MINNESOTA GEOLOGICAL SURVEY

MATT WALTON, *Director*

STRATIGRAPHY AND SEDIMENTOLOGY OF THE LOWER PROTEROZOIC VIRGINIA FORMATION, NORTHERN MINNESOTA

M.E. Lucente and G.B. Morey

Report of Investigations **28**

ISSN 0076-9177

UNIVERSITY OF MINNESOTA

Saint Paul - 1983

STRATIGRAPHY AND SEDIMENTOLOGY OF THE LOWER PROTEROZOIC VIRGINIA FORMATION, NORTHERN MINNESOTA

CONTENTS

Page

Abstract. 1

Introduction. 1

Stratigraphic nomenclature. 4

Stratigraphy. 4
  Lower argillaceous lithosome 5
  Upper silty and sandy lithosome. 5

Petrology 5
  Argillite and silty argillite. 5
  Sandstone and siltstone. 7
    Feldspathic graywacke 7
    Arkose. 9
  Limestone. 9
  Carbonate concretions. 9
  Cherty sideritic iron-formation. 12
  Chert. 12
  Ash-fall tuff. 12

Sedimentologic attributes 12
  Pelagic and hemipelagic deposits 12
  Turbidite deposits 14
    Thick-bedded turbidites 14
    Thin-bedded turbidites. 15
  Bottom-current deposits. 15
  Chemically precipitated deposits 15

Sedimentation and provenance. 15

Regional sedimentologic relationships 18

Conclusions 19

References cited. 19

Appendix - Lithic logs of the Virginia Formation. 21

ILLUSTRATIONS

Figure 1--Geologic map of northern and east-central Minnesota 2

2--Correlation chart 2

3--Geologic map of the Mesabi range. 3

4--Cross section of the Virginia Formation 4

5--Photographs of laminated argillite. 6

6--Diagrams summarizing mineralogic composition. 7

7--Photomicrograph of feldspathic graywacke. 10

8--Photomicrograph of unaltered plagioclase in feldspathic graywacke 10

9--Photomicrograph of highly altered plagioclase in feldspathic graywacke. 10

Figure 10--Photomicrograph of altered plagioclase with twinning in feldspathic graywacke. 10

11--Photomicrograph of quartz in feldspathic graywacke. . . . 10

12--Photomicrograph of intergrown plagioclase and quartz in feldspathic graywacke. 10

13--Photomicrograph of phyllitic rock fragment in feldspathic graywacke. 11

14--Photomicrograph of recrystallized clay matrix in feldspathic graywacke. 11

15--Photomicrograph of pseudomatrix material in feldspathic graywacke 11

16--Photomicrograph of authigenic sericite as rim cement in feldspathic graywacke. 11

17--Photomicrograph of detrital K-feldspar surrounded by authigenic cement in arkose. 11

18--Photomicrograph of quartz partly replaced by poikilitic sparry calcite cement in arkose 11

19--Photograph and radiograph of allochemical limestone . . . 13

20--Diagram showing abundance and types of bedding features in graywacke and siltstone 14

21--Photograph of a typical thick-bedded turbidite. 16

22--Photograph of a typical thin-bedded turbidite 16

23--Photograph of typical bottom-current deposits 16

24--Submarine fan environmental model 18

25--Diagrams comparing Virginia, Rove, and Thomson Formations with a hypothetical submarine fan sequence . . 18

TABLE

Table 1 - Mineralogic composition of selected Virginia Formation sandstones 8

STRATIGRAPHY AND SEDIMENTOLOGY OF THE LOWER PROTEROZOIC VIRGINIA FORMATION, NORTHERN MINNESOTA

By

M.E. Lucente and G.B. Morey

ABSTRACT

The lower Proterozoic Virginia Formation, a thick sequence of argillite, siltstone, and graywacke, forms the top of the Animikie Group on the Mesabi range in northern Minnesota. It is overlain by thick Quaternary deposits, but is exposed locally where the underlying Biwabik Iron Formation has been mined. Drill cores available from four sites provide stratigraphic and sedimentologic data, and the 450 m of core from a site south of Biwabik and 342 m of core from south of Calumet are proposed as alternate reference sections to the original type locality. The Virginia Formation can be divided into two informal members--a lower argillaceous lithosome and an upper silty and sandy lithosome. The argillaceous lithosome thickens toward the west end of the Mesabi range where it also contains appreciable quantities of chert and a discrete unit of cherty, sideritic iron-formation. The upper silty and sandy lithosome also consists predominantly of argillite, but is characterized by intercalated beds of siltstone and fine-grained graywacke. Mineralogic and sedimentologic data indicate that the graywackes were derived largely from granitic and low-grade metasedimentary and metavolcanic rocks like those now exposed in the Archean greenstone-granite north of the Mesabi range, and that they were deposited by turbidity currents on a southward-dipping paleoslope into a basin south of the range. In detail, the sedimentologic attributes of the formation resemble "thickening- and coarsening-upward" turbidite sequences associated with the lower and mid-fan parts of a prograding submarine fan complex.

INTRODUCTION

The Virginia Formation of early Proterozoic age forms the uppermost lithostratigraphic unit in the Animikie Group on the Mesabi range in northern Minnesota (Figs. 1 and 2). Along most of the Mesabi range, the Animikie Group forms a gently dipping homocline that strikes east-northeast and dips 5°-15° to the south. The homoclinal structure is interrupted locally by faults (Fig. 3) and southwest-plunging folds. An unknown amount of lower Proterozoic strata was eroded after tilting and prior to emplacement of the Duluth Complex at the eastern end of the range in middle Proterozoic time. During Cretaceous time the lower Proterozoic strata were extensively weathered, and the resulting saprolite was subsequently covered by a thin veneer of nonmarine to marine strata. Much of the bedrock is now covered by glacial and fluvial deposits formed during Pleistocene and Holocene times.

The Virginia Formation is a thick sequence that consists dominantly of argillite, siltstone, and fine-grained graywacke. It gradationally overlies the Biwabik Iron Formation along the south side of the Mesabi range, and is inferred to extend southward for an unknown distance; broadly correlative rocks reappear again in east-central Minnesota where they are assigned to either the Rabbit Lake Formation of the Cuyuna range or the Thomson Formation of Carlton and Pine Counties (Fig. 2).

Because of the nearly ubiquitous mantle of Pleistocene and Holocene materials, the Virginia Formation is exposed only locally in several iron-ore mines along the Mesabi range where a few meters of strata can be seen just above the Biwabik Iron Formation. The absence of natural exposures and the lack of subsurface information have precluded any detailed stratigraphic and sedimentologic studies of the Virginia Formation. However approximately 1,060 m of diamond drill core of essentially unmetamorphosed Virginia Formation at four sites (Fig. 3) were obtained during an evaluation of the possibility of underground mining of taconite in the underlying Biwabik Iron Formation (Pfleider and others, 1968). Although these cores represent only a small sample, they are the most complete and continuous record of the Virginia Formation available in the public domain and provide the materials that form the basis for this study.

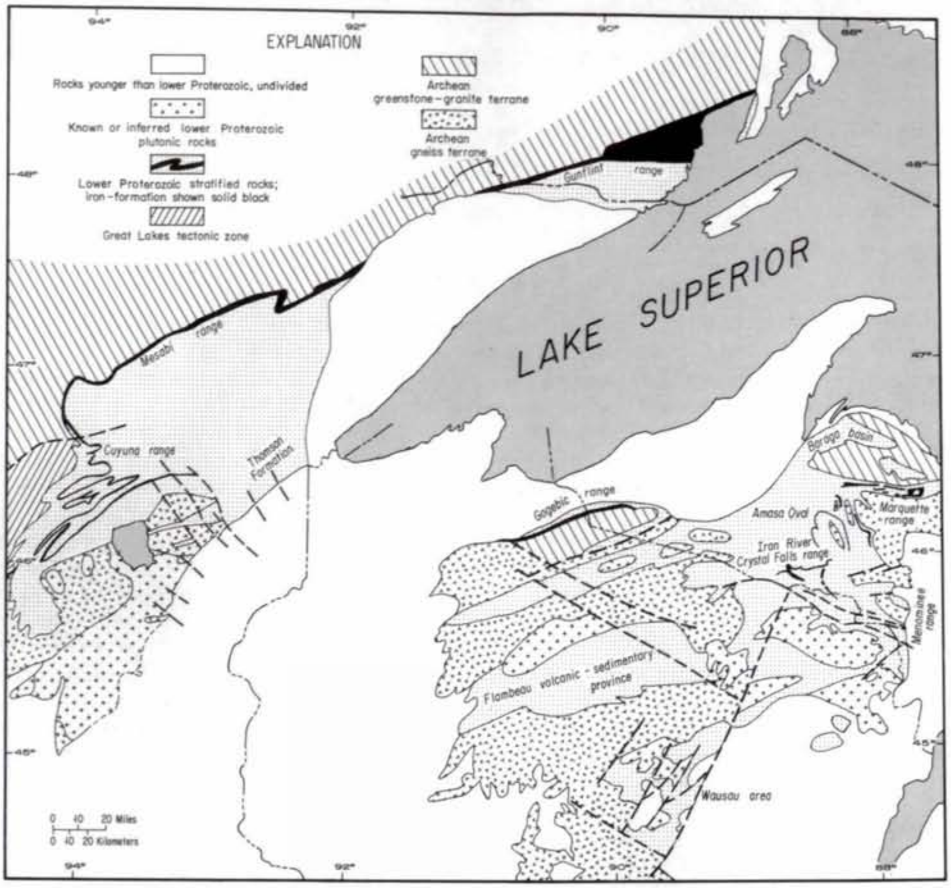
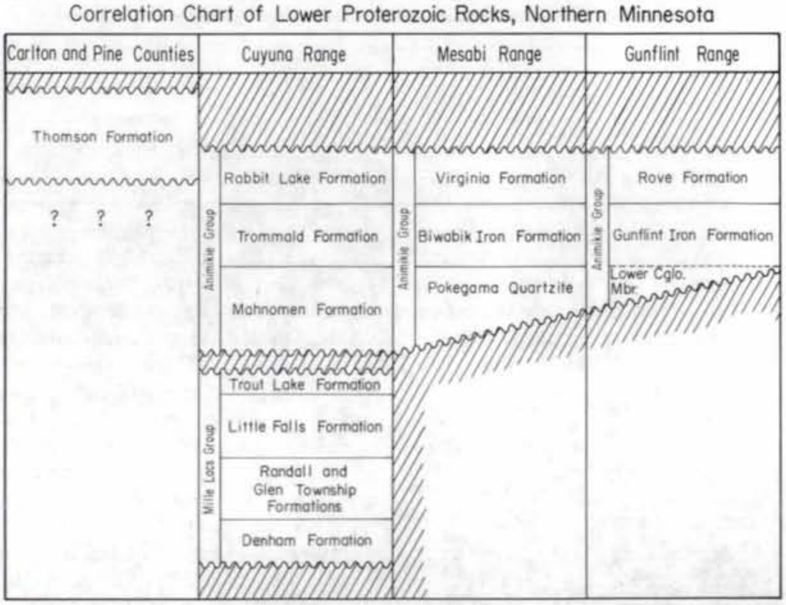
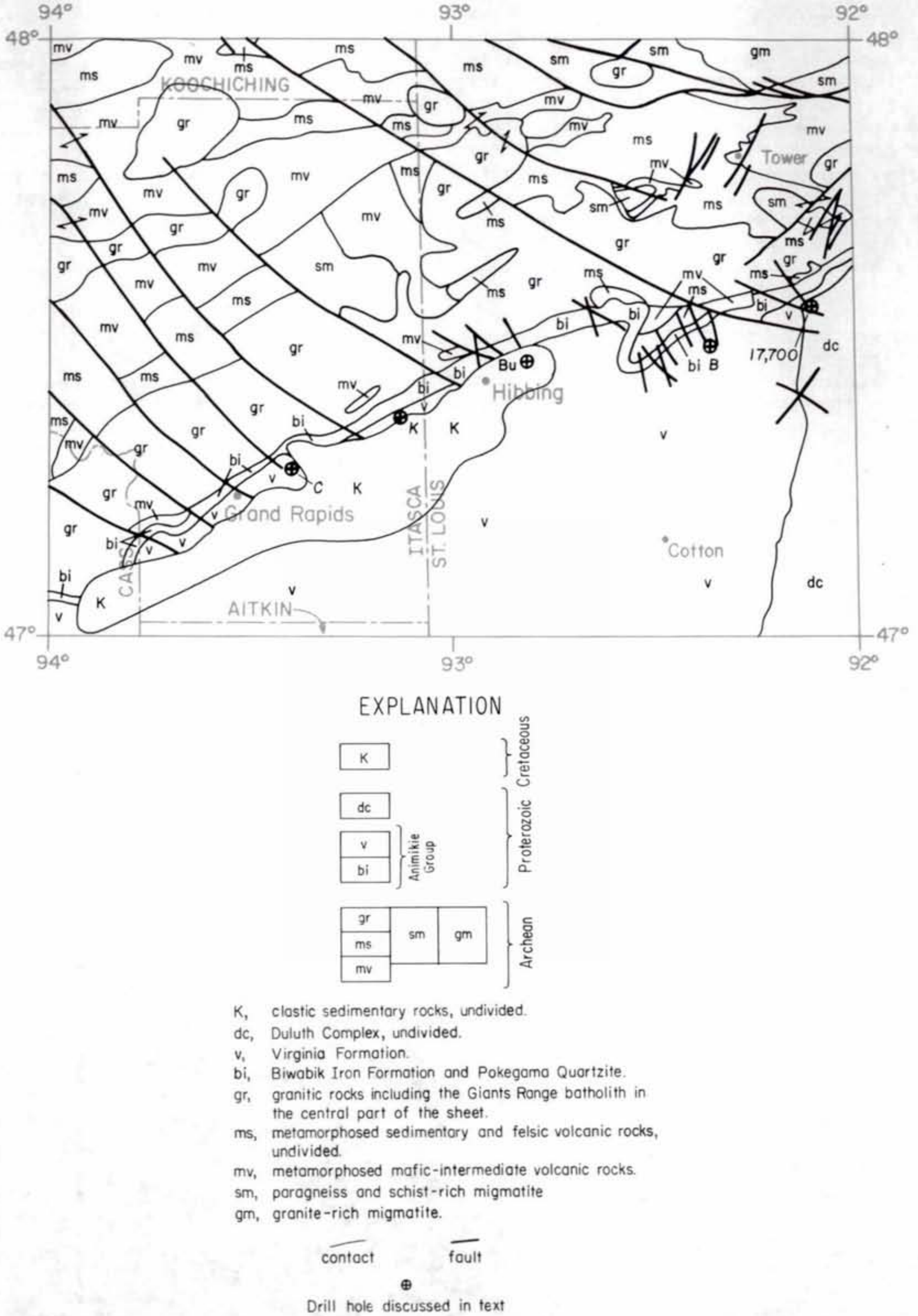


Figure 1. Generalized geologic map of the Lake Superior region showing the distribution of lower Proterozoic rocks and the major iron ranges.


Correlation Chart of Lower Proterozoic Rocks, Northern Minnesota

Carlton and Pine Counties	Cuyuna Range		Mesabi Range		Gunflint Range	
Thomson Formation						
? ? ?	Animikie Group	Rabbit Lake Formation	Animikie Group	Virginia Formation	Animikie Group	Rove Formation
		Trommald Formation		Biwabik Iron Formation		Gunflint Iron Formation
		Mahnomen Formation		Pokegama Quartzite		Lower Cglo. Mbr.
	Mille Lacs Group	Trout Lake Formation				
		Little Falls Formation				
		Randall and Glen Township Formations				
		Denham Formation				

Figure 2. Correlation chart of lower Proterozoic rocks, northern and east-central Minnesota.



K, clastic sedimentary rocks, undivided.
dc, Duluth Complex, undivided.
v, Virginia Formation.
bi, Biwabik Iron Formation and Pokegama Quartzite.
gr, granitic rocks including the Giants Range batholith in the central part of the sheet.
ms, metamorphosed sedimentary and felsic volcanic rocks, undivided.
mv, metamorphosed mafic-intermediate volcanic rocks.
sm, paragneiss and schist-rich migmatite
gm, granite-rich migmatite.

contact
fault

Drill hole discussed in text

Figure 3. Geologic map of the Mesabi range and environs (modified from Morey and others, 1982) showing the locations (C, Calumet; K, Keewatin; Bu, Buhl; B, Biwabik; 17,700, Drill Hole 17,700) of drill cores discussed in the text.

STRATIGRAPHIC NOMENCLATURE

The term "Virginia Slate" was first proposed by Van Hise and Leith (1901, p. 360) for exposures of "...dense, fine-grained, gray to black, sometimes graphitic slate and argillaceous siltstone...in numerous test pits and drill holes west of the town of Virginia in the central part of the Mesabi range." However because the strata are dominantly argillite, rather than true slate, and because beds of siltstone and sandstone make up an appreciable part of the sequence, the name was changed to "Virginia Formation" by White (1954, p. 18) and that terminology is retained here.

The original type locality is not easily accessible because the area in and around the city of Virginia contains numerous iron-ore mines. Furthermore Van Hise and Leith never described a specific type section. However the 450 m of Virginia core obtained from south of Biwabik and the 342 m of core obtained from south of Calumet (Fig. 3) are representative of the Virginia Formation at the eastern and western ends of the Mesabi range, respectively. In lieu of easily accessible exposures at a well-defined type locality, it is therefore proposed here that the core material obtained from these localities be established as alternative reference sections to the original type locality. Additional cores from south of Buhl and south of Keewatin intersect only 92 m and 175 m of strata, respectively, and therefore have limited stratigraphic value. The cores are described in detail in the appendix, and may be examined at the U.S. Bureau of Mines Core Depository, Fort Snelling, Minnesota. In addition to the unmetamorphosed material, approximately 158 m of metamorphosed Virginia strata from a fifth site--Drill Hole 17,700 (Morey and others, 1972)--also was examined for stratigraphic data, but a strong metamorphic overprint precludes any detailed sedimentologic study of this material.

STRATIGRAPHY

The Virginia Formation consists of intercalated beds of argillite, carbonaceous argillite, argillaceous siltstone, siltstone, very fine to fine-grained graywacke, and lesser amounts of arkose, limestone, chert, cherty sideritic iron-formation, and ash-fall tuff. In general the minor rock types are confined to the lower part of the formation, where they are intercalated with beds of argillite and carbonaceous argillite. In contrast, beds of siltstone and graywacke occur predominantly in the upper part of the formation. These differences serve to divide the Virginia Formation into two informal members--a lower argillaceous lithosome and an upper silty and sandy lithosome (Fig. 4).

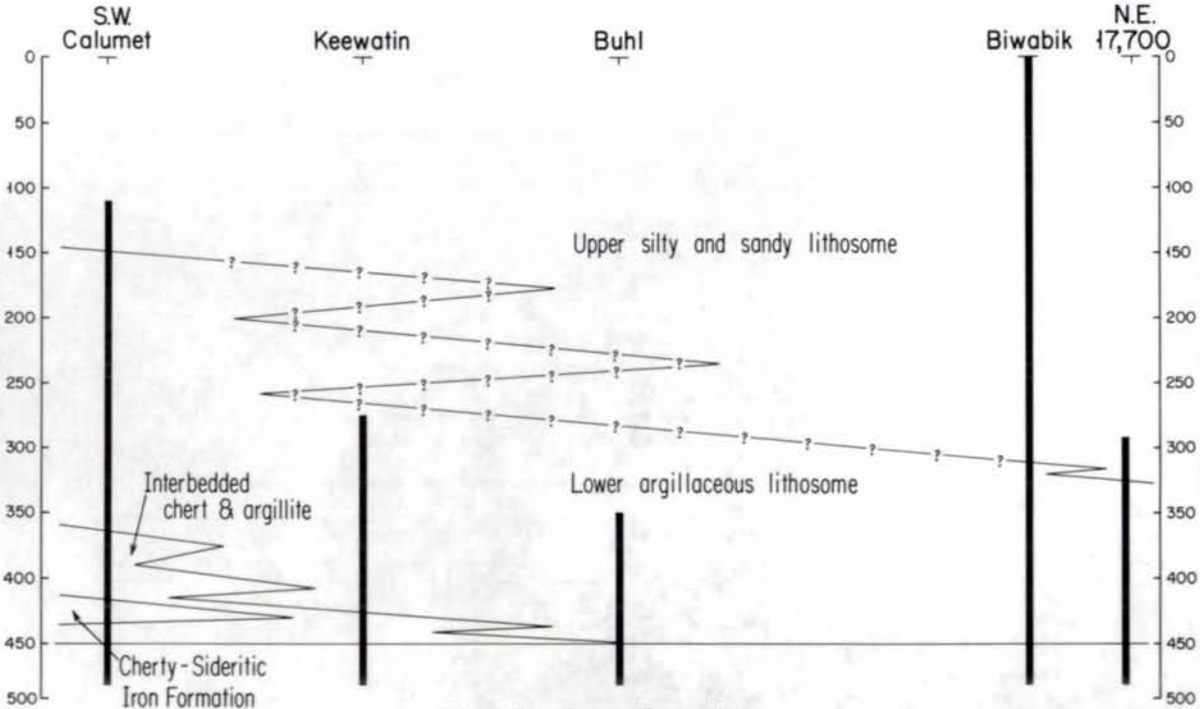


Figure 4. Diagrammatic northeast-southwest cross section of the Virginia Formation showing inferred relations between various rock types described in the text. Stratigraphic data from Drill Hole 17,700 (Morey and others, 1972) are included for comparative purposes. Datum is the inferred top of the Biwabik Iron Formation; vertical exaggeration is approximately x 500.

Lower Argillaceous Lithosome

The lower argillaceous lithosome is approximately 125 m thick in Drill Hole 17,700 at the eastern end of the Mesabi range and approximately 140 m thick at the drill site south of Biwabik. At the Biwabik site it consists predominantly of dark-colored, fissile, carbonaceous argillite (Fig. 5a). Very thin beds and laminae of dark-grayish-black argillaceous siltstone, light-grayish-black silty argillite, and bluish-gray to white chert also occur locally at both sites. This lithosome thickens westward; it makes up the entire 175 m of Virginia strata intersected south of Keewatin, and 300 m of the formation intersected south of Calumet. However these reported thicknesses are somewhat arbitrary in that both lower and upper contacts are gradational.

At Biwabik and Buhl, the contact with the Biwabik Iron Formation is placed arbitrarily at the top of the uppermost occurrence of bedded chert (Pfleider and others, 1968). Although the chert beds, and hence the inferred contact, need not be precisely correlative either spatially or temporally, the stratigraphic interval immediately beneath the uppermost chert beds at both localities is similar, and therefore is broadly correlative from place to place. Consequently this interval, which has been intersected at many places along the eastern and main parts of the Mesabi range (White, 1954), has been used traditionally to define the approximate top of the Biwabik Iron Formation. Intercalated beds of limestone, argillite, chert, slaty silicate-carbonate-facies iron-formation, and ash-fall tuff in the interval indicate that clastic sedimentation, chemical sedimentation, and volcanism were all more or less contemporaneous processes in the transition from Biwabik to Virginia time.

From near Keewatin westward along the western part of the Mesabi range, the limestone-bearing interval and its associated rock types were not deposited, and the Biwabik-Virginia transition is gradational over several tens of meters of dominantly argillaceous strata and lesser amounts of interbedded chert. Consequently the Biwabik-Virginia contact is arbitrarily placed where iron-bearing minerals characteristic of the Biwabik Iron Formation no longer make up an appreciable proportion of the argillite, as inferred from specific gravity values (Pfleider and others, 1968). As Gruner (1946) first noted, argillaceous material containing about 20 percent iron in the Biwabik Iron Formation has a specific gravity of about 3.0 to 3.2, whereas typical iron-poor argillite of the Virginia Formation has a specific gravity that rarely exceeds 2.85 and generally is about 2.75. Thus defined, the lower part of the Virginia Formation in the western part of the Mesabi range is characterized by appreciable quantities of bedded chert. At the site south of Keewatin the Biwabik-Virginia contact is 23 m beneath the uppermost bedded chert unit, whereas south of Calumet it is 88 m beneath the uppermost chert unit (Fig. 4).

The lower argillaceous lithosome south of Calumet is also characterized by scattered, centimeter-thick beds of arkose and by approximately 27 m of intercalated iron-poor argillite and cherty sideritic iron-formation (Fig. 4). The cherty sideritic rocks are lithologically similar to those that occur in the upper part of the Biwabik Iron Formation at this locality (Pfleider and others, 1968; White, 1954).

Upper Silty and Sandy Lithosome

Approximately 300 m of the upper silty and sandy lithosome were recovered from the drill site south of Biwabik (Fig. 4). Although the contact with the underlying argillaceous lithosome is gradational, the unit can be distinguished mainly by its appreciable quantities of siltstone (30% of the section) and fine-grained sandstone (5% of the section). The intercalated siltstone and sandstone beds, which generally occur in packages of strata 1 m to 5 m thick, are light colored and range in thickness from several millimeters to approximately a meter. More or less monotonous intervals of argillite 6 m to 30 m thick separate the siltstone-sandstone packages. These argillite intervals are light colored, silt rich, and nonfissile; they contain discrete laminae of light-gray siltstone (Fig. 5b).

PETROLOGY

For this study 70 thin sections representative of all rock types encountered in the diamond drill cores were cut perpendicular to bedding and studied using standard flat-stage petrographic procedures. The percentage of potassium feldspar in the coarser grained samples was estimated by staining thin sections etched by hydrofluoric acid with a potassium cobaltinitrite solution. X-ray diffraction was used to supplement petrographic observations in rocks too fine grained for optical studies. Lastly, sedimentary textures and structures too large to be studied in standard-size thin sections were examined using polished slabs and X-ray photography according to the techniques of Hamblin (1971).

Argillite and Silty Argillite

The term argillite is used here for both massive mudstone and fissile shale in which the original clay minerals have been recrystal-

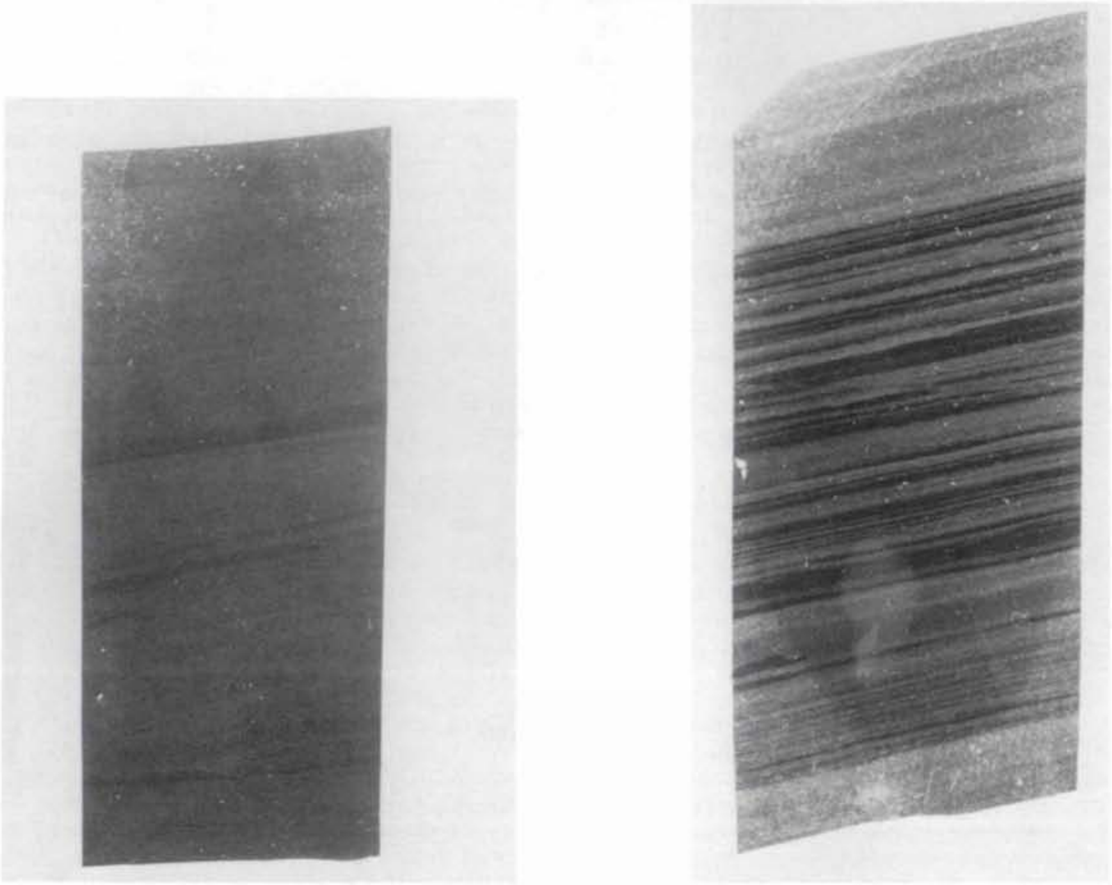


Figure 5. Polished slabs of core showing typical laminated argillite from (a) the lower argillaceous lithosome, and (b) the upper silty and sandy lithosome.

lized to various phyllosilicate minerals, either during diagenesis or during a very low grade metamorphic event. As defined, argillite is the dominant rock type in the Virginia Formation. It comprises 70 to 90 percent of the lower argillaceous lithosome and approximately 65 to 70 percent of the upper sandy and silty lithosome.

Argillite varies in color from black to light gray; darker hues dominate in the lower lithosome where carbonaceous material is an abundant constituent, whereas lighter hues dominate in the upper lithosome where silt-size detritus occurs either randomly interspersed within discrete argillite beds or as laminae and very thin beds between argillite layers. Many of the silt-rich layers are either size or content graded. Typically they are poorly sorted and have between 5 and 30 percent framework grains. Principal constituents include, in approximate order of abundance, muscovite, chlorite, quartz, plagioclase, and potassium feldspar. Muscovite and chlorite occur in subequal proportions. Quartz always exceeds plagioclase in modal abundance, and potassium feldspar is typically a trace to minor component. Both the quartz and the feldspar have irregularly embayed and indistinct grain boundaries indicative of recrystallization. Patchy areas of fine-grained calcite replace and enclose the phyllosilicate minerals, and euhedral grains of pyrite commonly occur in argillaceous units containing abundant carbonaceous material.

The modal mineralogy of the clay-size matrix, as measured by relative peak heights on X-ray diffractograms, is remarkably uniform throughout the Virginia Formation. Furthermore there is no evidence of in situ albitization or authigenesis of potassium feldspar in the argillite samples studied. Thus even though the original clay-size detritus has been thoroughly recrystallized, it appears that all the argillaceous rocks were of similar original composition and subjected to similar diagenetic or low-grade metamorphic processes.

Sandstone and Siltstone

Beds of sandstone and siltstone range in grain size from fine sand to medium silt, are poorly sorted, and are very well indurated by a recrystallized clay-size matrix of phyllosilicate minerals similar to those observed in argillite. Modal analyses of 20 selected samples are summarized in Table 1. Most of the sandstones contain somewhat more feldspar than quartz and from 21 to 35 percent matrix material. Siltstone samples are the fine-grained equivalents of the sandstones and both can be classified as feldspathic graywackes (Fig. 6). A few sandstone beds contain less than 15 percent matrix material, and accordingly are classified as arkoses (Fig. 6).

Feldspathic Graywacke

Detrital quartz makes up 16 to 35 percent of the sandstone samples examined and 36 to 52 percent of the framework grains. Apparent long dimensions of the quartz grains are markedly variable from sample to sample, ranging from 0.03 mm to 0.3 mm, but rarely exceed 0.2 mm. Most of the sand-size grains are angular to subangular in shape (Fig. 7), but the original shapes of many of the silt-size grains are difficult to resolve because of incipient recrystallization with enclosing matrix material at grain boundaries. There is no evidence of in situ precipitation of authigenic quartz, but a few detrital grains have rounded or abraded quartz overgrowths.

Feldspar forms 23 to 36 percent of the sandstone samples and 42 to 61 percent of the framework grains. Plagioclase dominates over potassium feldspar; both occur as angular to subrounded grains with average long dimensions about equal to those of the quartz grains. Although fresh grains occur (Fig. 8), much of the plagioclase is highly sericitized and nearly opaque (Fig. 9). Where measurable, the plagioclase grains have an apparent index of refraction less than quartz, and hence probably a sodic composition.

Potassium feldspar occurs in trace amounts to as much as 5 percent at the eastern end of the Mesabi range, but it makes up as much as 16 percent of the graywacke samples from south of Keewatin. Microcline with tartan-plaid twinning dominates among the fresher grains, but twinning is difficult to resolve in many grains because of extensive alteration (Fig. 10). Rare overgrowths on some feldspar grains always show evidence of rounding or abrasion.

Rock fragments of sedimentary, plutonic igneous, and metamorphic derivation average from trace amounts to 11 percent of the graywacke samples studied. Sedimentary rock fragments include grains of recrystallized chert or possibly iron-formation (Fig. 11) and quartzite. The plutonic igneous rock fragments are composed dominantly of intergrown grains of plagioclase and quartz (Fig. 12). A few dark-colored rock fragments have a very fine grained texture and may be of volcanic origin. Large grains of chlorite, biotite, and muscovite also are present locally in minor quantities; these detrital grains also

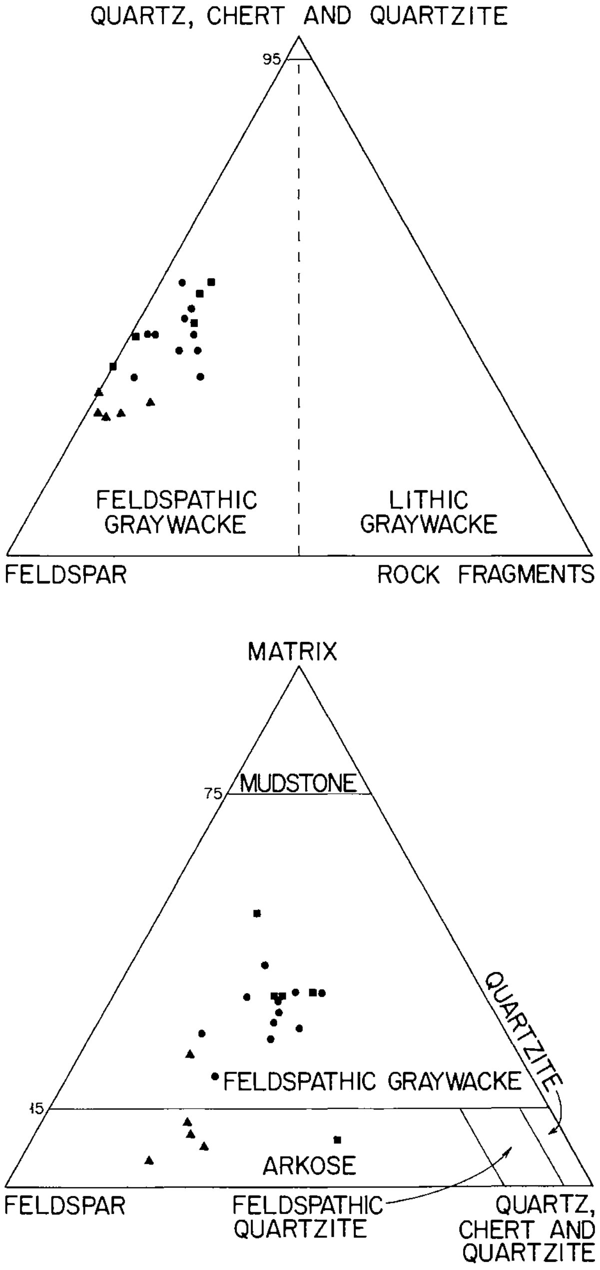


Figure 6. Summary of the mineralogic composition of the Virginia Formation using the classification scheme of Pettijohn (1957). Circles, hole south of Biwabik; squares, hole south of Keewatin; triangles, hole south of Calumet.

Table 1. Mineralogic composition of selected Virginia Formation sandstones
(estimated from 400 points per thin section)

	Framework constituents						Matrix constituents			Cement		Access[7]	Values recalculated to 100%					
Sample Number[1]	Qtz[2]	Plag[3]	K-spar	Chert & Qtzite	IRF[4]	MRF[5]	Mus & Chlor	Qtz+ Feld	Dark[6] color	Cal-cite	K-spar		Qtz[8]	Feld	RF[9]	Qtz	Feld	Matrix[10]
B-173-8	21	24	2	Tr[11]	Tr	3	18	4	2	19	-	5	42	52	6	30	37	33
B-198-3	26	25	2	Tr	Tr	4	22	4	Tr	13	-	4	45	47	7	28	36	35
B-215-10	17	26	2	2	3	6	29	4	1	4	-	4	34	50	16	23	35	42
B-630-10	20	26	Tr	1	Tr	7	23	2	2	14	-	5	39	48	13	28	35	36
B-1024-2	25	22	5	2	Tr	4	18	3	2	10	-	9	47	47	6	35	3	30
B-1051-6	23	31	2	2	2	4	14	3	6	6	-	3	39	51	9	31	1	28
B-1082	27	23	Tr	Tr	-	2	11	6	12	9	-	7	52	44	4	34	29	37
B-1099-1	20	31	5	Tr	Tr	3	25	4	15	3	-	5	34	61	5	23	41	36
B-1111-4	27	31	4	Tr	Tr	2	6	2	-	23	-	2	42	55	3	39	50	11
B-1112	24	28	3	Tr	-	2	20	2	3	17	-	2	42	54	4	30	39	31
K-520-7	23	20	8	4	2	4	10	6	17	Tr	-	6	44	46	10	31	32	37
K-530	28	17	8	2	3	2	12	4	18	2	-	4	50	42	8	34	28	37
K-570-6	23	22	12	2	Tr	1	1	3	31	2	-	2	42	57	1	27	36	36
K-586-6	16	12	16	Tr	-	Tr	Tr	2	2	48	-	2	36	64	-	17	30	52
K-589-11	33	18	8	2	3	3	4	2	18	6	-	2	52	39	9	52	39	9
C-823-7	16	11	31	Tr	-	1	2	2	4	24	4	4	27	71	2	25	63	12
C-855-8	18	11	34	-[12]	Tr	4	4	1	2	14	12	2	27	67	6	26	64	10
C-906	15	14	30	Tr	1	2	14	2	4	9	4	4	26	71	3	19	56	25
C-924	18	10	28	Tr	-	Tr	Tr	Tr	5	16	15	4	29	61	10	30	62	18
C-942-3	16	4	48	-	-	Tr	1	1	2	15	10	4	31	69	-	22	71	5

1. B, Biwabik; K, Keewatin; C, Calumet; numbers refer to depth in feet and inches below collar
2. Includes quartz grains with abraded overgrowths in trace amounts
3. Includes feldspar grains with abraded overgrowths in trace amounts
4. Igneous rock fragments. Dominantly of plutonic origin; includes grains of possibly volcanic origin in trace amounts
5. Metamorphic rock fragments
6. Dark-colored constituents. Includes carbonaceous material and very fine grained, dark-colored material of indeterminate but possibly volcanic origin
7. Includes heavy minerals and detrital grains of muscovite, chlorite, and biotite
8. Includes chert and quartzite
9. Rock fragments exclusive of chert and quartzite
10. May include digested rock fragments
11. Trace amounts of less than 1 percent
12. Not observed

may be of plutonic igneous origin. Metamorphic rock fragments include phyllitic and schistose rocks (Fig. 13) composed of various proportions of sericite and chlorite; quartz, sericite, or chlorite; and quartz, plagioclase, and sericite.

The matrix material in the graywackes is similar to that in the argillites. It consists mostly of sericite and chlorite with some very fine silt-size quartz and feldspar and randomly distributed carbonaceous material. The phyllosilicates occur as irregularly shaped patches having no preferred orientation. The fibrous or lacy habit of individual minerals within the patches (Fig. 14) implies that the phyllosilicates were recrystallized from some original clay-size protolith (protomatrix to orthomatrix according to the nomenclature of Dickinson, 1970). There also is evidence that some of the matrix formed by the "squeezing" of the low-grade metamorphic rock fragments (Fig. 15) around resistant framework grains so as to make the former appear as matrix (pseudomatrix of Dickinson, 1970). Furthermore, because some of the sericite occurs as thin coatings on a few of the framework grains (Fig. 16), some of the matrix may have formed by authigenic processes (epimatrix of Dickinson, 1970). Thus not all of the clay-size material in the feldspathic graywackes is of detrital origin.

Calcite cement also occurs in many graywacke samples, mainly as isolated patches of micrite enclosed within the phyllosilicate matrix. Some of the calcite, however, has a coarse-grained sparry habit and poikilitically encloses both framework grains and matrix material. Thus the calcite appears to have had a complex paragenetic history.

Arkose

Centimeter-thick beds of arkose intersected south of Calumet differ petrographically from the feldspathic graywackes by containing appreciably less matrix material, and in several other ways: (1) The framework grains are better sorted and consist predominantly of potassium feldspar with lesser amounts of quartz and plagioclase. (2) Authigenic potassium feldspar occurs as an early-formed cementing agent, whereas sparry calcite occurs exclusively as a paragenetically late, intergranular mineral. (3) Although metamorphic rock fragments and the accessory minerals, including detrital grains of muscovite, biotite, and chlorite, have the same general abundances as in the feldspathic graywackes, sedimentary and igneous rock fragments are lacking.

Feldspar makes up 26 to 52 percent of the arkose samples and 61 to 71 percent of the framework grains. On the average, somewhat less sodic plagioclase (~12%) occurs than quartz (~16%). Grains of perthitic or microperthitic potassium feldspar dominate the feldspar population, and most are highly altered, vacuolized, and surrounded by authigenic overgrowths (Fig. 17). Both the host grains (Fig. 18) and their overgrowths are extensively replaced by sparry calcite cement. Because of extensive alteration and replacement, it is difficult to determine if the original detrital grains were microcline or orthoclase.

As in the feldspathic graywackes, most matrix material is intergrown chlorite and sericite, but the arkose contains less carbonaceous material which occurs as discrete lenses or laminae rather than as irregular patches. The origin of the phyllosilicates is uncertain, but because well-sorted sediments typically lack much original detrital clay-size material, it seems likely that at least some of the matrix formed from recrystallized phyllitic and schistose rock fragments (pseudomatrix of Dickinson, 1970).

Limestone

Beds of light-gray limestone with trace to minor amounts of silt-size quartz and feldspar occur throughout the Virginia Formation, but are most abundant in the upper silty and sandy lithosome. Individual beds range in thickness from 4 cm to 8 cm, and have sharply defined bottom contacts and gradational tops. For the most part they have a very fine grained micritic texture that locally has been either recrystallized to a sparite or replaced by rhomb-shaped grains of dolomite. Many beds also contain scattered grains of euhedral pyrite. The micritic texture is similar in thin section to that of the Biwabik-Virginia transition zone, but in hand specimen these limestone beds have a parallel-laminated, cross-laminated, or convoluted fabric (Fig. 19) that the transition zone does not. Thus most of the limestone units in the Virginia Formation proper are allochemical, formed by the mechanical deposition of fine-grained calcareous detritus.

Carbonate Concretions

Carbonate concretions occur throughout the Virginia Formation. Most lie within argillaceous intervals and are lenticular or elliptical in shape. Although most concretions are even grained and structureless, some have an internal fabric defined by silt-size detritus that is crudely graded, laminated, or cross-bedded, and many are rimmed by cone-in-cone structures. The concretions themselves typically consist of sparry calcite that poikilitically encloses various proportions of

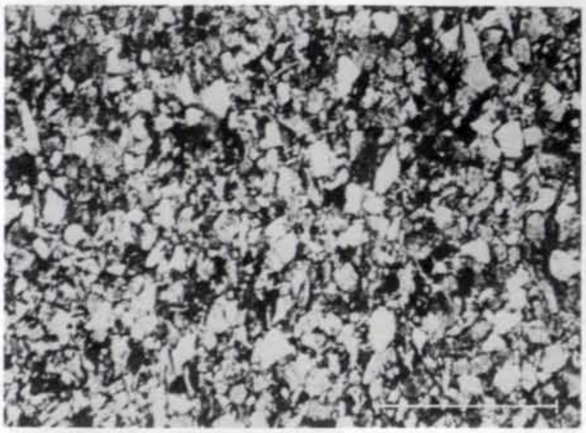


Figure 7. Photomicrograph of a typical feldspathic graywacke (plane light). Note that most grains are angular to subangular. Scale approximately 650 microns.

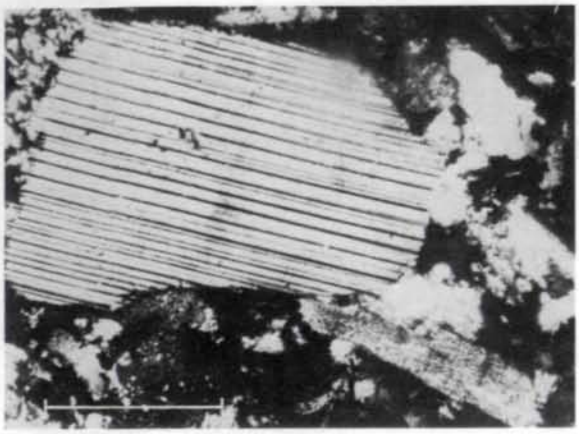


Figure 8. Typical framework constituents in feldspathic graywacke. Unaltered plagioclase with well-developed polysynthetic twinning. Note detrital chlorite in the lower right of the photomicrograph. Scale approximately 100 microns.

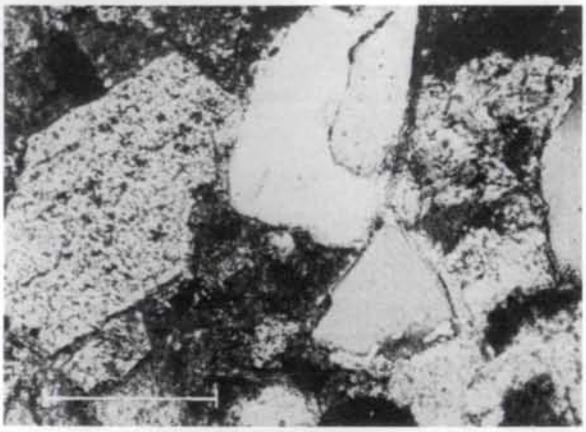


Figure 9. Typical framework constituents in feldspathic graywacke. Left center, highly altered plagioclase; top center, composite quartz; right center, semicomposite quartz. Note that the framework grains are dispersed in a poikilitic sparry calcite cement. Scale 100 microns.

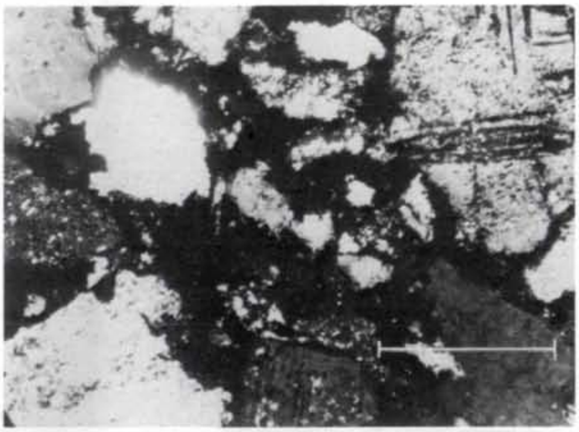


Figure 10. Typical framework constituents in feldspathic graywacke. Bottom left, altered plagioclase with vaguely developed polysynthetic twinning; top right, altered microcline with tartan-plaid twinning. Note irregular grain boundaries on both quartz and feldspar grains. Scale 100 microns.

Figure 11. Typical framework constituents in feldspathic graywacke. Top right, highly altered untwinned plagioclase; left center, stretched composite quartz; bottom right, rock fragment of recrystallized chert or very fine grained quartzite. Scale 100 microns.

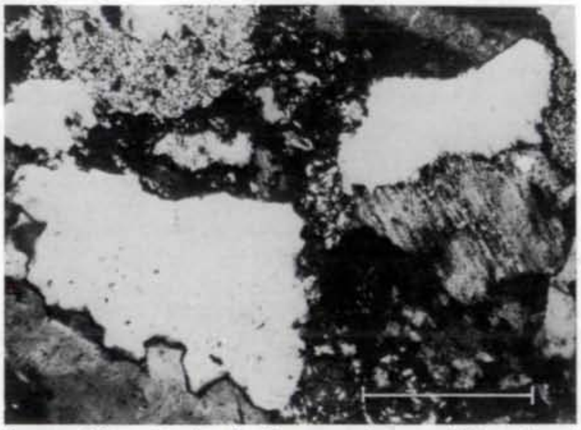


Figure 12. Typical framework constituents in feldspathic graywacke. Right center, igneous rock fragment consisting of intergrown plagioclase and quartz. Scale 100 microns.

Figure 13. Typical framework constituents in feldspathic graywacke. Bottom left, phyllitic rock fragment consisting predominantly of sericite and chlorite; other grains include sericitized plagioclase and monocrystalline quartz. Scale 25 microns.

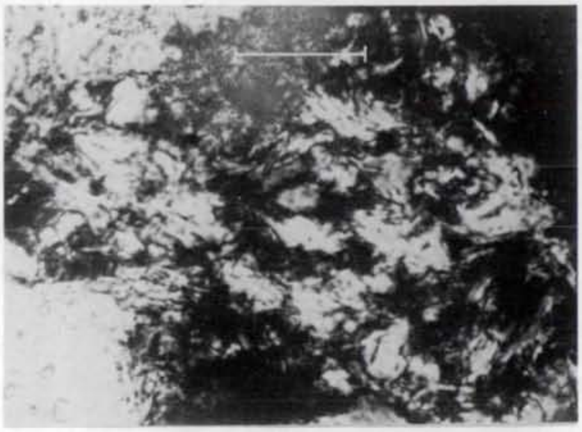


Figure 14. Matrix material formed by the recrystallization of original detrital clay-size material in feldspathic graywacke. Note random orientation of chlorite and sericite and presence of intergrown carbonaceous material. Scale 25 microns.

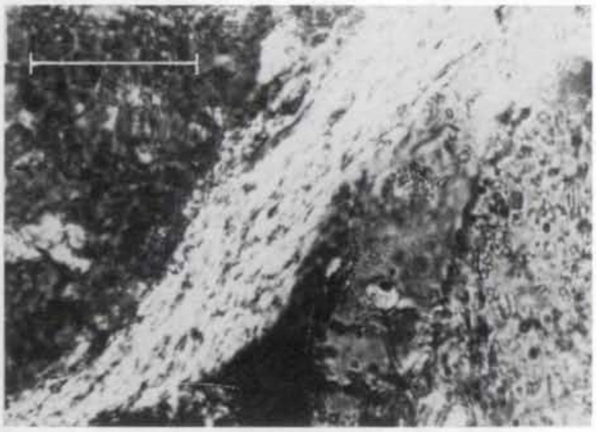


Figure 15. Pseudomatrix material formed from a "squeezed" phyllitic rock fragment so as to resemble an authigenic matrix in feldspathic graywacke. Scale 25 microns.

Figure 16. Authigenic sericite as rim cement around detrital framework grains in feldspathic graywacke. Scale 50 microns.

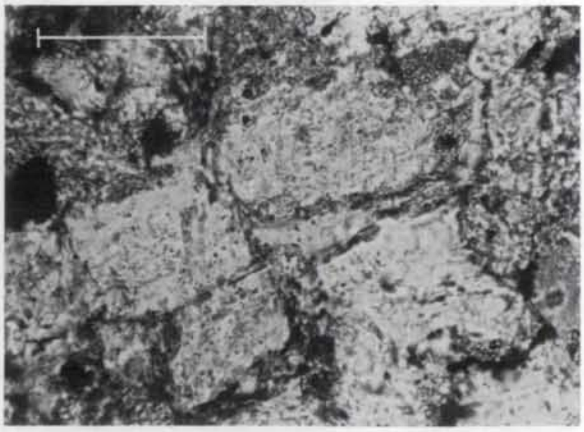


Figure 17. Detrital K-feldspar grains surrounded by authigenic K-feldspar cement in arkose. At higher magnifications the authigenic material appears to consist of very small (<1 micron) crystals. Scale 100 microns.

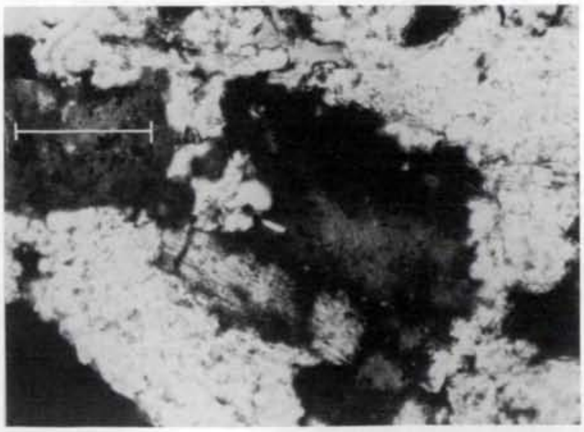


Figure 18. Detrital quartz partially replaced by poikilitic sparry calcite cement. Note the irregular, embayed grain boundaries. Scale 50 microns.

quartz, feldspar, and phyllosilicates. In contrast, the cone-in-cone structures have a fine-grained, microsparic texture and bladed or radial extinction patterns which imply that the cones formed from bladed aragonite that was subsequently transformed to calcite.

Cherty Sideritic Iron-Formation

Beds of cherty sideritic iron-formation intersected south of Calumet (Fig. 3) are irregularly laminated and grayish brown in color. Lenses and angular granule- to pebble-size fragments of light-bluish-gray and white cryptocrystalline chert commonly occur in the iron-rich layers.

The cherty sideritic material consists of finely intergrown siderite and chert in proportions of about 3:1. Chert grains are rarely more than 0.01 mm in diameter, and much of the siderite is microcrystalline although some grains are as large as 0.05 mm in diameter. A few beds have secondary rhombs of ankerite or dolomite that poikilitically enclose grains of chert and siderite, particularly near the edges of chert fragments. Although dominantly chemical in origin, the iron-rich units contain scattered, well-rounded, sand-size grains of quartz, which are clearly detrital in origin, and large blades of chlorite, which may be authigenic in origin.

Chert

Beds or nodules of light-bluish-gray to white and dark-gray to black chert generally less than 2 cm thick occur commonly in the lower part of the Virginia Formation, particularly in the western part of the Mesabi range. Although not studied in detail, these units, regardless of color, appear to consist entirely of an interlocking mosaic of individual crystallites and therefore appear to be typical sedimentary cherts.

Ash-Fall Tuff

Olive-green, structureless, waxy-appearing tuff generally occurs in beds less than 7 cm thick which have sharp upper and lower contacts. In thin section, the tuff is typically very fine grained and consists dominantly of sericite; however ghosts of shardlike features or of euhedral feldspar grains having oscillatory zones are preserved in a few samples. However because of extensive crystallization, the protoliths of these ash-fall tuff varieties could not be determined.

SEDIMENTOLOGIC ATTRIBUTES

Four discrete sedimentologic processes were operative in the Virginia Formation at one time or another. These are: (1) The deposition of mudstone by pelagic processes involving the slow accumulation of fine-grained sediments from dilute suspension, or by hemipelagic processes involving the action of slowly flowing diffuse turbidity currents. (2) The deposition of poorly sorted sandy and silty beds, including allochemical limestone units, by the action of sediment-laden turbidity currents. (3) The deposition of well-sorted sandy beds by the action of nonturbidity currents that reworked previously deposited sediments. (4) The deposition of chert and iron-rich beds by chemical processes during periods of reduced clastic influx.

Pelagic and Hemipelagic Deposits

The Virginia Formation is dominated throughout by mudstone, now recrystallized to argillite, but the character of the argillite changes with stratigraphic position. Argillite in the lower argillaceous lithosome typically occurs in thick and uninterrupted sequences. Because of their more or less homogeneous texture, these argillite units were probably formed by the gradual sedimentation of suspended clay. In modern environments, similar fine-grained, black, carbonaceous and pyritic sediments form in a variety of sedimentologic regimes ranging from restricted shallow lagoons to deep basins with anoxygenic bottom conditions. However, the extensive development of the lower argillaceous lithosome, the apparent lack of associated shallow-water strata, and the presence of primitive amino acids of organic origin in some of the argillite beds (Niehaus and Swain, 1972), imply that sedimentation occurred by pelagic processes in a large basin having anoxygenic bottom conditions.

Much of the argillite in the upper silty and sandy lithosome also may have formed by pelagic processes. However many of the argillaceous beds in this lithosome contain appreciable quantities of randomly dispersed silt. Silt-size detritus also occurs concentrated in very thin laminae that have well-defined lower contacts. Therefore it appears likely that some of the argillaceous material in the upper lithosome formed by hemipelagic processes involving the action of either weak turbidity currents or bottom currents. Although the pelagic and hemipelagic deposits typically exhibit parallel bedding types, scattered stratigraphic intervals generally less than a meter thick are characterized by

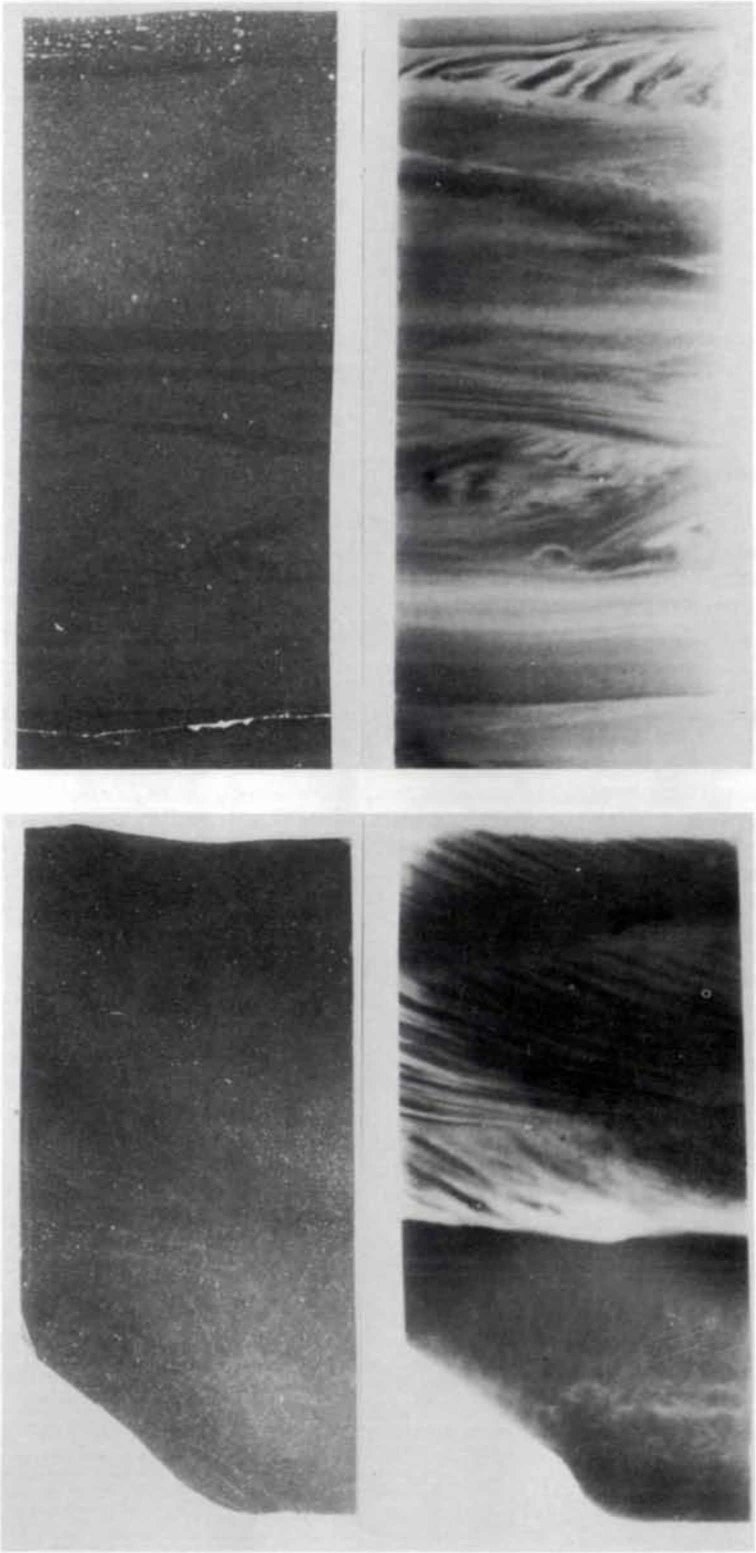


Figure 19. Typical allochemical limestone. Polished core slab on the left and radiograph on the right are of the same specimen.

contorted bedding features indicative of slumping. Therefore it seems likely that at least some of the pelagic and hemipelagic sediments were deposited on a sloping surface.

Turbidite Deposits

Many of the siltstone and sandstone beds and all of the allochemical limestone beds in the Virginia Formation are sedimentation units having basal contacts that are sharply defined and upper contacts that are gradational into overlying argillaceous sequences. Where they occur as discrete entities, the sandstone sedimentation units are rarely more than 1 m thick, and most are less than 50 cm thick. However many of the dominantly sandstone intervals are in fact amalgamated sequences of thin sandstone sedimentation units not separated by intervals of argillite. Siltstone-rich beds, in contrast, occur in sedimentation units rarely more than 20 cm to 30 cm thick, and most are less than 10 cm thick.

Most sandstone and siltstone sedimentation units have internal bedding features and textures indicative of sedimentation from turbidity currents (e.g., Kuenen, 1964). Bouma (1962) noted that these features occur in a definite order that defines an "ideal" turbidite bed (Fig. 20). In an ideal Bouma bed, the lowest or A division is massive or very faintly laminated and graded. Division B is parallel-laminated and is transitional with division C which is ripple-laminated or convolutely laminated. Division D is finely laminated and grades upward into pelagic and hemipelagic mudstone of division E. Walker (1965, 1967) and Walker and Mutti (1973) have noted that most turbidite units beginning with the Bouma A division lack the B, C, and D divisions. Sedimentation units beginning with the Bouma A division, which have high sand-to-shale ratios, are referred to as "thick-bedded turbidites," and are interpreted as having been deposited from fast-flowing turbidity currents. In contrast, sedimentation units beginning with Bouma B, C, or D divisions have high shale-to-sand ratios, and are referred to as thin-bedded turbidites. They are interpreted as having been deposited from slow-flowing turbidity currents.

Thick-bedded Turbidites

Thick-bedded turbidites starting with the Bouma A division make up only a minor part of the Virginia Formation. Nonetheless they occur prominently in a sandstone-dominated interval some 24 m thick in the lower argillaceous lithosome intersected south of Keewatin, and as scattered sedimentation units in the upper silty and sandy lithosome intersected south of Biwabik and Calumet.

The amalgamated sandstone beds intersected south of Keewatin have well-developed Bouma A divisions; the beds range in apparent thickness from 5 cm to 1 m and are coarse grained and very poorly sorted. Many are structureless, but some contain imbricated mudstone clasts in their lower parts and evidence of coarse-tail grading in their upper parts. Although the upper parts of many of these sedimentation units are truncated by the succeeding unit, the few units that can be seen in their entirety appear to consist wholly of the Bouma A division. However a few rare units also contain diffuse laminae in their upper parts and thus appear to be AB turbidites (Fig. 21).

Only 10 percent of all the siltstone and sandstone sedimentation units intersected in the upper silty and sandy lithosome south of Biwabik contain the Bouma A division. Moreover the presence of an A division in any given bed appears to be strongly dependent on the grain size or on the thickness of that bed. Of the beds containing the Bouma A division, nearly all (~97%) of the sandstone beds, regardless of thickness, and most (~80%)

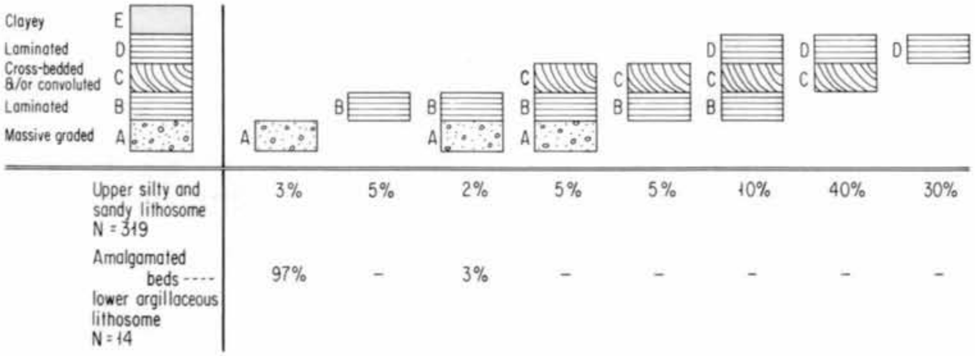


Figure 20. Abundance and types of bedding features observed in graywacke and siltstone beds of the Virginia Formation. The ideal "Bouma bed" is after Bouma (1962).

of the siltstone beds 20 cm or more thick start with the Bouma A division. These beds also typically contain other Bouma divisions. Consequently thick-bedded turbidites are not a major sedimentological attribute of the upper silty and sandy lithosome.

Thin-bedded Turbidites

Most sandstone and siltstone beds in the Virginia Formation are thin-bedded turbidites. However thin-bedded turbidites starting with the Bouma B division are relatively rare in the upper silty and sandy lithosome south of Biwabik. Most of those which are 20 cm or more thick also contain Bouma C and D divisions. Typically however, the B division is poorly developed and the C and D divisions make up half to two thirds of the sedimentation unit. A few sedimentation units between 5 cm and 20 cm thick also contain the B division, but most of these begin with the Bouma C division (Fig. 22). The C division is rarely present in sedimentation units less than 5 cm thick and most of these very thin sedimentation units consist entirely of the D division. The D division, wherever it occurs, appears to pass uninterrupted into very finely laminated, hemipelagic sediments of the Bouma E division.

Bottom-Current Deposits

The upper part of the lower argillaceous lithosome intersected south of Calumet contains scattered sandstone lenses 1 cm to 3 cm thick (Fig. 23) that have many sedimentary attributes in common with sediments deposited by bottom-hugging currents in modern environments (Hubert, 1964). The sandstone lenses have sharply defined upper and lower contacts, and in places appear to fill bottom irregularities. They are better sorted and contain less matrix material than either the thick-bedded or thin-bedded turbidites described above. Furthermore they commonly are either laminated or cross-bedded, but they are not graded and they lack typical Bouma sequences.

Although the term "contourite" is used for deposits of bottom-hugging currents in modern environments, it applies particularly to sediments transported and deposited by currents flowing parallel to bathymetric contours and driven by tides, internal waves, or thermohaline gradients (Heezen and Hollister, 1963). Circulation patterns in the Virginia Formation, however, cannot be reconstructed from available data, and therefore these sandstone lenses are termed bottom-current deposits to avoid implication as to origin or orientation of the bottom currents.

Chemically Precipitated Deposits

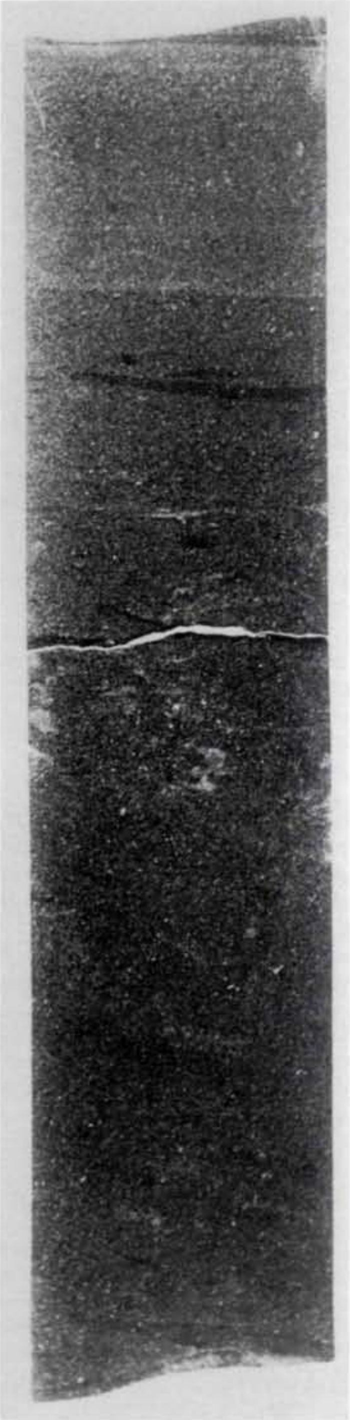
The iron-bearing strata intersected south of Calumet are sedimentologically similar to the upper part of the Upper Slaty member of the Biwabik Iron Formation in the westernmost part of the Mesabi range (White, 1954). Inasmuch as the Biwabik-Virginia contact is gradational, it seems that iron-formation precipitation and clastic sedimentation were contemporaneous, and that the iron-bearing strata mark episodes of diminished clastic input into the basin rather than major changes in basin geometry in early Virginia time.

The presence of bedded chert in the lower part of the Virginia Formation also implies that clastic sedimentation was episodic in early Virginia time. The fact that the chert units are free of iron-bearing minerals implies that the chemical precipitation of silica and siderite were not contemporaneous processes. Therefore the reappearance of siderite-bearing strata in the Virginia Formation must mark a period of increased influx of dissolved iron or carbon dioxide into the chemical environment of deposition.

SEDIMENTATION AND PROVENANCE

A simple depositional model can account for the sedimentologic attributes described above. Early Virginia time was characterized by the slow deposition of black mud--now argillite--in quiet water below wave base. The presence of locally abundant quantities of carbonaceous material implies deposition under anoxygenic conditions, possibly in deep water. Beds of iron-formation, limestone, dolomite, and chert, interlayered with the argillites in the Biwabik-Virginia transition zone indicate short periods of diminished clastic supply to the depositional basin and an episodic return to a sedimentologic regime dominated by chemical processes like that of late Biwabik time. However, the relatively abrupt change from a chemical to a clastic sedimentologic regime implies that the depositional system underwent an abrupt transformation, most likely involving subsidence of the basin and uplift of the bordering craton. The added presence of minor amounts of volcanic material in the chemical to clastic transition implies that the transformation was accompanied by volcanism. However because the volcanic material is very fine grained, pyroclastic in origin, and subordinate in quantity, it seems likely that its source area was located elsewhere in the Lake Superior region.

The sedimentologic significance of bottom-current deposits in the lower argillaceous lithosome is not well understood. Heezen and



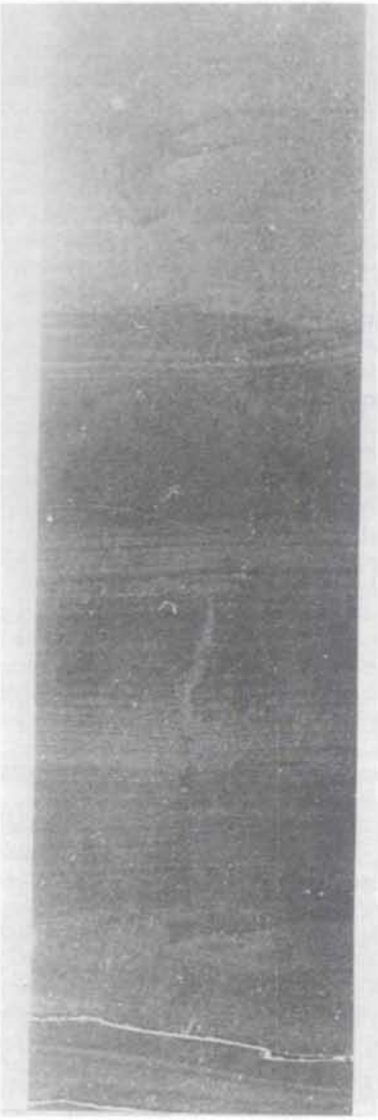


Figure 23. Polished core slabs showing bottom-current deposits from the lower argillaceous lithosome south of Calumet. The top slab shows vaguely defined climbing-ripple sets, whereas the sandstone lenses in the bottom slab appear to be structureless.

Figure 22. Polished slab of core showing typical thin-bedded turbidites from the upper silty and sandy lithosome south of Biwabik. Note that most siltstone units are CD or D turbidites.

Figure 21. Polished slab of core showing a typical thick-bedded turbidite from the lower argillaceous lithosome south of Keewatin. Note that the upper part is finely laminated and the remainder is massive to vaguely laminated (AB turbidite).

Hollister (1963) have suggested that detrital material affected by bottom currents in modern environments is moved by turbidity currents to deeper water environments where it is subsequently reworked and retransported. However bottom currents in modern environments are most active around the edges of a depositional basin--not in its deepest parts (Bouma and Hollister, 1973). If these observations can be extrapolated to the Virginia Formation, it appears that the area of the Mesabi range was located toward the edge of the depositional basin in an area where both turbidity and bottom currents were active.

The basin of deposition must have continued to subside in Virginia time at a rate such that filling did not keep pace with downwarping. As the water gradually deepened, a bottom slope developed, and silt- and sand-size detritus was introduced into the basin by means of turbidity currents. Most sandstone and siltstone beds in the Virginia Formation are thin-bedded turbidites that were deposited by slow-flowing currents. In modern environments, analogous thin-bedded turbidites form along the lower parts of submarine fan complexes (Walker, 1978, 1979) in environments considerably distant from the source of the turbidity currents (Fig. 24). However, similar thin-bedded turbidites can be deposited by slowly flowing currents in environments near the source of the currents under conditions of diminished sediment supply or in environments characterized by a very gently sloping bottom topography. Thus the presence of thin-bedded turbidites in the Virginia Formation need not indicate deposition in an environment well removed from the source of the turbidity currents. However the widespread occurrence of thin-bedded turbidites in the Virginia Formation does indicate simultaneous deposition from a number of partially overlapping submarine fan complexes, so that the sedimentologic attributes of any single fan complex would be modified by deposits from adjacent fan complexes.

In contrast to the general situation outlined above, the amalgamated sandstone sequence intersected south of Keewatin appears to consist of thick-bedded turbidites which form, by analogy with modern turbidite environments (Fig. 24), in areas near or within channels that feed submarine fan complexes (Normark, 1978). In modern environments feeder channels commonly originate near the edge of a depositional basin, and thus the presence of thick-bedded turbidites could be considered an indication of proximity to a basin margin. However, feeder channels extending far into the depositional basin also have been observed in modern environments. They can form any place where the sediment supply increases considerably or where the paleoslope into the basin is increased by tectonism. Conversely if the sediment supply for a fan complex is cut off at the source or is diverted elsewhere, the fan will be abandoned and covered by rather uniform layers of pelagic and hemipelagic mud. Thus the presence of thick-bedded turbidites intercalated with hemipelagic or pelagic muds in the Virginia Formation south of Keewatin records the birth and death of the feeder system for one submarine fan complex.

Most sedimentologic models developed to account for the graywacke sequences in northern Minnesota have suggested that the edge of the depositional basin was located to the north of the Mesabi range in an area where strata subsequently were eroded in post-Virginia time (e.g., Morey, 1973). This contention cannot be corroborated by direct paleocurrent observations from the unoriented drill cores, but many of the mineralogic attributes in the Virginia Formation imply a source area to the north of the Mesabi range.

Quartz and feldspar having types that indicate a source area of dominantly plutonic or high-rank metamorphic rocks are relatively abundant in the Virginia Formation. Although not as abundant, stretched composite quartz types in the formation imply that the source area also contained a variety of low-rank metamorphic rocks. The sparse presence of "granitic" rock fragments and sand-size grains of chert, iron-formation, phyllite, schist, and fine-grained volcanic rocks of uncertain affinity also indicates a source area of mixed composition. Because many of the phyllitic and schistose rock fragments have been at least partially recrystallized to form pseudomatrix material, it is difficult to estimate the abundance of low-grade metamorphic rocks in the source area. Nonetheless the presence of pseudomatrix material in the graywackes of the Virginia Formation is consistent with the conclusions of Morey and Schulz (1977) who suggested on chemical grounds that other lower Proterozoic graywacke sequences in Minnesota were derived from a mixed source of quartz monzonitic, metasedimentary, and metavolcanic rocks like those which now crop out in the Archean greenstone-granite terrane to the north of the Mesabi range.

The above conclusions notwithstanding, the occurrence in some of the graywackes of sand-size quartz and feldspar grains with abraded overgrowths and the presence of detrital limestone beds having sedimentary structures indicative of turbidite deposition imply that the source area was not entirely confined to igneous and metamorphic rocks of Archean age. Although speculative, it seems very likely that both the terrigenous and calcareous detritus were derived from lower Proterozoic units deposited either shortly before the time of Virginia deposition or from contemporaneous shelf deposits formed near the strandline during Virginia time.

Regardless of the precise composition of the source area, all of the mineralogic evidence implies that a craton existed to the north of the Mesabi range. It follows that the northern edge of the Virginia depositional basin also was located to the north of, and possibly subparallel to, the east-northeast-trending strike of the Mesabi range. Unfortunately however, there is nothing in the geologic evidence to indicate how far north of the Mesabi range the edge of the depositional basin was.

REGIONAL SEDIMENTOLOGIC RELATIONSHIPS

The Rove Formation of the Gunflint range in northeastern Minnesota and adjoining parts of Ontario, the Rabbit Lake Formation of the Cuyuna range, and the Thomson Formation of east-central Minnesota are broadly correlative (Fig. 2) with the Virginia Formation. They all occupy similar stratigraphic positions in the Animikie Group and are characterized by broadly similar stratigraphic successions (e.g., Morey, 1973, 1978).

There are marked stratigraphic and sedimentologic similarities between the Virginia and Rove Formations (Fig. 25). At least 970 m thick, the Rove Formation contains a lower argillaceous unit 120 m to 130 m thick, which is overlain by 600 m of argillite and intercalated thin-bedded turbidites. The uppermost 240 m of the exposed section contains turbidites and other sedimentary attributes indicative of deposition from moderately fast flowing turbidity currents (Morey, 1969); it also contains thick to medium-thick beds of quartzose sandstone that have sedimentologic attributes indicative of bottom-current activity (Morey, 1969, p. 37).

The Rabbit Lake Formation is not exposed to any great extent, but scattered drill holes have penetrated a stratigraphic succession very much like that in the Virginia Formation at the western end of the Mesabi range (Marsden, 1972). Although the Rabbit Lake Formation has not been studied in detail, it can be subdivided into a lower black carbonaceous argillite or slate member some 60 m thick; an intermediate cherty sideritic iron-formation member as much as 300 m thick; and an upper member of gray, green, or black argillite or slate intercalated with thin to thick beds of graywacke, chert, and iron-formation.

The stratigraphic position of the Thomson Formation is somewhat problematic because neither its upper nor lower contact is exposed. Goldich and others (1961, p. 5), however, have suggested on the basis of radiometric dating that the Thomson Formation is lower Proterozoic in age, and Morey and Ojakangas (1970) have demonstrated that it is lithologically and sedimentologically akin to the upper part of the Rove Formation. The Thomson Formation differs in detail from the upper part of the Rove Formation in that tur-

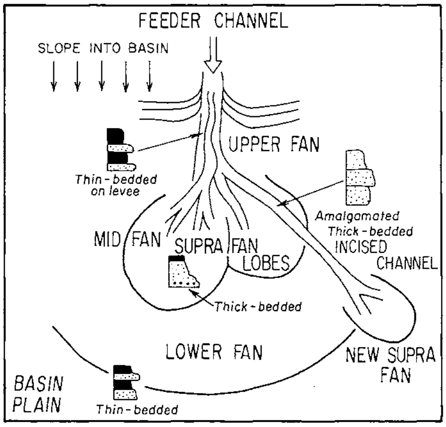


Figure 24. Submarine fan environmental model (modified from Walker, 1979) showing major turbidite types recognized in the Virginia Formation and other lower Proterozoic graywacke sequences in Minnesota. No relative scale is implied.

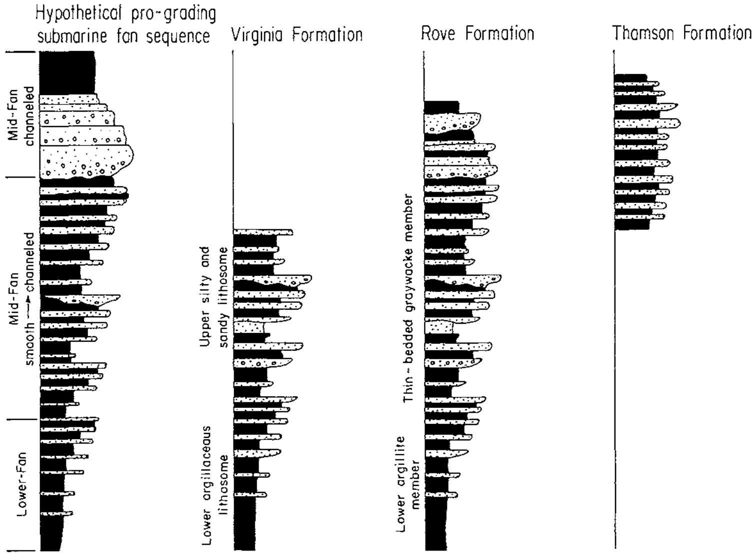


Figure 25. Diagrammatic stratigraphic and sedimentologic sequences in the Virginia, Rove, and Thomson Formations compared to a hypothetical prograding submarine fan sequence as proposed by Walker (1979). No vertical scale is implied; the stratigraphically higher Thomson Formation lacks evidence of mid-fan channels because of its location in the axial part of the depositional basin.

bidites starting with the Bouma A division are very common regardless of stratigraphic position (Morey and Ojakangas, 1970). The typically size- and content-graded nature of the Thomson turbidites implies that the Thomson Formation occupies a stratigraphic position somewhat akin to the upper parts of the sequences described from the Mesabi and Gunflint ranges (Fig. 25).

From a sedimentologic point of view, the stratigraphic reconstruction summarized in Figure 25 resembles "thickening- and coarsening-upward" sequences typically associated with prograding submarine fan complexes (Walker and Mutti, 1973; Walker, 1979). According to Walker (1979), the progradation of a submarine fan complex would result in a stratigraphic sequence passing upward from lower fan, through mid-fan, into upper fan deposits. Thus progradation in the outer fan area would result in the deposition of a sequence of turbidites that would become thicker bedded upwards. In this model, the upward transition from dominantly pelagic and hemipelagic muds to intercalated thin-bedded turbidites in the Virginia, Rove, and possibly Rabbit Lake Formations represents the transition from pelagic sedimentation on a basin plain to sparse thin-bedded turbidite deposition in the lower fan area to abundant thin-bedded turbidite deposition in the outer part of the mid-fan area. The presence of thick-bedded turbidites in the Thomson Formation implies that sedimentation there occurred in the inner part of a prograding submarine fan complex. Most likely this general thickening- and coarsening-upward sequence reflects either subsidence of the axial part of the depositional basin or uplift of the source area, either of which would lead to steeper depositional gradients in the basin and to increased amounts of detritus being supplied to the basin.

CONCLUSIONS

It can be concluded that sediments in the Virginia Formation were derived in large part from the Archean greenstone-granite terrane located to the north of the Mesabi range, and to a lesser extent from lower Proterozoic strata slightly older or equivalent to the Virginia Formation. The original muds in early Virginia time were deposited by a slow raining down of suspended clay particles in a basin whose axis was located to the south of the Mesabi range. It is inferred that continued subsidence led to a paleoslope dipping generally southward into the basin and to the transport and deposition of silt and sand by turbidity currents that mostly flowed down the paleoslope. In detail, the sedimentologic attributes of the Virginia Formation resemble those associated with deposition on the lower and mid-fan parts of a submarine fan complex. Walker's (1979) model involving the basinward progradation of a number of submarine fan complexes provides a simple and elegant explanation for the various sedimentologic phenomena observed in the lower Proterozoic graywacke sequences in northern and east-central Minnesota.

REFERENCES CITED

Bouma, A.H., 1962, Sedimentology of some flysch deposits: Amsterdam, Elsevier, 168 p.

Bouma, A.H., and Hollister, C.D., 1973, Deep ocean basin sedimentation, in Middleton, G.V., and Bouma, A.H., eds., Turbidites and deep water sedimentation: Society of Economic Paleontologists and Mineralogists (Pacific Section) Short Course Notes (Los Angeles), p. 79-118.

Dickinson, W.R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 46, p. 695-707.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p.

Gruner, J.W., 1946, The mineralogy and geology of the taconites and iron ores of the Mesabi range, Minnesota: St. Paul, Office of Commissioner, Iron Range Resources and Rehabilitation, 127 p.

Hamblin, W.K., 1971, X-ray photography, in Carver, V.C., ed., Procedures in sedimentary petrology: New York, Wiley-Interscience, 653 p.

Heezen, B.C., and Hollister, C.D., 1963, Evidence of deep sea bottom currents from abyssal sediments [abs.]: International Union of Geodesy and Geophysics, v. 6, p. 111.

Hubert, J.F., 1964, Textural evidence for deposition of many western North Atlantic deep-sea sands by ocean-bottom rather than turbidity currents: Journal of Geology, v. 22, p. 757-785.

Kuenen, P.H., 1964, Deep-sea sands and ancient turbidites, in Bouma, A.H., and Brouwer, A., eds., Developments in sedimentology: Amsterdam, Elsevier, 266 p.

Marsden, R.W., 1972, Cuyuna district, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota--a centennial volume: Minnesota Geological Survey, p. 227-237.

Morey, G.B., 1969, The geology of the Middle Precambrian Rove Formation in northeastern Minnesota: Minnesota Geological Survey Special Publication SP-7, 62 p.

_____, 1973, Stratigraphic framework of Middle Precambrian rocks in Minnesota, in Young, G.M., ed., Symposium on Huronian sedimentation: Geological Association of Canada Special Paper 12, p. 211-249.

_____, 1978, Lower and Middle Precambrian stratigraphic nomenclature for east-central Minnesota: Minnesota Geological Survey Report of Investigations 21, 52 p.

Morey, G.B., and Ojakangas, R.W., 1970, Sedimentology of the Middle Precambrian Thomson Formation, east-central Minnesota: Minnesota Geological Survey Report of Investigations 13, 32 p.

Morey, G.B., Papike, J.J., Smith, R.W., and Weiblen, P.W., 1972, Observations on the contact metamorphism of the Biwabik Iron-Formation, East Mesabi District, Minnesota, in Doe, B.R., and Smith, D.K., eds., Studies in mineralogy and Precambrian geology: Geological Society of America Memoir 135, p. 225-264.

Morey, G.B., and Schulz, K.J., 1977, Petrographic and chemical attributes of some Lower and Middle Precambrian graywacke-shale sequences in Minnesota [abs.]: Institute on Lake Superior Geology, 23rd Annual Meeting, Thunder Bay, Ontario [Proceedings], p. 34.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geologic map of the Lake Superior region: Minnesota Geological Survey State Map Series S-13, scale 1:1,000,000.

Niehaus, J.R., and Swain, F.M., 1972, Amino acids in some Middle Precambrian rocks of northern Minnesota and Southern Ontario, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota--a centennial volume: Minnesota Geological Survey, p. 272-277.

Normark, W.R., 1978, Fan valleys, channels and depositional lobes on modern submarine fans: characters for recognition of sandy turbidite environments: American Association of Petroleum Geologists Bulletin, v. 62, p. 912-931.

Pettijohn, F.J., 1957, Sedimentary rocks: Harper and Row, 718 p.

Pfleider, E.P., Morey, G.B., and Bleifuss, R.L., 1968, Mesabi deep-drilling project, progress report no. 1: in Pfleider, E.P., and Berger, F.E., eds., Minnesota Mining Symposium, 29th Annual: Minneapolis, University of Minnesota Center for Continuing Education, p. 59-92.

Van Hise, C.R. and Leith, C.K., 1901, The Mesabi district: U.S. Geological Survey 21st Annual Report, Part 3, p. 351-370.

Walker, R.G., 1965, The origin and significance of the internal sedimentary structures of turbidites: Yorkshire Geological Society Proceedings, v. 33, p. 1-29.

_____, 1967, Turbidite structures and their relationship to proximal and distal depositional environments: Journal of Sedimentary Petrology, v. 37, p. 25-43.

_____, 1978, Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps: American Association of Petroleum Geologists Bulletin, v. 62, p. 932-966.

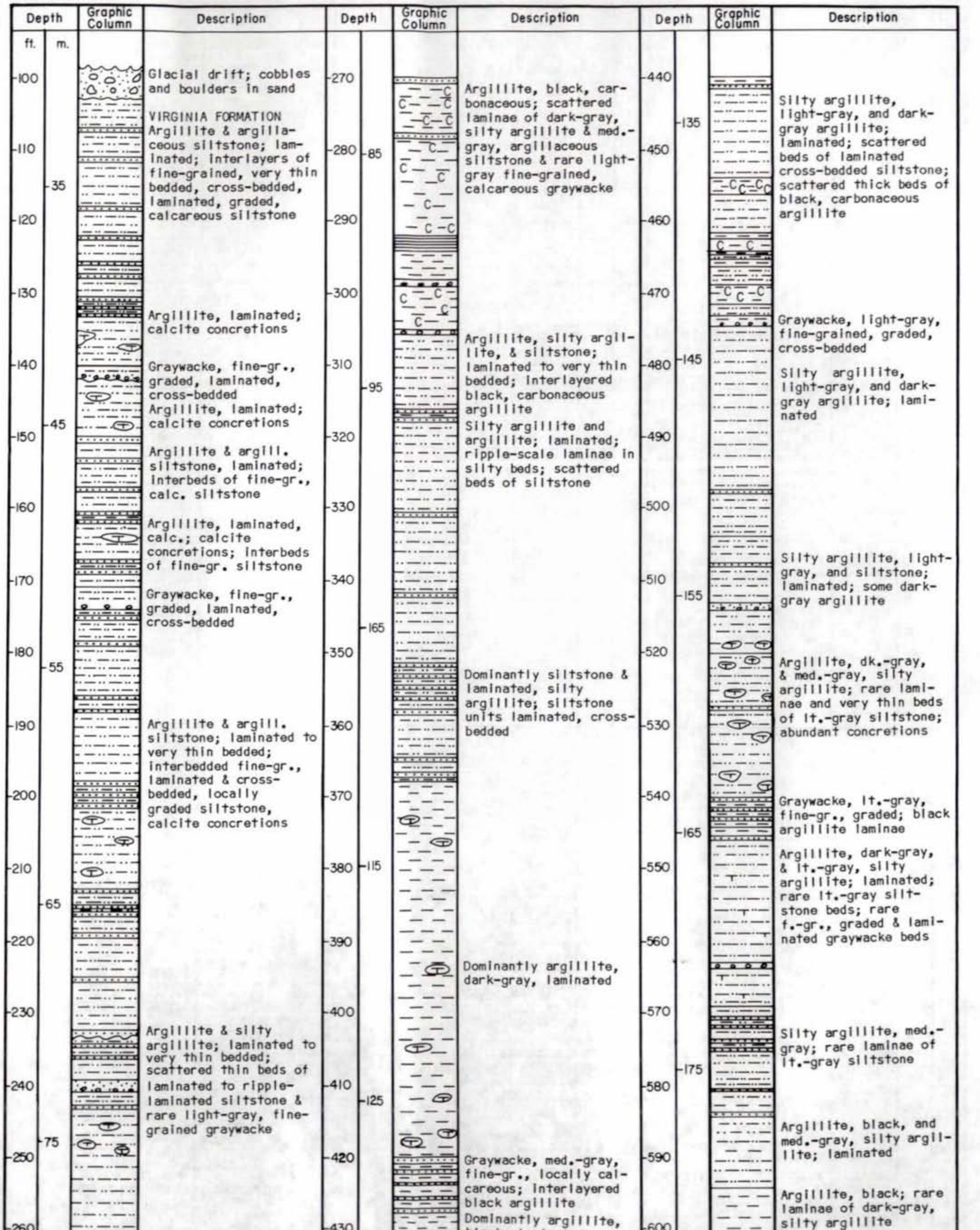
_____, 1979, Turbidites and associated coarse clastic deposits, in Walker, R.G., ed., Facies models: Geoscience Canada Reprint Series 1, p. 91-103.

Walker, R.G. and Mutti, E., 1973, Turbidite facies and facies associations, in Middleton, G.V., and Bouma, A.H., eds., Turbidites and deep water sedimentation: Society of Economic Paleontologists and Mineralogists (Pacific Section) Short Course Notes (Los Angeles), p. 119-157.

White, D.A., 1954, Stratigraphy and structure of the Mesabi range, Minnesota: Minnesota Geological Survey Bulletin 38, 92 p.

APPENDIX--LITHIC LOGS OF THE VIRGINIA FORMATION

Biwabik 1 of 3

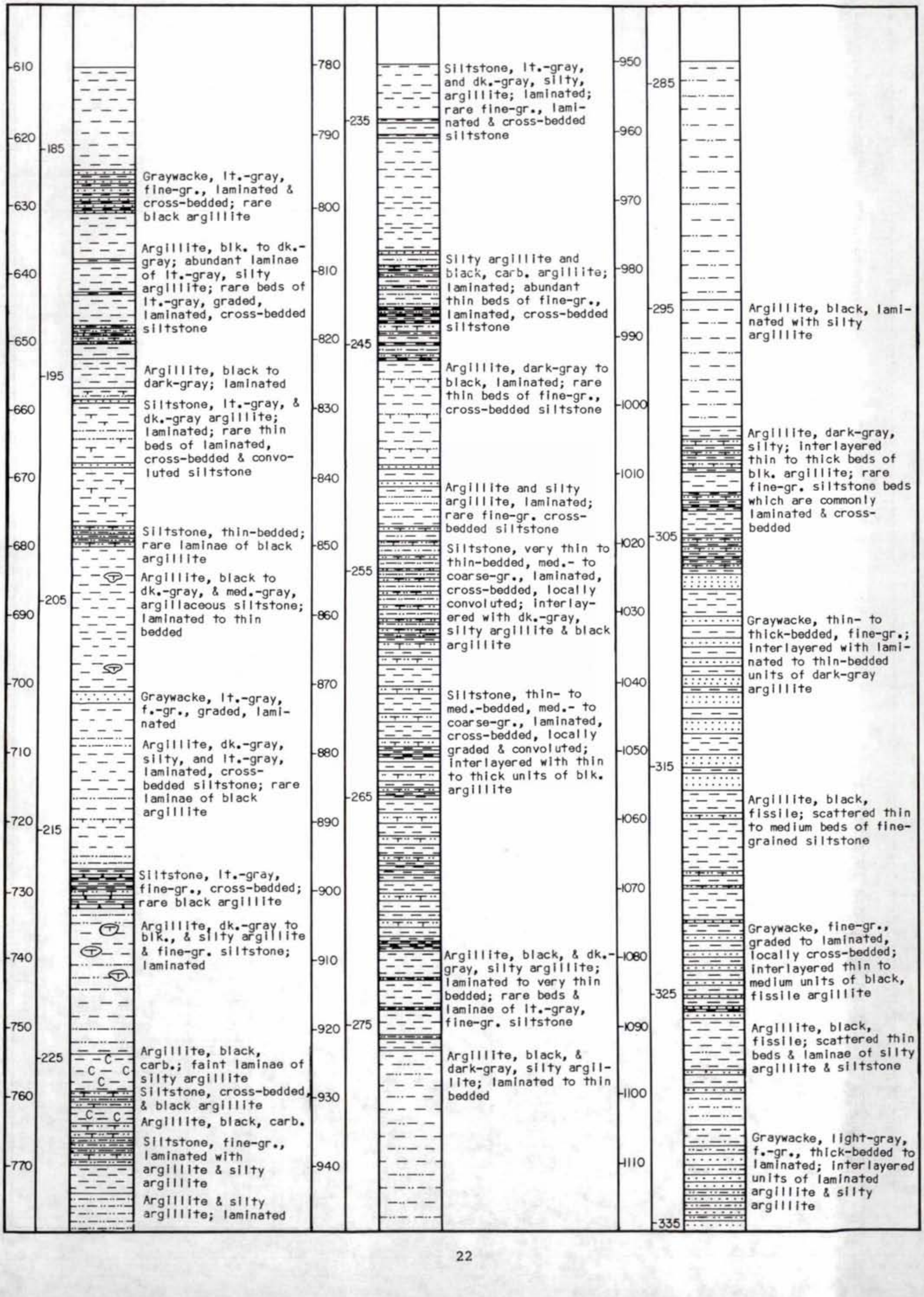


Depth ft.	Depth m.	Description
100		Glacial drift; cobbles and boulders in sand
110	35	VIRGINIA FORMATION Argillite & argillaceous siltstone; laminated; interlayers of fine-grained, very thin bedded, cross-bedded, laminated, graded, calcareous siltstone
120		
130		Argillite, laminated; calcite concretions
140		Graywacke, fine-gr., graded, laminated, cross-bedded
150	45	Argillite, laminated; calcite concretions Argillite & argill. siltstone, laminated; interbeds of fine-gr., calc. siltstone
160		Argillite, laminated, calc.; calcite concretions; interbeds of fine-gr. siltstone
170		Graywacke, fine-gr., graded, laminated, cross-bedded
180	55	
190		Argillite & argill. siltstone; laminated to very thin bedded; interbedded fine-gr., laminated & cross-bedded, locally graded siltstone, calcite concretions
200		
210	65	
220		
230		Argillite & silty argillite; laminated to very thin bedded; scattered thin beds of laminated to ripple-laminated siltstone & rare light-gray, fine-grained graywacke
240		
250	75	
260		

Depth ft.	Depth m.	Description
270		Argillite, black, carbonaceous; scattered laminae of dark-gray, silty argillite & med.-gray, argillaceous siltstone & rare light-gray fine-grained, calcareous graywacke
280	85	
290		
300		
310	95	Argillite, silty argillite, & siltstone; laminated to very thin bedded; interlayered black, carbonaceous argillite
320		Silty argillite and argillite; laminated; ripple-scale laminae in silty beds; scattered beds of siltstone
330		
340		
350	165	Dominantly siltstone & laminated, silty argillite; siltstone units laminated, cross-bedded
360		
370		
380	115	
390		Dominantly argillite, dark-gray, laminated
400		
410	125	
420		Graywacke, med.-gray, fine-gr., locally calcareous; interlayered black argillite
430		Dominantly argillite, black, laminated Graywacke, light-gray, f.-gr.; interlayered black argillite

Depth ft.	Depth m.	Description
440		Silty argillite, light-gray, and dark-gray argillite; laminated; scattered beds of laminated cross-bedded siltstone; scattered thick beds of black, carbonaceous argillite
450	135	
460		
470		Graywacke, light-gray, fine-grained, graded, cross-bedded
480	145	Silty argillite, light-gray, and dark-gray argillite; laminated
490		
500		
510	155	Silty argillite, light-gray, and siltstone; laminated; some dark-gray argillite
520		Argillite, dk.-gray, & med.-gray, silty argillite; rare laminae and very thin beds of lt.-gray siltstone; abundant concretions
530		
540	165	Graywacke, lt.-gray, fine-gr., graded; black argillite laminae
550		Argillite, dark-gray, & lt.-gray, silty argillite; laminated; rare lt.-gray siltstone beds; rare f.-gr., graded & laminated graywacke beds
560		
570		Silty argillite, med.-gray; rare laminae of lt.-gray siltstone
580	175	
590		Argillite, black, and med.-gray, silty argillite; laminated
600	185	Argillite, black; rare laminae of dark-gray, silty argillite

Biwabik 2 of 3



Graywacke, lt.-gray, fine-gr., laminated & cross-bedded; rare black argillite

Argillite, blk. to dk.-gray; abundant laminae of lt.-gray, silty argillite; rare beds of lt.-gray, graded, laminated, cross-bedded siltstone

Argillite, black to dark-gray; laminated

Siltstone, lt.-gray, & dk.-gray argillite; laminated; rare thin beds of laminated, cross-bedded & convoluted siltstone

Siltstone, thin-bedded; rare laminae of black argillite

Argillite, black to dk.-gray, & med.-gray, argillaceous siltstone; laminated to thin bedded

Graywacke, lt.-gray, f.-gr., graded, laminated

Argillite, dk.-gray, silty, and lt.-gray, laminated, cross-bedded siltstone; rare laminae of black argillite

Siltstone, lt.-gray, fine-gr., cross-bedded; rare black argillite

Argillite, dk.-gray to blk., & silty argillite & fine-gr. siltstone; laminated

Argillite, black, carb.; faint laminae of silty argillite

Siltstone, cross-bedded, & black argillite

Argillite, black, carb.

Siltstone, fine-gr., laminated with argillite & silty argillite

Argillite & silty argillite; laminated

Siltstone, lt.-gray, and dk.-gray, silty, argillite; laminated; rare fine-gr., laminated & cross-bedded siltstone

Silty argillite and black, carb. argillite; laminated; abundant thin beds of fine-gr., laminated, cross-bedded siltstone

Argillite, dark-gray to black, laminated; rare thin beds of fine-gr., cross-bedded siltstone

Argillite and silty argillite, laminated; rare fine-gr. cross-bedded siltstone

Siltstone, very thin to thin-bedded, med.- to coarse-gr., laminated, cross-bedded, locally convoluted; interlayered with dk.-gray, silty argillite & black argillite

Siltstone, thin- to med.-bedded, med.- to coarse-gr., laminated, cross-bedded, locally graded & convoluted; interlayered with thin to thick units of blk. argillite

Argillite, black, & dk.-gray, silty argillite; laminated to very thin bedded; rare beds & laminae of lt.-gray, fine-gr. siltstone

Argillite, black, & dark-gray, silty argillite; laminated to thin bedded

Argillite, black, laminated with silty argillite

Argillite, dark-gray, silty; interlayered thin to thick beds of blk. argillite; rare fine-gr. siltstone beds which are commonly laminated & cross-bedded

Graywacke, thin- to thick-bedded, fine-gr.; interlayered with laminated to thin-bedded units of dark-gray argillite

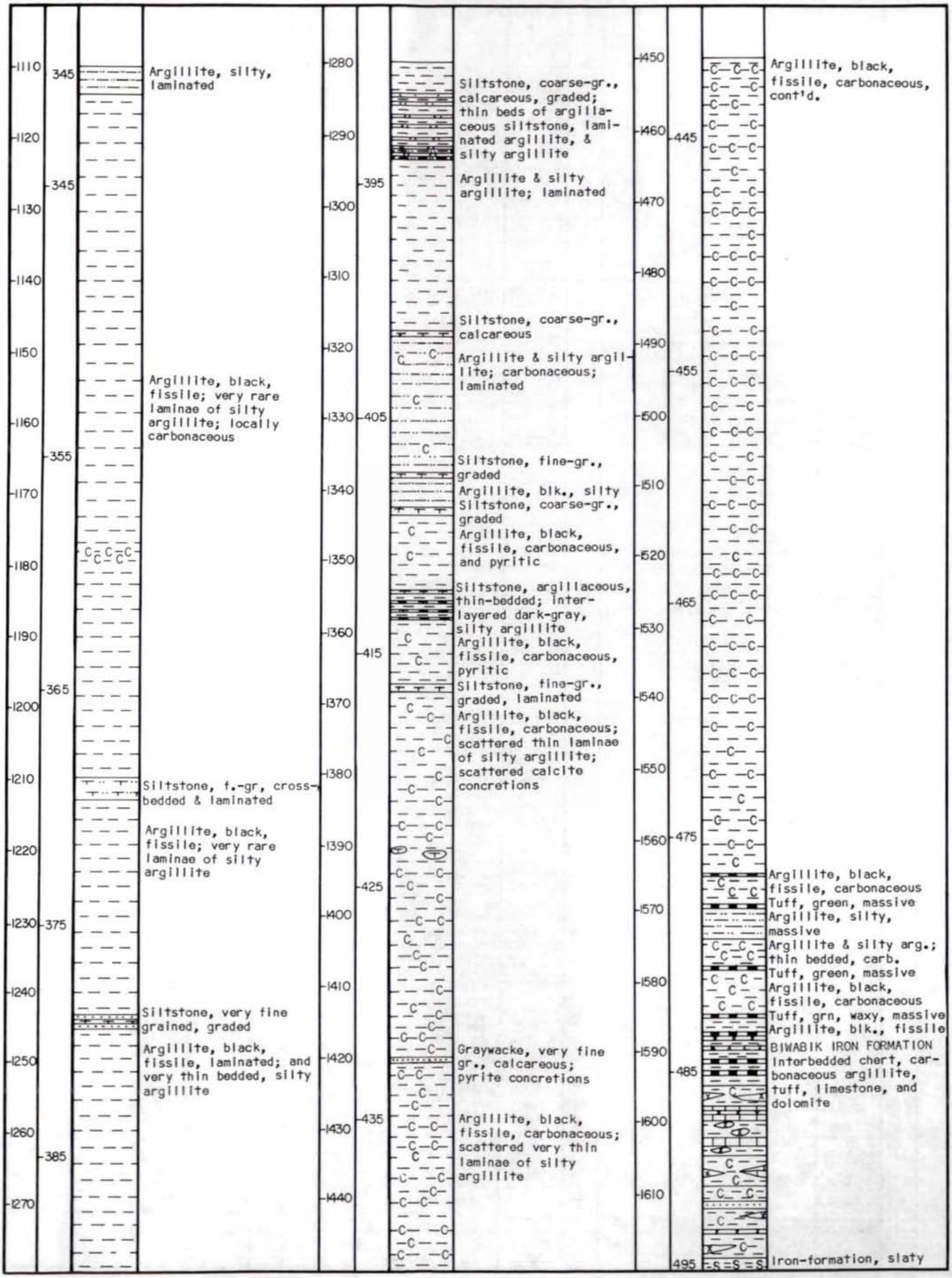
Argillite, black, fissile; scattered thin to medium beds of fine-grained siltstone

Graywacke, fine-gr., graded to laminated, locally cross-bedded; interlayered thin to medium units of black, fissile argillite

Argillite, black, fissile; scattered thin beds & laminae of silty argillite & siltstone

Graywacke, light-gray, f.-gr., thick-bedded to laminated; interlayered units of laminated argillite & silty argillite

Biwabik 3 of 3



Argillite, silty, laminated

Argillite, black, fissile; very rare laminae of silty argillite; locally carbonaceous

Siltstone, f.-gr, cross-bedded & laminated

Argillite, black, fissile; very rare laminae of silty argillite

Siltstone, very fine grained, graded

Argillite, black, fissile, laminated; and very thin bedded, silty argillite

Siltstone, coarse-gr., calcareous, graded; thin beds of argillaceous siltstone, laminated argillite, & silty argillite

Argillite & silty argillite; laminated

Siltstone, coarse-gr., calcareous

Argillite & silty argillite; carbonaceous; laminated

Siltstone, fine-gr., graded

Argillite, blk., silty

Siltstone, coarse-gr., graded

Argillite, black, fissile, carbonaceous, and pyritic

Siltstone, argillaceous, thin-bedded; interlayered dark-gray, silty argillite

Argillite, black, fissile, carbonaceous, pyritic

Siltstone, fine-gr., graded, laminated

Argillite, black, fissile, carbonaceous; scattered thin laminae of silty argillite; scattered calcite concretions

Graywacke, very fine gr., calcareous; pyrite concretions

Argillite, black, fissile, carbonaceous; scattered very thin laminae of silty argillite

Argillite, black, fissile, carbonaceous, cont'd.

Argillite, black, fissile, carbonaceous

Tuff, green, massive

Argillite, silty, massive

Argillite & silty arg.; thin bedded, carb.

Tuff, green, massive

Argillite, black, fissile, carbonaceous

Tuff, grn, waxy, massive

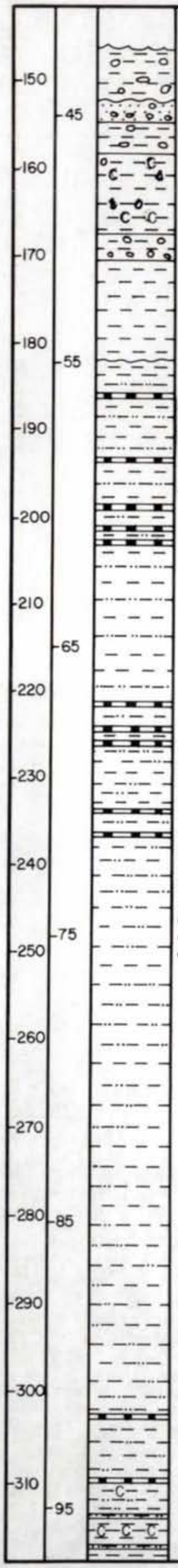
Argillite, blk., fissile

BIWABIK IRON FORMATION

Interbedded chert, carbonaceous argillite, tuff, limestone, and dolomite

Iron-formation, slaty

Buhl 1 of 1



Drift--sand, clay, scattered boulder horizons

CRETACEOUS

Siltstone, fine-gr., greenish-gray, cgl. with chert fragments

Clay, lt.-yellowish-gray, cgl.

Clay, carb., pyritic; and argillaceous siltstone

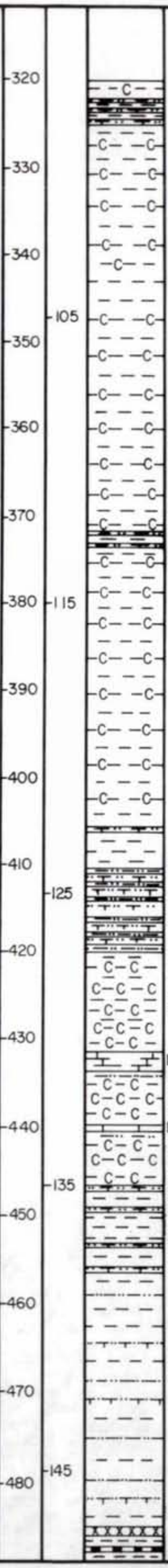
Clay, carb., cgl.

Clay, black, plastic; interlayered black, fissile argillite

VIRGINIA FORMATION

Argillite, black, locally calc., and dk.-gray, silty, argillite; laminated; beds and partings of olive-grn. tuff common

Argillite, black, and dk.-gray, silty, thin-bedded to laminated argillite; interlayered lt. gray argillaceous siltstone; scattered very thin beds of fine-gr. siltstone and argill. siltstone near top of unit. Partings of olive-grn. tuff concentrated near base of unit



Argillite, blk., fissile, carbonaceous, and dark-gray, silty, carbonaceous argillite; laminated; carbonate concretions with & without cone-in-cone structures common; scattered very thin beds & laminae of argillaceous, calc., graded, and laminated siltstone

Siltstone, coarse-gr., calc., graded, & laminated; interlayered with laminated blk. argillite & dk.-gray, silty argillite

Argillite, black, massive, carbonaceous; calcite concretions common

Limestone, argill., blk.

Argillite, blk., carbonaceous with laminae of silty argillite

Limestone, argill., blk.

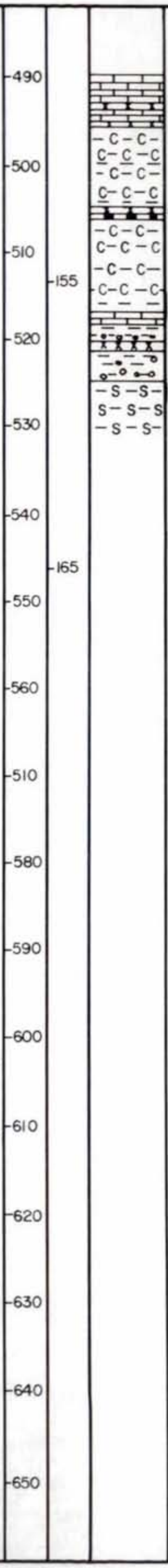
Argillite, blk., carbonaceous with laminae of silty argillite

Siltstone, fine-gr., graded, laminated, cross-bedded; interlayered with black, fissile argillite

Argillite, black, carbonaceous, fissile; with thin laminae of silty argillite & argillaceous siltstone

BIWABIK IRON FORMATION

Argillite, blk., fissile, & olive-grn. tuff



Limestone, chert, & olive-green tuff; interbedded

Argillite, black, carbonaceous, fissile

Chert & olive-grn. tuff

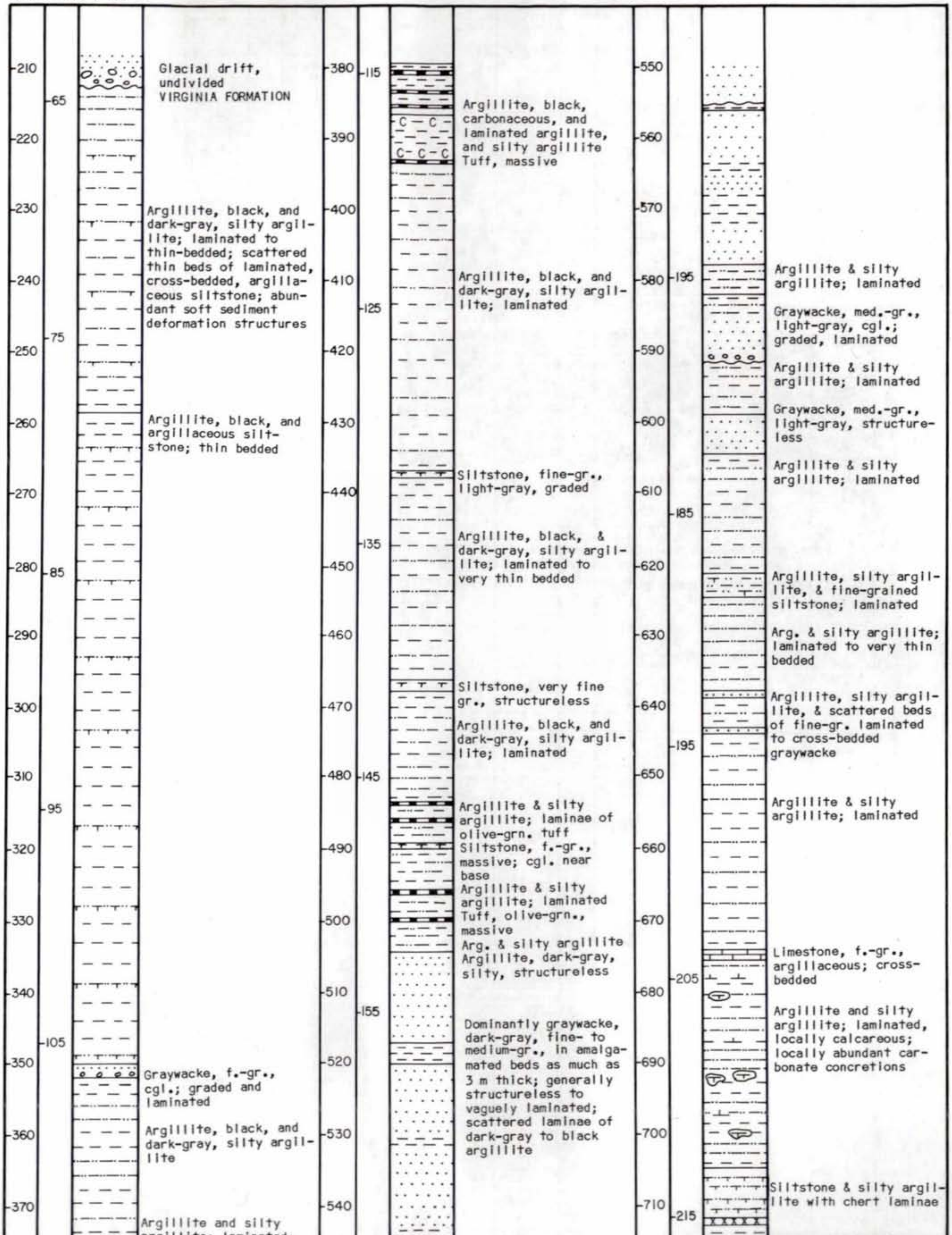
Argillite, black, carbonaceous, fissile

Limestone, blk., argill.

Argillite, black, fissile, cgl., with chert fragments & interbedded black chert

Iron-formation, slaty, silicate facies

Keewatin 1 of 2



Glacial drift, undivided
VIRGINIA FORMATION

Argillite, black, and dark-gray, silty argillite; laminated to thin-bedded; scattered thin beds of laminated, cross-bedded, argillaceous siltstone; abundant soft sediment deformation structures

Argillite, black, and argillaceous siltstone; thin bedded

Graywacke, f.-gr., cgl.; graded and laminated

Argillite, black, and dark-gray, silty argillite

Argillite and silty argillite; laminated; interlayered olive-grn. tuff

Argillite, black, carbonaceous, and laminated argillite, and silty argillite
Tuff, massive

Argillite, black, and dark-gray, silty argillite; laminated

Siltstone, fine-gr., light-gray, graded

Argillite, black, & dark-gray, silty argillite; laminated to very thin bedded

Siltstone, very fine gr., structureless

Argillite, black, and dark-gray, silty argillite; laminated

Argillite & silty argillite; laminae of olive-grn. tuff
Siltstone, f.-gr., massive; cgl. near base
Argillite & silty argillite; laminated
Tuff, olive-grn., massive
Arg. & silty argillite
Argillite, dark-gray, silty, structureless

Dominantly graywacke, dark-gray, fine- to medium-gr., in amalgamated beds as much as 3 m thick; generally structureless to vaguely laminated; scattered laminae of dark-gray to black argillite

Argillite & silty argillite; laminated

Graywacke, med.-gr., light-gray, cgl.; graded, laminated

Argillite & silty argillite; laminated

Graywacke, med.-gr., light-gray, structureless

Argillite & silty argillite; laminated

Argillite, silty argillite, & fine-grained siltstone; laminated

Arg. & silty argillite; laminated to very thin bedded

Argillite, silty argillite, & scattered beds of fine-gr. laminated to cross-bedded graywacke

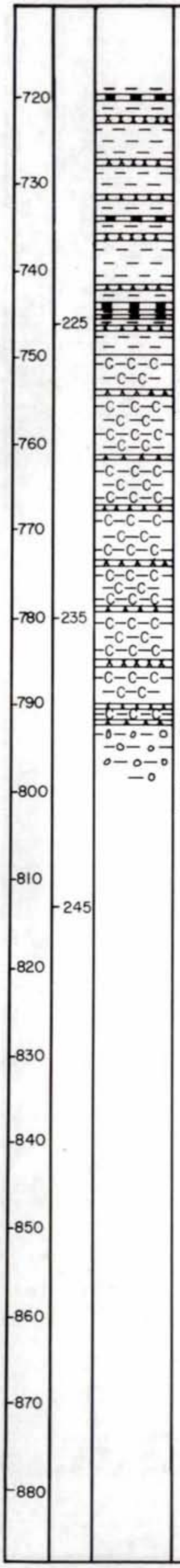
Argillite & silty argillite; laminated

Limestone, f.-gr., argillaceous; cross-bedded

Argillite and silty argillite; laminated, locally calcareous; locally abundant carbonate concretions

Siltstone & silty argillite with chert laminae

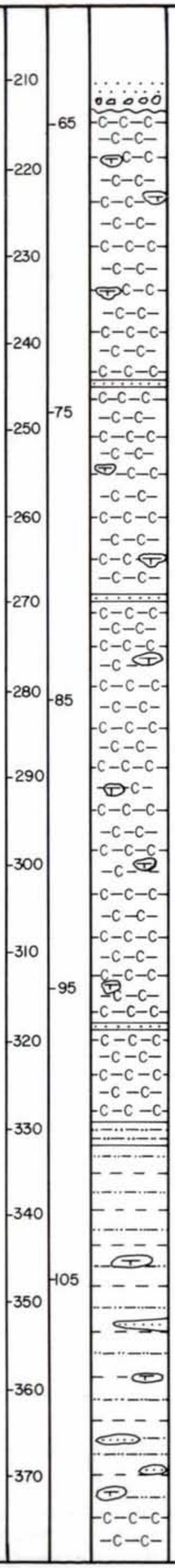
Argillite, black, carbonaceous, pyritic



Argillite & argillaceous siltstone; thin bedded to laminated; interbedded thin beds of chert & laminae of olive-grn. tuff

Argillite, black, carbonaceous, pyritic; interbedded laminae & thin beds of chert

BIWABIK IRON FORMATION
Chert & argillite, interbedded
Iron-formation, cherty, silicate facies, conglomeratic, nonmagnetic



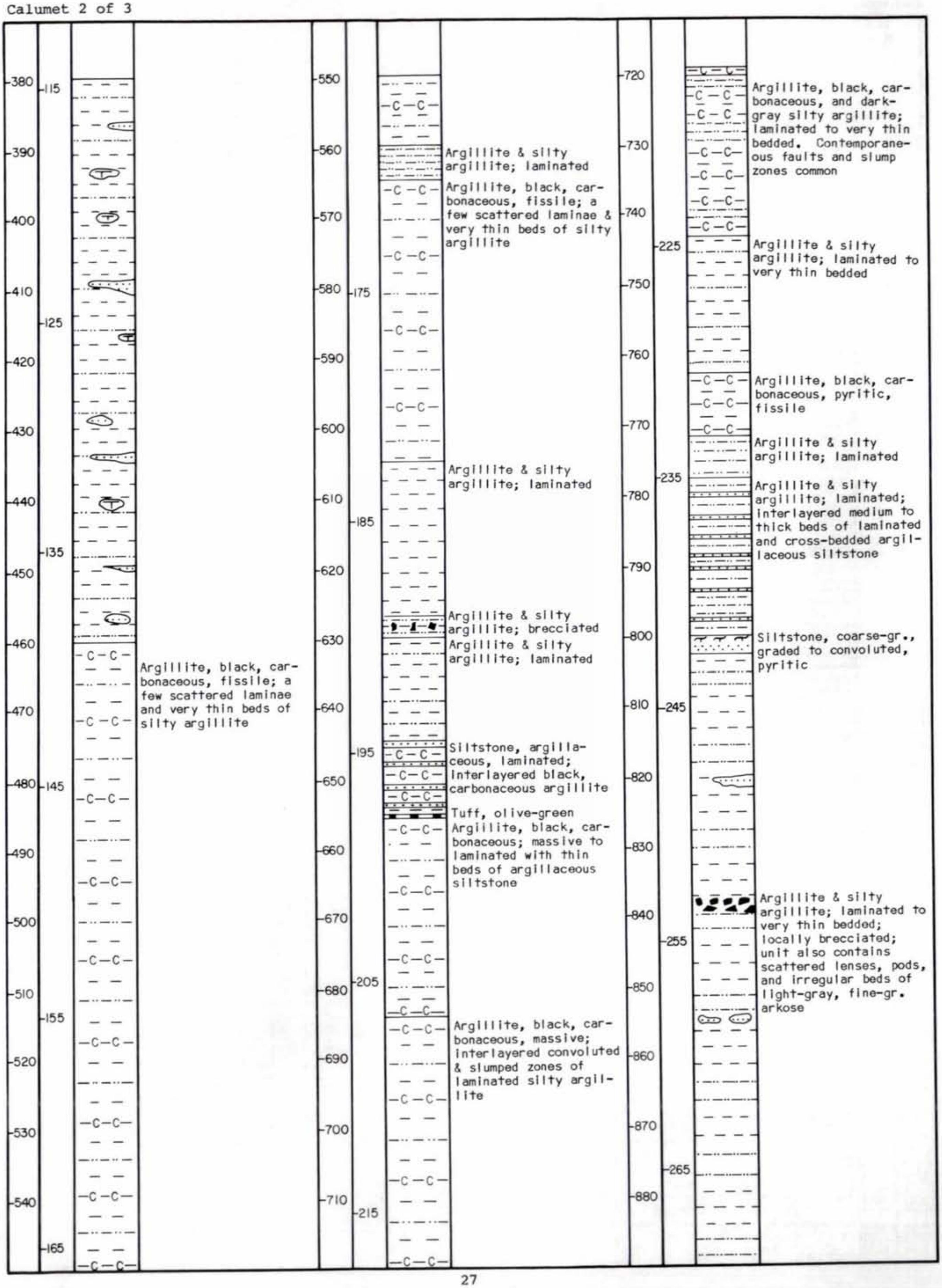
Glacial drift, undivided

VIRGINIA FORMATION

Argillite, black, carbonaceous, fissile; scattered laminae and thin beds of silty, graded and cross-bedded argillite

Argillite, silty, laminated, locally calcareous

Argillite, black, pyritic, & dark-gray, silty argillite; laminated. Scattered pods & lenses of fine-gr., light-gray arkose. Carbonate concretions with & without cone-in-cone structures



Argillite, black, carbonaceous, fissile; a few scattered laminae and very thin beds of silty argillite

Argillite & silty argillite; laminated

Argillite, black, carbonaceous, fissile; a few scattered laminae & very thin beds of silty argillite

Argillite & silty argillite; laminated

Argillite & silty argillite; brecciated

Argillite & silty argillite; laminated

Siltstone, argillaceous, laminated; interlayered black, carbonaceous argillite

Tuff, olive-green

Argillite, black, carbonaceous; massive to laminated with thin beds of argillaceous siltstone

Argillite, black, carbonaceous, massive; interlayered convoluted & slumped zones of laminated silty argillite

Argillite, black, carbonaceous, and dark-gray silty argillite; laminated to very thin bedded. Contemporaneous faults and slump zones common

Argillite & silty argillite; laminated to very thin bedded

Argillite, black, carbonaceous, pyritic, fissile

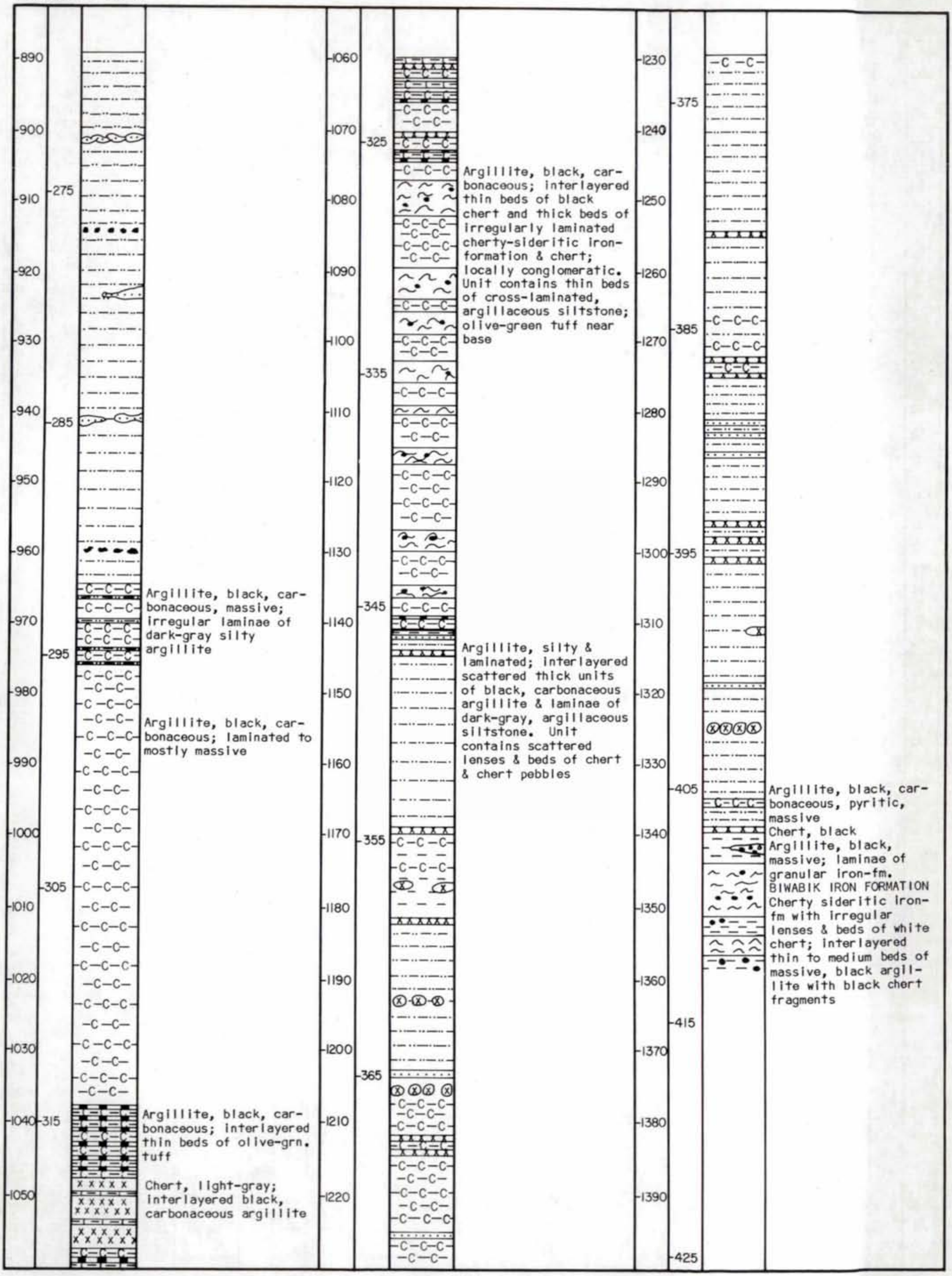
Argillite & silty argillite; laminated

Argillite & silty argillite; laminated; interlayered medium to thick beds of laminated and cross-bedded argillaceous siltstone

Siltstone, coarse-gr., graded to convoluted, pyritic

Argillite & silty argillite; laminated to very thin bedded; locally brecciated; unit also contains scattered lenses, pods, and irregular beds of light-gray, fine-gr. arkose

Calumet 3 of 3



Argillite, black, carbonaceous, massive; irregular laminae of dark-gray silty argillite

Argillite, black, carbonaceous; laminated to mostly massive

Argillite, black, carbonaceous; interlayered thin beds of olive-grn. tuff

Chert, light-gray; interlayered black, carbonaceous argillite

Argillite, black, carbonaceous; interlayered thin beds of black chert and thick beds of irregularly laminated cherty-sideritic iron-formation & chert; locally conglomeratic. Unit contains thin beds of cross-laminated, argillaceous siltstone; olive-green tuff near base

Argillite, silty & laminated; interlayered scattered thick units of black, carbonaceous argillite & laminae of dark-gray, argillaceous siltstone. Unit contains scattered lenses & beds of chert & chert pebbles

Argillite, black, carbonaceous, pyritic, massive

Chert, black

Argillite, black, massive; laminae of granular iron-fm.

BIWABIK IRON FORMATION

Cherty sideritic iron-fm with irregular lenses & beds of white chert; interlayered thin to medium beds of massive, black argillite with black chert fragments