size and micaceous material. Insoluble residues in limestones from several localities contain chlorite, $1M_d$ "illite", pyrite, detrital 2M muscovite, oligoclase, rounded and embayed doubly terminating quartz grains, actinolite, drusy chert, and leucoxene.

Carbonate concretions distributed throughout much of the lower part of the formation were described by Logan (1863, p. 69), Tanton (1931, p. 40), and Grout and Schwartz (1933, p. 20). Moorhouse (1963) also described the concretions and discussed their origin.

Quartzite

Several types of quartzite occur in the Rove Formation. Type 1 is a lag deposit found in the upper part of many of the graywacke layers. Generally, it is associated with an uncommonly thick graywacke bed, but it is physically separated from it by an irregular and often indistinct contact. Unlike the graywackes, these quartzites rarely grade upward into argillite or siltstone; the upper contact generally is marked by a sharp irregular plane over which an argillaceous bed was deposited.

Type 1 quartzite is typically light medium-gray, fine- to medium-grained, and fairly well sorted. The beds generally are slightly graded or cross-bedded. Although their composition varies, they may be characterized in thin-section as sandstones or siltstones with only a small amount of matrix. The sand- or silt-size grains are predominantly quartz and feldspar. Sutured contacts between quartz grains are fairly common, but no overgrowths were noted. The quartz grains rarely exceed 2.5 mm in maximum length, and most are from 0.3 to 0.7 mm. The feldspar, which has been slightly sericitized, is fine-grained and angular. Sodic plagioclase is most common, although andesine and microcline are present in minor amounts. Well rounded rock fragments of fine-grained quartzite or chert are abundant in several samples, but completely absent in many others. The matrix, which makes up five to 15 percent of the rock, is composed of intergrown radiating patches of fibrous muscovite and chlorite, and always is confined to interstitial spaces and to rims surrounding and replacing some of the smaller feldspar grains. Accessory constituents, mainly magnetite and apatite and less commonly sphene and garnet, make up less than five percent of the rock. Modal analyses of four samples are given in Table 4. On the basis of the predominance of feldspar over rock fragments and a matrix of less than 15 percent, Type 1 rocks are classified as feldspathic quartzites.

Type II quartzites are confined to approximately the upper 700 feet of the Rove Formation. In large part they occur as beds with irregular but sharp bottoms and tops; the latter are commonly ripple-marked. In addition, some units are cross-bedded. Many varieties are nearly white, but others are various shades of gray and pink. They are composed mostly of quartz with only minor amounts of chert and feldspar. Pink rocks have more feldspar, so color is primarily a function of purity. The quartz grains are 0.05 to 0.5 mm in diameter but a few exceed two mm. The original grains are wellrounded to angular and show tiny fluid inclusions arranged in straight lines in the interior and around the edges. Such inclusions are useful in ascertaining the original grain shape because almost all are now covered by irregular, interlocking rims of secondary quartz. The feldspar, which is mainly twinned plagioclase and minor orthoclase, has been altered to different degrees. More advanced alteration has produced a mosaic of green weakly pleochroic chlorite and muscovite. The matrix, present in interstitial voids, is muscovite, chlorite, and quartz, which are intergrown into a fine-grained mass of indistinct grains. Where observable, the quartz is angular and shard-like and does not contain inclusions as in the sand-size quartz grains. These facts indicate that the matrix is in part recrystallized clay and fine-grained quartz. The matrix also has replaced to varied degree the quartz and plagioclase grains. Magnetite, rutile, earthy iron oxides, tourmaline, epidote, garnet, zircon, apatite, and pyrite are common accessory minerals.

Graywacke and Siltstone

Graywacke-sandstones comprise major parts of the non-argillaceous part of the Rove Formation. In addition, coarse-grained siltstones of a similar composition are widespread, comprising as much as 40 percent of the formation. The siltstones contain from 40 to 70 percent silt-size detritus and the remainder is a clay-size material. Such rocks comprise only about 10 percent of the lower argillite unit, but they are more abundant upward in the section, where they comprise 30-80 percent.

Table 4 – Mineralogic composition of coarse-grained Rove Formation estimated from 500 point counts per thin section

	Framework Constituents in %						Matrix Constituents in %			
Sample No.[1]	Quartz	Plagioclase	Microcline	Quartzite	Schist	Access.	Authigenic Carbonate	Chlorite	Muscovite	Biotite
Graywacke										
M-10, 020	21	7	Tr[2]	1	—	5	—	4	32	30
M-10, 022	38	17	—	1	—	5	—	4	35	—
M-10, 023	56	21	—	—	—	2	—	4	17	Tr
M-10, 025	38	26	—	3	—	1	Tr	4	25	3
M-10, 026	49	18	—	Tr	—	5	—	Tr	10	18
M-10, 027	44	13	—	—	—	2	—	2	25	14
M-10, 028	46	19	—	1	—	4	—	5	25	—
M-10, 029	28	10	—	Tr	—	2	—	2	36	22
M-10, 033	54	18	—	2	Tr	2	—	Tr	5	19
M-10, 034	44	16	—	2	—	2	—	Tr	2	34
M-10, 036	36	23	—	1	—	1	—	2	3	34
M-10, 042	55	21	—	5	—	2	—	3	9	5
M-10, 047	58	24	—	3	2	2	—	5	6	—
M-10, 048	41	21	—	2	—	2	—	4	11	19
M-10, 051	42	33	—	3	—	1	—	—	2	19
M-10, 066	50	28	—	4	—	2	—	15	1	Tr
M-10, 067	58	21	—	4	2	1	—	13	—	1
M-10, 068	48	36	—	4	—	3	—	7	2	Tr
M-10, 069	74	10	—	2	—	2	—	12	Tr	—
M-10, 073	44	12	3	1	—	7	5	6	22	Tr
M-10, 076	59	24	—	Tr	—	1	—	9	7	—
M-10, 080	47	28	—	3	—	3	—	18	1	—
M-10, 081	59	20	—	1	—	1	—	18	1	—
M-10, 082	53	23	—	5	—	3	—	9	7	—
M-10, 084	40	32	—	2	—	3	—	9	14	Tr
M-10, 085	36	29	—	3	—	1	—	6	14	11
M-10, 087	45	22	—	4	3	4	—	7	13	2
M-10, 088	46	17	—	5	2	2	—	9	9	10
M-10, 092	52	19	—	6	—	4	2	6	11	Tr
M-10, 093	40	23	—	7	—	—	—	Tr	30	—
M-10, 095	47	14	—	2	4	1	—	2	30	—
M-10, 099	41	21	—	2	—	4	—	11	19	2
M-10, 100	94	2	2	—	—	—	—	1	1	—
Quartzite — Type I										
M-10, 021	67	14	—	1	—	2	—	2	4	10
M-10, 024	68	21	2	1	—	5	—	Tr	3	—
M-10, 038	52	30	—	—	—	2	—	7	9	Tr
M-10, 065	76	9	—	—	—	3	—	9	3	Tr
Quartzite — Type II										
M-10, 102	97	—	—	—	—	—	—	3	—	—
M-10, 110	95	1	—	—	—	—	—	2	2	—
M-10, 111	93	3	—	—	—	—	—	—	3	1

1. Samples on file with the Minnesota Geological Survey
2. Less than one percent

Approximately 75 thin sections of graywacke and siltstone from many localities were examined. Most thin sections were cut perpendicular to bedding. Five hundred points were counted in each thin section of 32 samples to determine the percentage compositions given in Table 4. The percentage of potassium feldspar was estimated by staining thin sections etched by hydrofluric acid with a potassium cobalt-nitrite solution.

Although several types of graywacke were found, all may be characterized in thin section as poorly sorted rocks composed essentially of a framework of sand- or silt-size grains in a clay-size matrix that comprises 15 to 75 percent of the rock. Recrystallization and metamorphism have altered the original size of the matrix particles and have produced a strongly indurated rock, which prevents textural analyses. As an approach to grain size analysis the apparent long dimension of 200 randomly chosen sand- or silt-size grains was measured and plotted using histograms (fig. 17).

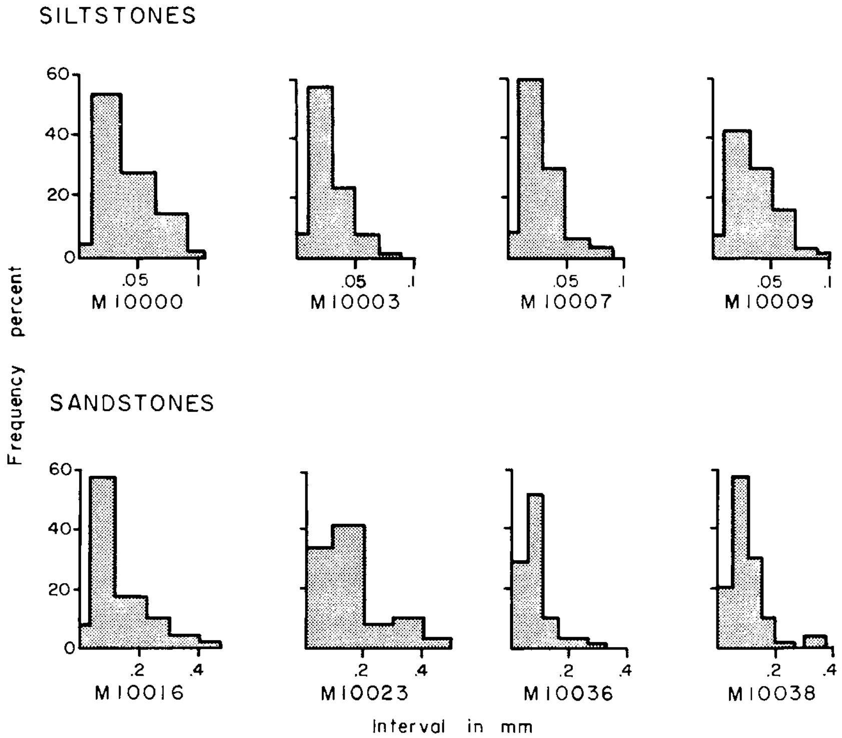


Figure 17. **Histograms summarizing apparent grain-size distribution of selected samples from the Rove Formation. Data is based on the measurement of the apparent long dimension of 200 randomly selected grains in thin section.**

The upper size limit of clay-size or matrix particles was taken to be 0.03 mm following the convention of Pettijohn (1943). The matrix is chlorite, muscovite, quartz, plagioclase, and opaque minerals. Chlorite occurs in lacy radiating patches and as fibrous intergrowths with muscovite. Both chlorite and muscovite replace edges of framework grains, indicating that they formed by the recrystallization of detrital clay minerals. In metamorphosed graywacke, patches of muscovite and chlorite are larger and are partly altered to biotite.

The major framework minerals are quartz and sodic plagioclase. Rock fragments generally constitute less than five percent, but locally as much as 10 percent of the framework. Rock fragments (excluding intraformational fragments) rarely exceed 1 mm, and most are 0.1 to 0.5 mm in diameter. The larger grains typically are more rounded and appear fresh; the shape of smaller grains has been more or less modified by replacement.

Quartz comprises 20 to 70 percent of the typical graywackes. Grain diameters rarely exceed two mm and average between 0.1 and 0.5 mm. Suturing of contacts or matrix replacement (resulting in serrated edges) has modified many grain boundaries so that shape or roundness studies have little value. Inclusions in individual grains are very common but are generally too small to be identifiable.

Feldspar is the second most abundant constituent in the graywackes, generally ranging from 5 to 35 percent, but locally constituting a larger percentage of the rock than does quartz. The feldspar grains are angular to sub-angular, and their average size is less than that of the accompanying quartz. Sodic plagioclase (An_2-An_{30}) is most common, but andesine makes up a large proportion of the feldspar in a few specimens. Most grains are dusty and highly sericitized. Potassium feldspar is present in minor amounts; gridiron-twinned microcline is also present although rare.

Rock fragments that are mostly recrystallized chert or fine-grained quartzite or rarely, badly weathered schist or greenstone fragments occur only in small amounts. Iron oxide and pyrite are the most abundant accessory minerals, but garnet, sphene, zircon, zoisite and calcite are present in small amounts.

The siltstones are fine-grained equivalents of the graywackes and differ from them only in containing more quartz, mica, pyrite, and carbonaceous material and less feldspar, and in having no rock fragments. Although poorly sorted, they nevertheless are better sorted than most graywackes. The silt-size grains are typically angular and are concentrated in thin laminae that alternate with mica-rich laminae similar to those found in most argillites. The mica flakes and elongate quartz grains have a strong orientation sub-parallel to the internal laminae, many of which are vaguely cross-laminated.

Several chemical analyses of graywackes and siltstones in the Rove Formation are available (table 5). Although graywackes sometimes are defined on the basis of chemical composition, more properly they are defined on the basis of being a poorly sorted sediment of mixed grain-size. The only requirement for them to form is an environment in which erosion, transportation, and deposition are so rapid that complete chemical weathering of the materials does not take place. The relative importance of the rate of chemical differentiation vs. the rate of mechanical disintegration in the source area of the Rove sediments may be assessed from two indices suggested by Pettijohn (1957, p. 509). An average alumina to soda ratio of 5.3 for Rove graywackes indicates an immature sediment that underwent little chemical differentiation. Likewise, a value of 2.3 for the ratio of quartz to feldspar grains, as determined by point counts on thin sections, does not approach the value of 5.8 for an average sandstone. Both indices indicate that the rate of disintegration exceeded the rate of chemical alteration in the source area.

Table 5 – Chemical analyses of the Rove Formation

	Argillite						Graywacke								
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9
SiO_2	64.77	59.71	63.82	51.77	61.93	64.45	82.15	74.22	73.65	73.14	71.00	73.64	72.25	73.85	81.86
TiO_2	0.60	Tr	2.66	.89	0.72	.45	.35	.16	Tr	.04	.44	Tr	Tr	.05	–
Al_2O_3	14.45	18.32	14.65	18.52	17.35	17.36	5.37	10.61	11.08	12.60	12.88	11.25	10.73	10.91	9.87
Fe_2O_3	1.84	8.11	3.16	5.23	–	2.44	1.47	7.45	7.24	7.57	6.69	6.24	8.01	6.98	1.44
FeO	4.54	0.85	5.12	2.52	5.48	.30	1.08	.85	.77	1.31	.65	1.04	.38	.89	2.36
MnO	0.11	N.D.	–	–	0.05	–	–	–	Tr	Tr	Tr	–	Tr	–	–
MgO	2.34	3.54	2.08	2.72	3.01	2.84	2.22	1.48	1.52	1.67	1.68	1.57	1.85	1.52	.86
CaO	2.33	1.05	0.70	3.11	0.20	.53	1.85	.56	.40	.43	.21	.36	.42	.44	.46
Na_2O	1.37	1.93	1.95	2.48	2.07	2.11	1.84	2.12	1.67	1.78	1.43	3.04	2.03	2.28	1.61
K_2O	5.03	3.43	2.81	4.11	5.47	4.44	1.09	1.08	1.65	1.00	2.95	1.42	2.56	1.39	.45
P_2O_5	0.20	N.D.	0.19	–	0.14	–	–	–	–	–	–				–
H_2O+	1.92	3.24	2.62	2.11	–	2.17	.74	1.79	1.88	.83	2.03	1.98	2.05	1.88	1.43
H_2O-	0.07		–	.15	–	.65	.07								
CO_2	0.41	–	–	–	(0.22)	–	–	–	–	–	–	–	–	–	–
C	N.D.	–	–	–	(1.39)	2.59	–	–	–	–	–	–	–	–	–
SO_3	0.60	–	.33	–	(0.06)	–	–	–	–	–	–	–	–	–	–
S	N.D.	–	–	–	–	–	–	–	–	–	–	–	–	–	–
H	–	–	–	–	(0.13)	–	–	–	–	–	–	–	–	–	–
N	–	–	–	–	(0.40)	–	–	–	–	–	–	–	–	–	–
Ign. Loss	–	–	–	–	3.76	–	–	–	–	–	–	–	–	–	–
Org. C.	–	–	–	–	(1.33)	–	–	–	–	–	–	–	–	–	–
	100.58	100.18	100.09	99.61	100.18	100.33	98.23	100.32	99.86	100.37	99.96	100.54	100.28	100.19	100.29

Argillites

1. Slate near Gunflint Lake; T.M. Chatard, analyst; Grout, 1933.
2. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
3. Pigeon Point; J.E. Whitfield, analyst; Bayley, 1893.
4. Near gabbro, Cook County, D.M. Davidson, analyst; Davidson, 1926; Grout, 1933.
5. West end of Gunflint Lake; V.C. Bye, analyst; Swain and others, 1958.
6. Sec. 24, T. 65 N., R. 3 W., D.M. Davidson, analyst; Grout, 1933.

Graywacke

1. Loon Lake graywacke; D.M. Davidson, analyst; Grout and Schwartz, 1933.
2. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
3. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
4. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
5. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
6. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
7. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
8. Pigeon Point; R.B. Riggs, analyst; Bayley, 1893.
9. Sec. 25, T. 64 N., R. 5 E.; C.F. Sidener, analyst, Final Report Minn. Geol. Nat. History Survey, vol. 5.

Argillite

Fresh samples of argillite are black to dark gray, although they commonly weather light gray or reddish- and yellowish-brown. The black argillite ranges from a mica-rich rock to a very fine-grained siltstone. Mica-rich argillite is fissile, whereas the siltstones are thin- to thick-bedded; all variations in bedding exist and appear to reflect the amount of the silt-size fraction.

The mineralogy of approximately 50 argillite specimens was determined by X-ray diffraction. Quartz, plagioclase, muscovite, chlorite (14Å) and septechlorite (7Å) are the most abundant minerals. Estimated amounts based on relative peak areas indicate that in most argillites quartz > plagioclase and muscovite > chlorite. Pyrite or pyrrhotite and carbonaceous material are in all samples.

Because much of the formation was metamorphosed slightly, the 2M polytype of muscovite is common. However, several unmetamorphosed samples from Sibley Peninsula and Slate River in Ontario contain mixed layer dioctahedral-trioctahedral illite, and $1M_d$ and 1M muscovite polytypes. This indicates that most layered silicates in the formation were recrystallized to a more ordered polytype. However, fibrous intergrowths of chlorite and muscovite from apparently unmetamorphosed units also indicate recrystallization. James (1955, p. 1463) suggested that some chlorite in the Animikie rocks of northern Michigan may have formed by diagenetic processes, rather than by metamorphism. This also may be the case in the Rove Formation.

The texture of about 20 argillite and argillaceous siltstone samples was studied in thin section and by radiographs. The samples contain from 5-50 percent angular quartz and plagioclase silt grains (less than 0.1 mm), the remainder being clay-size muscovite, chlorite, quartz, opaque carbonaceous material, and well-developed euhedral crystals of pyrite and pyrrhotite. The samples contain only a minor amount of calcite. In all specimens examined, the silt grains are irregularly embayed by chlorite and muscovite. Preservation of the original clastic texture is largely a function of grain-size; in the very fine-grained rocks the shapes of the clastic grains are very poorly preserved, but in the coarser-grained siltstones the individual grains are well defined with only minor peripheral alteration. The size distribution of silt grains in several selected samples is shown in Figure 17.

Several chemical analyses (table 5) from various sources show an average Al_2O_3/Na_2O ratio of 9.2. Nanz (1953) and Pettijohn (1957, p. 358) consider such a ratio indicative of a sediment that is rather immature, and which was derived from a slightly weathered source area.

Provenance

The mineralogy of the Rove Formation is summarized in Figure 18. Because rock fragments constitute only a small part of the total rock, they were not plotted. On the basis of the predominance of feldspar over rock fragments, most samples are feldspathic graywackes or feldspathic siltstones.

The coarse fraction of the argillites has a mineralogic composition similar to that of the graywackes, indicating that both were derived from essentially the same terrane. Similar textures such as poor sorting and angularity of clastic grains show further that the argillite and graywacke were derived and deposited under similar conditions. Alumina-soda and quartz-feldspar ratios and the presence of unstable heavy minerals such as apatite and zoisite indicate rapid mechanical disintegration and little chemical weathering.

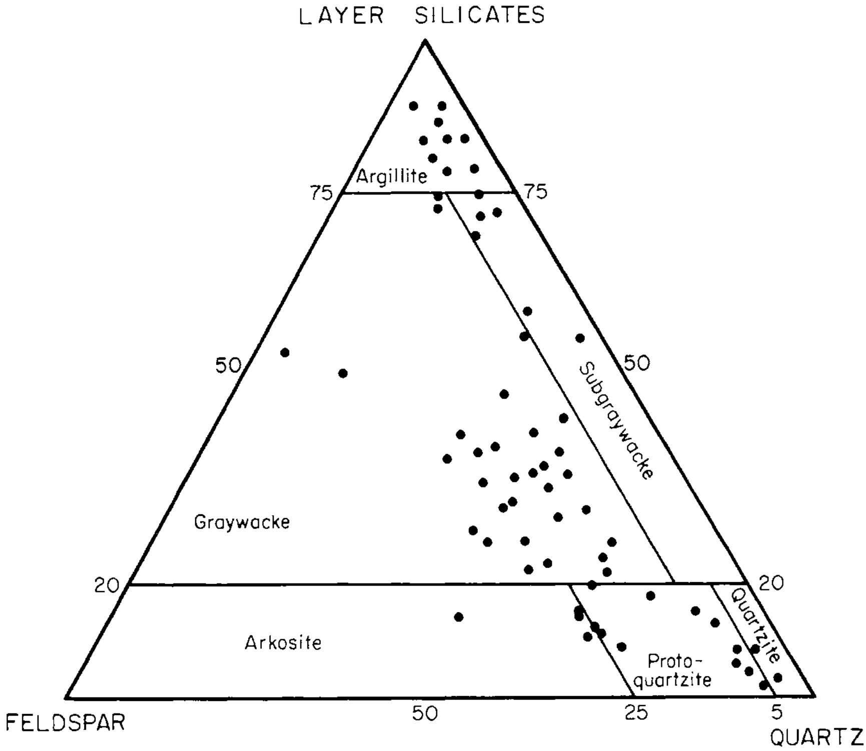


Figure 18. **Triangular diagram showing modal composition of selected samples from the Rove Formation. Diagram modified from Pettijohn, 1957, p. 48.**

The graywacke in the Rove Formation is similar in composition to other graywackes of various ages throughout the world (Engel and Engel, 1953, p. 1085; Balk, 1953; Reed, 1957) in that the amount of soda present exceeds that of potassium. Among the explanations offered (Middleton, 1961) to account for this characteristic are: (1) the sequence underwent soda metasomatism, (2) the strata were derived from soda-rich source rocks, or (3) weathering of the source rocks was incomplete.

Petrographic information from Rove samples indicate that most of the soda is concentrated in detrital plagioclase. There is no textural evidence to indicate albitization *in situ.* Although some feldspar grains near igneous masses are surrounded by a narrow rim of clear albite, metamorphism cannot account for all the sodic plagioclase found in the formation. Moreover, if the graywackes were albitized, the argillites should have been altered similarly. The analyses in Table 5 show a normal ratio for the argillites in contrast to that of the cogenetic graywackes. Therefore, it must be concluded that the sodic content of the graywackes is related to the original character of the source rocks.

Although Middleton (1961, p. 1018) concluded that most graywackes with a low K_2O/Na_2O ratio " . . . are the result of a partial volcanic (spilitic) provenance, combined with rapid erosion and little chemical weathering . . . " there is no evidence for such a source for the Rove Formation. Although the mineralogy of the Rove is diversified, the following facts indicate that the graywackes were derived mainly from a plutonic terrane of acid igneous rocks, granitic gneiss, and metamorphosed sedimentary rocks: (1) the dominant mineral assemblage is quartz, alkali feldspar, muscovite, and chlorite, (2) the quartz grains are indicative of granites, gneisses, and other metamorphic rocks (Krynine, 1940), (3) fragments of schist, quartzite, chert, and greenstone occur in the rocks but are rare, (4) a high ratio of feldspar to rock fragments indicates a plutonic rather than a supracrustal source, and (5) basic plagioclase, amphibole, and pyroxene minerals are absent.

Sedimentary directional structures and a suite of heavy minerals (table 6) similar to the assemblages that characterize the Algoman and older granitic rocks (Tyler and others, 1940, p. 1483-1503) indicate that these rocks, now exposed to the north of the present Rove outcrop belt, were a possible source of the Rove sediments.

Table 6 – Heavy minerals of the Rove Formation (in percent)

Mineral	M-10, 089(1)	M-10, 091	M-10, 092(2)	M-10, 094	M-10, 106
Andalusite	1	–	–	–	–
Apatite	28	22	16	20	24
Augite	1	–	–	–	–
Biotite	3	9	3	3	4
Chlorite	5	7	60	3	4
Epidote	2	1	–	1	2
Garnet	1	3	–	–	1
Hematite	–	7	5	5	15
Hornblende	9	7	–	12	6
Magnetite	2	–	2	–	3
Muscovite	–	–	–	–	1
Pyrite	1	–	–	–	–
Sphene	7	8	4	18	9
Tourmaline	13	3	1	9	10
Zircon	5	14	8	8	9
Zoisite	20	18	4	21	12
Unknown	–	–	–	2	–

(1)Samples on file with Minnesota Geological Survey.
(2)Metamorphosed chloritic quartzite.

While these potential source rocks are generally called granites (i.e., the Saganaga Granite, Snowbank Lake Granite, Vermilion Granite, and Giants Range Granite), detailed petrographic and chemical data to support this conclusion are almost completely lacking. A review of the chemical analyses available in the literature (Ruotsala and Tufford, 1965) indicates that many of the rocks, in fact, belong to the granodiorite clan. Most analyzed rocks are generally high in soda relative to potassium with an average K_2O/Na_2O ratio of 0.73. This value is close to that of 0.74 for an average granodiorite (Daly, 1933, p. 15). In addition, normative mineral calculations for these rocks indicates that on the average there is four times as much albite + anorthite as orthoclase. Middleton (1963, p. 1018) pointed out that granodioritic rocks also are a suitable source for many graywackes.

In summary, all the evidence seems to indicate that granodioritic rocks provided the source for the material now found in the Rove Formation.

GEOLOGIC HISTORY OF THE ANIMIKIE GROUP

The history of the Middle Precambrian rocks in the Lake Superior region is poorly known, but a few major events can be elucidated. These rocks apparently were deposited in an elongate basin that extended from Minnesota through Wisconsin to Michigan, and possibly to the Labrador trough (Goldich and others, 1961, p. 6). A generalized correlation chart of the Middle Precambrian in the Lake Superior region is given in Table 7. It is obvious that the Animikie Group in Minnesota, and particularly the Rove Formation, records only a small part of the depositional history of this basin.

The Animikie Group in Minnesota was deposited in the northern or miogeosynclinal part of the basin (Goldich and others, 1961, p. 118), the configuration of which was probably controlled by a pre-existing northeast-trending grain in the older rocks (Van Hise and Leith, 1911, p. 623). The present Animikie outcrop belt in northern Minnesota closely coincides with the southern contact of the Giants Range batholith and the north shore of the Animikie Sea apparently was parallel to this feature. The eastern and western limits of the basin are unknown, but White (1954, p. 43) suggested that the western shoreline was located somewhat to the west of the present Animikie exposures; the group extended to the east beyond the Thunder Bay district in Ontario (Goodwin, 1956). The basin extended southward into Wisconsin (Aldrich, 1929) and northern Michigan where typical eugeosynclinal accumulations are now exposed (James, 1958).

A few topographic irregularities existed on the Eparchean erosion surface upon which the Animikie rocks in northern Minnesota were deposited, but for the most part it was a broad relatively flat plain. Although a post-Algoman-pre-Animikie dolomite was reported from central Minnesota (Grout and Wolff, 1955), it was never deposited in northeastern Minnesota, or was removed by erosion or is now deeply buried, for no record of it remains at the surface. Subsidence caused the Animikie Sea to spread slowly across the low-lying land mass. Beach or shallow water deposits of conglomeratic material – the Pokegama Quartzite and its Canadian equivalent, the Kekabeka Formation – were deposited discontinuously during the sea's advance. Local irregularities in the surface crossed by the advancing sea are reflected by the presence of different thicknesses of these formations at different places.

The locus of deposition in Gunflint time in northeastern Minnesota was a broad shallow basin with limited marginal circulation. It is not known whether there was a direct connection between the Gunflint and Biwabik basins (table 7), but some evidence (Wolff, 1917; Broderick, 1920; Gill, 1926; Tanton, 1931) indicates that one existed.

Goodwin (1956, p. 594) demonstrated that the lithofacies in the Gunflint Iron-formation resulted from marine deposition at various water depths associated

Table 7. Generalized correlation chart of Middle Precambrian rocks in the Lake Superior region.

Gunflint District Minnesota & Canada (Goldich & others 1961; Tanton, 1931)	Mesabi District Minnesota (White, 1954)	Cuyuna District Minnesota (Grout & Wolff, 1955; Schmidt, 1963)	Gogebic District Wisconsin (Aldrich, 1929)	Menominee District Michigan (James, 1958)	
Upper Precambrian Sedimentary and Igneous Rocks. (younger than ~1.7 b.y.)					
		unconformity			
				Paint River Grp.	Animikie Series
				Boraga Grp.	
Animikie Grp. Rove Formation Gunflint Iron-formation Kekabeko Quartzite	Animikie Grp. Virginia Formation Biwabik Iron-formation Pokegoma Quartzite	Rabbit Lake Formation Trommald Formation Mahnomen Formation	Tyler Slate Ironwood Iron-formation Palms Quartzite	Menominee Grp.	
		Dolomite (unnamed)	Bad River Dolomite Sunday Quartzite	Randville Dolomite Sturgeon Quartzite Fern Creek Tillite	
		unconformity			
Lower Precambrian Igneous and Metamorphic Rocks. (older than ~2.5 b.y.)					

with periods of crystal unrest and volcanic activity. Goodwin (p. 587) suggested that this volcanic activity caused subsidence near the end of Gunflint time. The basin configuration was changed so as to permit the widespread entry of seawater from which the Upper Limestone Member of the Gunflint Iron-formation was deposited. Continued tectonic instability brought uplift of rocks to the north of the basin, resulting in a great influx of shaly material far into the basin. The abrupt change from chemical to clastic sedimentation is characteristic of much of the basin. It is reflected by rocks on the Mesabi range, Minnesota (White, 1954), on the Cuyuna range, Minnesota (Schmidt, 1963), and on the Gogebic range, Wisconsin (Aldrich, 1929).

The mechanism that produced the change from non-clastic to clastic deposition is not well understood. Evidence indicates that the basin in northeastern Minnesota was situated in a volcanic region, but it must have been somewhat distant from the center of igneous activity because the proportion of volcanic material present is relatively small. However, there is ample evidence of extensive volcanic activity and tectonic unrest in other parts of the basin. Schmidt (1963) emphasized the importance of pyroclastic materials which accumulated subsequent to the deposition of the main iron-formation of the Cuyuna district. He suggested that some of the materials may represent basaltic lavas that were poured out following the deposition of the iron-formation. James (1958, p. 35) noted that the interpretation of rocks approximately equivalent to the Rove Formation in northern Michigan is complicated by the presence of much volcanic material. The Animikie Group in Minnesota is correlated with a thick sequence of interbedded lenticular slate, graywacke, quartzite, iron-formations, and metamorphosed basalts in Michigan, which James (1958, p. 35) assigned to the Menominee and Baraga Groups (table 7). The fact that individual formations in these groups are lenticular and variable in thickness indicates that they were deposited in a series of small basins in a tectonically unstable area. Therefore, it seems reasonable to postulate that tectonic instability in other parts of the basin is reflected in northeastern Minnesota by rather abrupt changes in the kinds of sediments that were deposited.

Early Rove time was characterized by the deposition of black shales that accumulated in quiet water. The depth of water in which they accumulated was not necessarily very great as evidenced by black muds that are accumulating in shallow water today. Limestone and dolomite beds interlayered with the shales contain minor amounts of volcanic material, indicating that some volcanism continued into early Rove time. They also indicate short periods of diminished clastic supply to the basin with a return to depositional conditions like that in late Gunflint time.

The basin must have slowly subsided at a rate such that filling did not keep pace with downwarping. The water gradually deepened and a bottom slope developed that permitted introduction of much silt- and sand-size material to the basin by means of turbidity currents. The transition of the rocks in the lower argillite unit into thin-bedded graywacke records an increase in the frequency and intensity of turbidite deposition. Here again, tectonic instability in other parts of the basin probably is reflected in the rocks of the Rove Formation.

Although modern marine turbidites are accumulating in water depths of less than 600 feet in Lake Mead (Gould, 1951), other modern turbidites are recognized in water depths from 3,000 feet (Bouma and Shepard, 1964) to greater than 15,000 feet (Heezen and others, 1964). Ancient turbidites that are similar in many aspects to the Rove Formation have been reported in inferred water depths of more than several thousand feet (Sullwold, 1960; Natland and Kuenen, 1951). Thus, while it generally has been assumed that ancient turbidites were deposited in "deep-water", this conclusion cannot be demonstrated for the Rove Formation. Because there is no fossil evidence and because neither the shoreline nor the center of the Animikie basin can be located with any degree of certainty, it is not possible to determine specifically in which part of the basin the Rove Formation was deposited. In addition, the presence of turbidites in a basin tells nothing of the distance to a shoreline. Modern marine turbidites are found from as close as three miles (Gorsline and Emery, 1959) to as much as 300 miles offshore (Heezen and others, 1959). However, because many recent turbidites are initiated at the heads of submarine valleys that funnel and direct the current, it is possible that the bulk of each turbidity current load in the Rove Formation was deposited near the mouths of such valleys at a break in slope. Rocks in the shoreward facies are not now found because of pre-Keweenawan tilting and erosion.

A large land mass is postulated as the source of the material found in the Rove Formation. If a high narrow cordillera was the source of the material found in the Rove Formation (estimated to have a volume of at least 400 cubic miles), it would have necessitated high relief and rapid erosion. Consequently, much coarse material would necessarily have been produced, a situation not found in the formation. On the other hand, large, modern sedimentary basins such as the Gulf of Mexico receive most of their fine-grained material from large streams that drain low-lying continental areas.

Algoman and older igneous and metamorphic rocks now found to the north of the basin were probably the source of the Rove Formation, as indicated by paleocurrent directions and by the mineralogy of the sediments. The immaturity of the clastic constituents and the heavy mineral suite in the Rove indicate that the source area was elevated sufficiently for erosion to proceed rapidly with little chemical weathering.

It is not possible to quantitatively estimate the rate of deposition except in a very crude way. Sujkowski (1957, p. 555) estimated that the deposition of interturbidite shale beds in the Carpathian flysch proceeded at an average rate of 0.8 to 1 inch of compacted mud per 1,000 years. If the same sedimentation rate is applied to the Rove sediments, the interlayered argillites were deposited in approximately 20 million years. This is only a minimum value, however, for it does not take into account the time necessary for the deposition of the turbidite material, which was probably almost instantaneous in terms of geologic time, nor does it account for any of the Rove Formation deposited but not now visible because of pre-Keweenawan erosion or Keweenawan igneous activity. If this value is of the correct order of magnitude, and even if the deposition of the underlying Gunflint Iron-formation proceeded at a much slower rate, Animikie sedimentation in northeastern Minnesota can account for only 10-20 percent of Middle Precambrian time.

Goldich and others (1961, p. 120) suggested that during later stages of deposition, the basin became unstable and the near-axial portion was folded and intruded by igneous rocks at about 1.7 billion years ago. Because the locus of folding followed a line south of the present site of Lake Superior, the rocks in northern Minnesota were little affected, whereas those in central Minnesota, northern Wisconsin, and northern Michigan were strongly deformed and metamorphosed. This deformation, called the Penokean orogeny, marked the end of the Middle Precambrian in the Lake Superior region.

METAMORPHISM

Much of the Rove Formation has been metamorphosed by the intrusion of Middle Keweenawan igneous rocks. These changes are considered briefly and limits are placed on the degree of metamorphism, in order to understand more clearly the mineral composition of the original rock.

Rather extensive petrographic studies of metamorphosed Rove rocks were made by Davidson (1926) and Grout and Schwartz (1933). In addition, Grout (1933) provided some chemical and microscopic analyses of metamorphic effects on many Minnesota slates and graywackes, including some from the Rove Formation. However, the microscopic data were not correlated with chemical data, so the latter have been of only limited value in this investigation.

Textural Changes

Several lines of evidence are necessary to demonstrate that metamorphism has affected a rock. The most obvious of the various criteria, as set forth by Zen (1963, p. 929-947), is that of textural readjustment. Textural readjustment indicates that during recrystallization an opportunity existed for the simultaneous establishment of new mineral assemblages in chemical equilibrium with their environment.

The textures of Rove rocks near the Duluth Complex and the Logan sills clearly indicate recrystallization. The width of the recrystallized aureole is directly proportional to the size of the igneous body. This is best seen at the contact of the Duluth Complex, where the Rove Formation has been completely recrystallized to a sugary, granular – granulitic, granoblastic, or hornfelsic – rock that extends at several localities several tens of feet away from the contact. Individual grains are mostly less than one millimeter in diameter, but they are somewhat larger near the gabbro. Poikiloblastic texture, in which grains of feldspar, quartz, magnetite, and other minerals are included in pyroxene and biotite, is very common. Such contact rocks have long been confused with a "chilled-phase" of the gabbro, but at a large number of localities – e.g. the south shore of Alder Lake, locality 57 – there is a complete gradation from normal sedimentary to gabbroic rock types. This thermal metamorphism, which is somewhat complicated by the introduction of material from the gabbro, was briefly described by Grout (1933). Some specimens collected during the present study were taken from the contact zone, both near and far from the present gabbro contact, and are characteristic of the features induced by the gabbro.

Extreme metamorphism has resulted in a rock that superficially resembles gneiss (fig. 19a). The banding is the result of differences in composition controlled by the original mineralogy of the sediment. The light-colored layers, which were originally the sand- and silt-size fraction, are rich in quartz and plagioclase, whereas the dark-colored, originally clayey layers are now biotite- and chlorite-rich. Within a distance of 10 feet of the contact there has been complete recrystallization to a massive fine- to medium-grained, quartz-biotite-plagioclase-pyroxene hornfels (fig. 19b). The concentration of biotite in laminae probably reflects initial sedimentary layering. The laminae are not foliated, but characteristically have a decussate fabric, indicating recrystallization under thermal rather than under stress conditions. Pyrrhotite occurs extensively as small to large blebs. In addition, minor amounts of andalusite and cordierite, most grains of which are altered to chlorite or sericite, are common.

Figure 19. Textural changes due to metamorphism of the Rove Formation.

a. Gneiss-like metasedimentary rock from near the Duluth Complex. The white bands are quartz and feldspar-rich, and the dark bands are rich in layer silicates; Alder Lake, section 10, T. 64 N., R. 1 E.

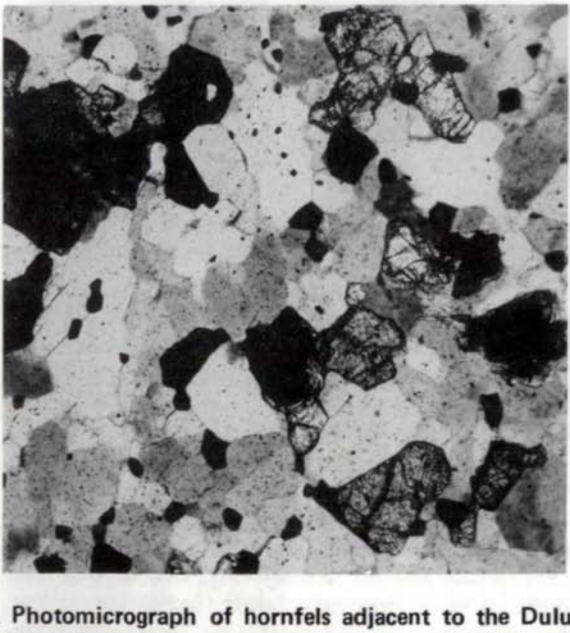


Figure 19 (Con't.) b. Photomicrograph of hornfels adjacent to the Duluth Complex. The black grains are magnetite; those with high relief are orthopyroxene; gray grains are feldspar and white grains quartz; M-10, 090 (X-nicols, x75).

Samples taken 50 to 100 feet from the contact contain chlorite, muscovite, quartz, plagioclase, and some biotite. Angular sedimentary quartz grains and a few altered sericitized plagioclase fragments are still visible. The fine-grained matrix is cloudy and consists of slightly recrystallized quartz, muscovite, and chlorite, with a little biotite and plagioclase.

A similar change can be seen in the sedimentary rocks beneath many of the thicker Logan sills – *e.g.* locality 24, fig. 2. Near many smaller sills, metamorphic textures indicative of less severe temperature conditions also are commonly developed. Recrystallization and segregation into distinct microscopic bands in the coarse-grained clastic portions of the Rove has occurred immediately adjacent to the sills. The basal planes of the clay minerals are oriented parallel to the plane of foliation. Quartz grains are roughly rectangular (fig. 19c), and hence two edges are parallel to the foliation. Plagioclase grains are surrounded by clear rims of plagioclase (An_{10}), which further tends to accentuate the rectangular outlines.

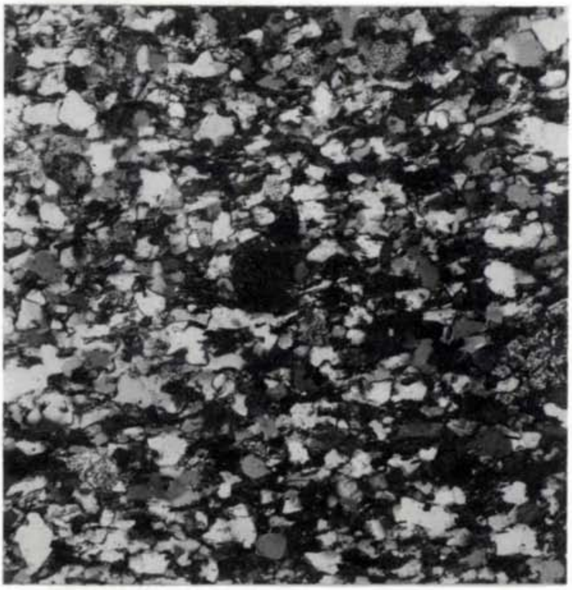


Figure 19 (Con't.) c. Photomicrograph of a metamorphosed siltstone from near the contact with a sill showing recrystallization of the clastic material into elongate grains parallel to a secondary foliation. Such textures are common near the Logan Intrusives; M-10, 090 (x63).

Platy minerals in the fine-grained rocks, however, show the most definitive evidence of metamorphic recrystallization. Microporphyroblasts up to two mm in diameter composed of chlorite-muscovite intergrowths are common in the argillites. They are randomly oriented but generally cut across the lamination and foliation. They are filled with carbonaceous inclusions, but are surrounded by inclusion-free rims. Around the outside of the rims, however, there are secondary concentrations of carbonaceous material that tend to merge into a general carbon-rich background (fig. 20a). This evidence implies the following interpretation. First, the originally carbonaceous rock was progressively metamorphosed, thereby destroying the carbon and forming the clear rims by the reaction: Graphite + hematite + silicate phase = chlorite +CO_2 (Zen, 1963, p. 934). Carbon-residues isolated from the reacting system by growth of chlorite produce the turbid appearance in the centers of the porphyroblasts. With a further increase in temperature, the smaller porphyroblasts merged into larger clusters and the rock became cleaner (fig. 20b), indicating the bulk of the carbonaceous material was lost, presumably as carbon dioxide. Second, the carbonaceous rims concentrated around the porphyroblasts indicates that material not destroyed by metamorphism and not incorporated in the crystal was pushed aside during crystal growth.

Biotite may or may not be associated with the above mentioned minerals. When present, it occurs as sheaves of fine- to coarse-grained books that are commonly wrapped around larger grains of quartz and feldspar.

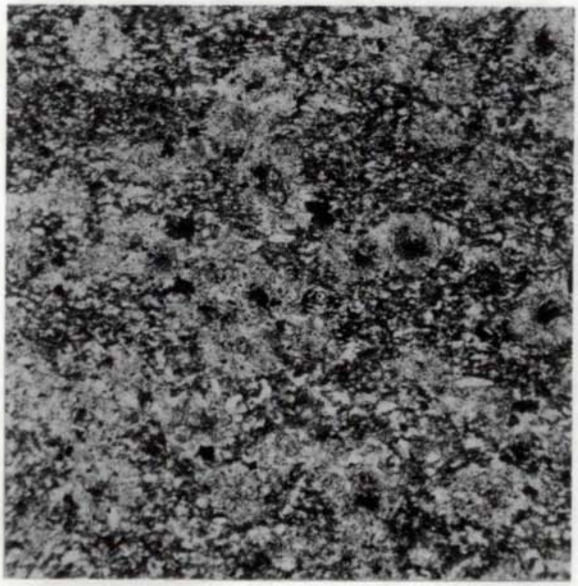


Figure 20. Photomicrographs showing the progressive metamorphism of an argillite near the contact of a sill; section 21, T. 65 N., R. 2 W.

a. Weakly metamorphosed argillite. Note the poorly developed micro-porphyroblasts of muscovite with carbonaceous rims and centers. Many also have pyritic centers; M-10, 003, eight feet beneath the contact (x63).

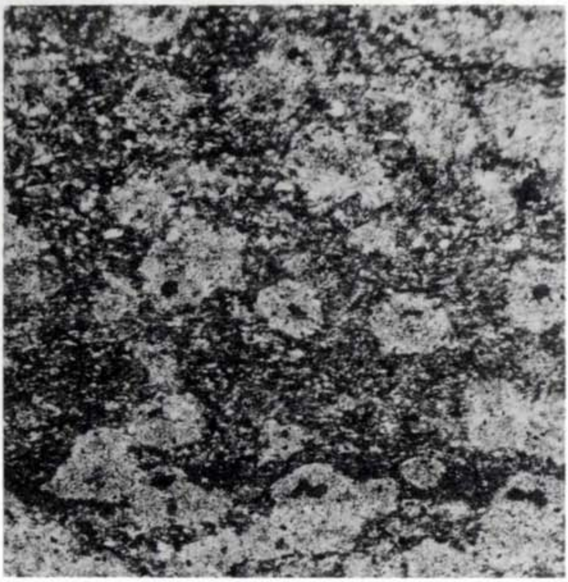


Figure 20 (Con't.) b. Note the well developed micro-porphyroblasts which are almost merged. The dark background is a mixture of chlorite, quartz, plagioclase, carbonaceous material and pyrite; M-10, 004, four feet beneath the contact (x63).

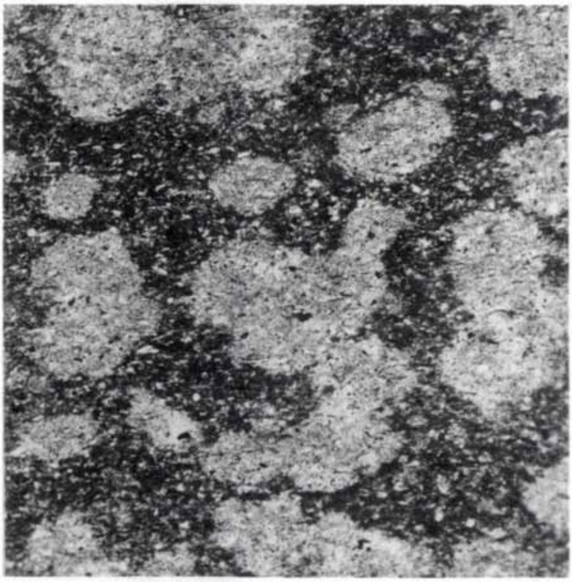


Figure 20 (Con't.) c. Near the sill the micro-porphyroblasts are large and intergrown isolating parts of the original matrix; M-10, 005, one foot beneath the contact (x63).

Mineral Assemblages

Chemical changes in the mineralogy of the Rove Formation must have been associated with the textural changes described above. Therefore, the various mineralogic assemblages noted are listed below. This approach emphasizes the dependence of the observed assemblages on the original bulk composition and on the metamorphic environment. The list does not indicate relative amounts of the minerals present, although such differences may be the result of slight differences in either the composition of the original rock or in the pressure-temperature conditions associated with the metamorphic environment. Also, the accessory or "heavy minerals" are not included in the list. The assemblages are roughly arranged by their rock type and by geologic occurrence.

I. Quartzitic and quartzo-feldspathic rocks.
   A. Assemblages distant from igneous rocks.
      1. Muscovite-chlorite-sodic plagioclase-quartz.
      2. Muscovite-chlorite-quartz.
      3. Muscovite-epidote-sodic plagioclase-quartz.
      4. Muscovite-biotite-sodic plagioclase-quartz.
      5. Muscovite-biotite-sodic plagioclase-potassium feldspar-quartz.
      6. Muscovite-biotite-chlorite-sodic plagioclase-quartz.
   B. Assemblages near igneous rocks.
      7. Biotite-muscovite-quartz.
      8. Biotite-muscovite-plagioclase-quartz.
      9. Biotite-muscovite-microcline-plagioclase-quartz.

II. Argillites and Graywackes

In addition to having the same assemblages as above, the following assemblages occur near the Duluth Complex and some of the larger Logan sills.

10. Andalusite-plagioclase-quartz.
11. Andalusite-plagioclase-muscovite-quartz.
12. Andalusite-cordierite-biotite-quartz.
13. Cordierite-biotite-muscovite-plagioclase-quartz.
14. Cordierite-hypersthene-plagioclase-quartz.
15. Hypersthene-plagioclase-quartz.
16. Amphibole-plagioclase-quartz.
17. Amphibole-plagioclase-biotite-quartz.

III. Concretions
   A. Assemblages distant from igneous rocks.
      18. Calcite-quartz-albite-potassium feldspar-muscovite-chlorite.
      19. Dolomite-quartz-plagioclase-muscovite-chlorite.
      20. Calcite-dolomite-quartz-plagioclase-muscovite-chlorite.
   B. Assemblages near igneous rocks.
      21. Calcite-epidote-chlorite-quartz.
      22. Diopside-grossularite-plagioclase-quartz.
      23. Diopside-grossularite-calcite-quartz.

The foregoing list of mineral assemblages can be plotted in terms of ternary phase diagrams (fig. 21). The phase diagrams make it easier to understand the mutual stability relationships of the mineral phases in a given pressure-temperature environment. The fact that the assemblages can be plotted and the fact that there is no evidence to refute the idea of equilibrium strongly implies that equilibrium was attained. The argument for phase equilibrium would be more persuasive if it could be demonstrated that the phase relations depicted in the diagrams are obeyed in detail. However, a lack of accurate chemical data on individual minerals makes this impossible at the present time.

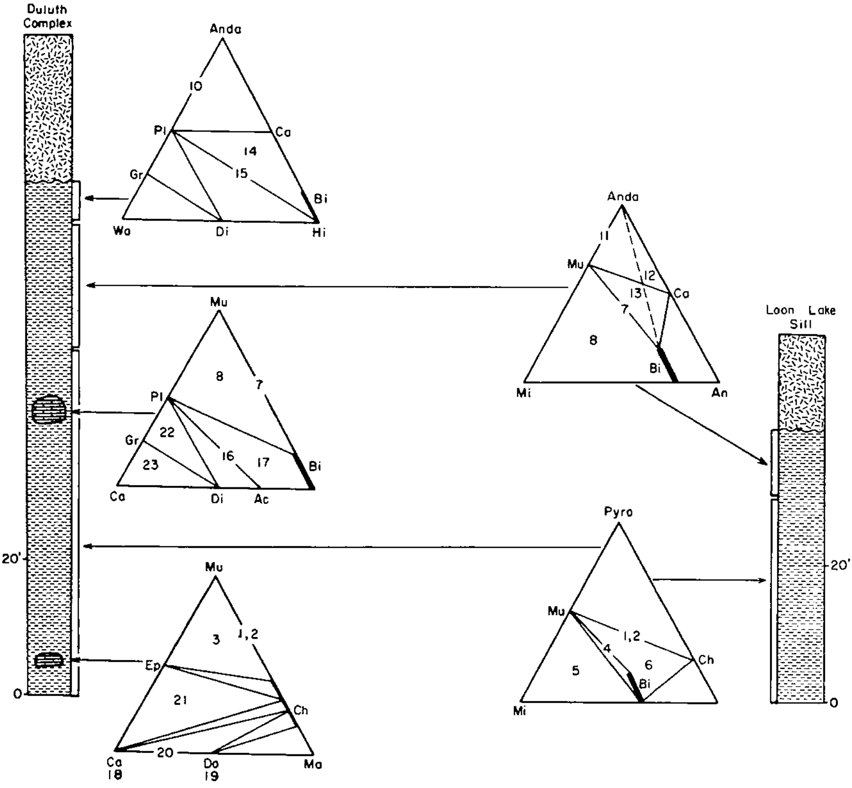


Figure 21. Distribution of metamorphic mineral assemblages near the Duluth Complex and the Logan Intrusives. (Anda = andalusite; Pl = plagioclase; Co = cordierite; Gr = garnet; Wa = wollastonite; Di = diopside; Bi = biotite; Hy = hypersthene; Mu = muscovite; Ca = calcite; Ac = actinolite; Mi = microcline; Ep = epidote; Do = dolomite; Ma = magnesium oxide; Ch = chlorite; Pyro = pyrophyllite; An = anthophyllite).

Discussion

Temperatures at which the mineral assemblages formed can be determined only by the application of experimental data. The lower limit is controlled by reaction kinetics whereby sedimentary clays and micas ($1M_d$ and 1M polymorphs of muscovite) and chlorites are reorganized to 2M muscovite and aluminous chlorites. At the same temperature, high temperature minerals – quartz and plagioclase – are replaced by appropriate combinations of albite, epidote, chlorite, and calcite.

The upper temperature limit is difficult to estimate. Non-calcareous rocks immediately adjacent to the contact contain a quartz-plagioclase-hypersthene-cordierite assemblage. They are assigned to the pyroxene-hornfels facies, which is stable at 655° to 830° C at P_{water} = approximately 1,000 bars (Turner and Verhoogen, 1960).

Concretions metamorphosed by the Duluth Complex to an assemblage characterized by diopside are assigned to the hornblende-hornfels facies. Turner and Verhoogen (1960, p. 519) suggested that diopside forms at around 500° to 600° C in the pressure range P_{water} = 1,000 to 3,000 bars.

Some pelitic rocks near the larger Logan sills are characterized by the assemblage andalusite-cordierite-muscovite-plagioclase-quartz which, because of the muscovite, is assigned to the hornblende-hornfels facies. Cordierite and andalusite are locally present in much of the metamorphosed part of the formation, imparting a speckled appearance. This kind of speckling is common in many thermally metamorphosed rocks and seems to form early in the metamorphic history of a rock originally high in alumina and chloritic material and deficient in potassium feldspar (Harker, 1956, p. 49). Winkler (1957) placed the temperature limit for this assemblage between 525° and 560° in lime-free clay systems.

From the foregoing discussion it is concluded that Rove material adjacent to the various Keweenawan intrusives reached temperatures ranging from 300° to 800° C.

As noted previously, the intrusion of the Keweenawan rocks – and hence the metamorphism of the Rove – is dated at approximately 1.115± .15 b.y. ago (Silver and others, 1963, p. 107). Although rocks equivalent to the Rove Formation in other parts of the Animikie basin were involved in an earlier metamorphic event at 1.7 billion years ago, no evidence was found to indicate such an event in the Rove part of the basin. Rocks exposed in the northeastern part of the Rove area are the only ones not affected by Keweenawan igneous activity, and represent a "window" through which the effects of pre-Keweenawan metamorphism, if present, should be observable. However, $1M_d$ and 1M muscovite polytypes are common in many specimens sampled from this area, and if they were affected by the earlier regional metamorphism, it is expected that the more stable 2M polytype of muscovite would be present. Although the foregoing evidence does not completely rule out the possibility that Rove rocks in the southwestern part of outcrop area were affected by the 1.7 billion year event, it appears likely that all of the metamorphic assemblages now found in the formation are related to the 1.115 billion year event.

Therefore, the rocks exposed in these "windows" probably reflect the original mineralogy of the Rove Formation. They probably were composed of a simple assemblage of detrital quartz and plagioclase in a matrix of chlorite, muscovite, illite, and minor amounts of iron sulfides.

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