MINNESOTA GEOLOGICAL SURVEY

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RESULTS OF SUBSURFACE INVESTIGATIONS IN NORTHWESTERN MINNESOTA, 1972

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CONTENTS

ILLUSTRATIONS

TABLES

RESULTS OF SUBSURFACE INVESTIGATIONS IN NORTHWESTERN MINNESOTA, 1972

by

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ABSTRACT

Two test wells were drilled in northwestern Minnesota during a test drilling program conducted by the Minnesota Geological Survey in 1972. Total footage drilled was 851.5 feet (260 m). Together, the wells represent a relatively complete stratigraphic section of the Paleozoic and Mesozoic rocks found in northwestern Minnesota, which are covered by thick Pleistocene overburden and do not crop out. Four stratigraphic units are present. The basal unit is the Winnipeg Formation, a Middle Ordovician unit approximately 160 feet (49 m) thick composed of quartzose sandstone and shale. It is overlain by the Red River Formation, an Upper Ordovician unit about 200 to 300 feet (61 to 91 m) thick composed of dolomitic limestone and dolomite.

The other two units are interpreted to be Mesozoic. The lower unit is a reddish-brown shale with a thin layer of dolomite at the top. It is as much as 105 feet (32 m) thick in Minnesota. It may be equivalent to the red beds in adjoining parts of Manitoba and North Dakota that are assigned a Jurassic age, although no paleontologic evidence was found to indicate its age. The uppermost unit is a gray shale that is provisionally interpreted to be Cretaceous.

Two tills can be recognized in the Pleistocene section on the basis of the lithology of the sand-size fraction and size-grade distribution. The surficial Pleistocene unit is clay associated with Glacial Lake Agassiz.

The Precambrian basement in the area is principally volcanogenic metasedimentary rock and metamorphosed volcanic rock of Early Precambrian age. It was penetrated in one well where it is represented by actinolitic hornblende-plagioclase schist, a mafic, tuffaceous, sedimentary rock that has been metamorphosed.

INTRODUCTION

Two wells totaling 851.5 feet (260 m) in footage were drilled in extreme northwestern Minnesota, primarily to evaluate the possibilities for occurrence of mineable gypsum in the subsurface (fig.1). Gypsum has been mined by subsurface techniques at Silver Plains, Manitoba, approximately 30 miles (48 km) north of the international boundary (Lambo, 1964), and is known to occur in the subsurface in North Dakota (Downey, 1971, p. 375-

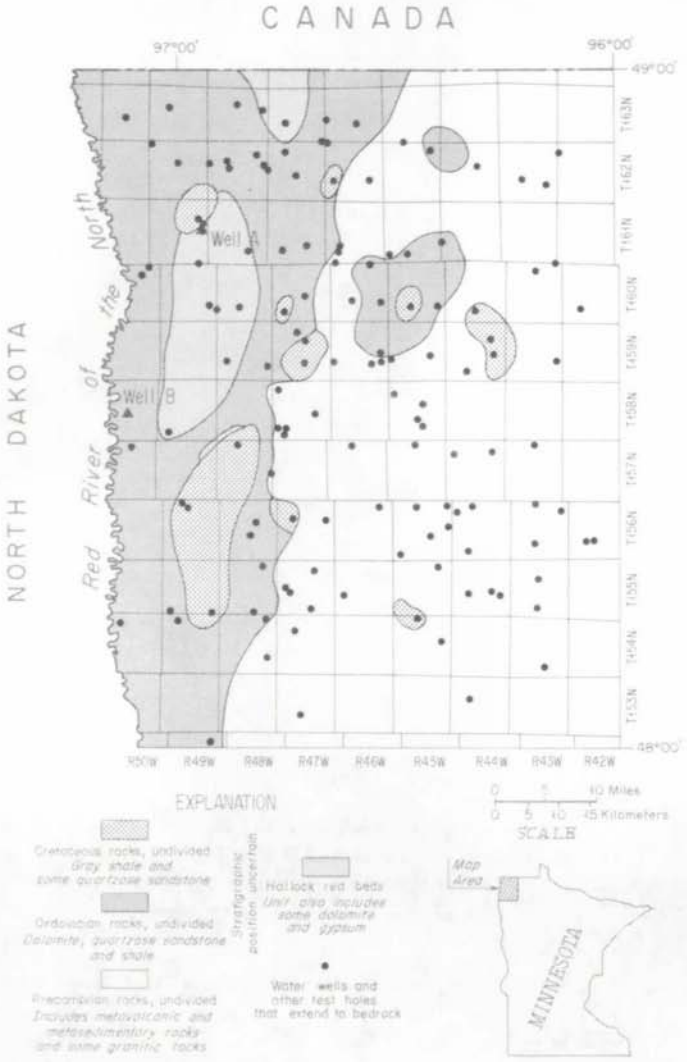

Figure 1 — Generalized bedrock geologic map of northwestern Minnesota showing test well locations.

377; Arndt, 1975; North Dakota Geological Survey, 1968). Results of the test drilling program failed to establish commercial possibilities for gypsum (Minnesota Geological Survey, 1972). However, the geological data collected during the test drilling program are valuable for interpreting geology in the northwestern corner of the state. Together, the wells present a fairly complete composite section of the Paleozoic and Mesozoic rocks of northwestern Minnesota, which do not crop out because of thick (200 to 400 feet; 61 to 122 m) Pleistocene overburden (fig.2).

Era	System	Formation	Dominant Lithology	Maximum Thickness (feet)
Cenozoic	Quaternary	Lake Agassiz lacustrine clay Lower Red Lake Falls till equivalent Marcoux till equivalent	Lacustrine clay and glacial till	200+
Mesozoic	Cretaceous (?)	Not formally named	Medium gray shale; minor sandstone at base	25-50
	Age uncertain Jurassic (?)	Not formally named; Hallock red beds	Reddish-brown shale minor dolomite at top	105
Paleozoic	Ordovician	Red River Fm.	Dolomite and dolomitic limestone	200-300
		Winnipeg Fm.	Sandstone and shale	165
Early Precambrian			Schist	

▨ denotes important pre-Pleistocene unconformities

Figure 2 -- Generalized stratigraphic column for northwestern Minnesota drilling project.

Geologic Setting

The wells were drilled in an area that was part of a shelf during the Paleozoic along the eastern edge of the Williston basin. As a result, the Paleozoic rocks have a low westward dip toward the basin. Mesozoic rocks onlap beveled erosional edges of the underlying Paleozoic formations. Although rocks of every geological period from Cambrian to Tertiary are represented in the center of the Williston basin in western North Dakota (Carlson and Anderson, 1965), only Ordovician and Cretaceous rocks have been identified with certainty along the eroded margin of the basin in

Minnesota. Rocks of uncertain (Jurassic?) age also occur in northwestern Minnesota and adjoining areas of Manitoba and North Dakota; however no definitive paleontological evidence has been found for their Jurassic age assignment, which is based on physical stratigraphy.

Ordovician rocks reach a maximum thickness of approximately 300 feet (91 m) in northwestern Minnesota. Jurassic (?) age rocks reach a maximum thickness of 105 feet (32 m) and Cretaceous rocks range in thickness from 25 to 50 feet (8 to 15 m).

Precambrian basement in the area is inferred from gravity and magnetic data and scattered drill holes to consist mainly of volcanogenic metasedimentary rocks and volcanic rocks of Early Precambrian age, and subordinate felsic and intermediate intrusive rocks (Sims, 1970).

Pleistocene glacial drift ranges in thickness from 200 to 400 feet (61 to 122 m). The lower part of the sequence is composed principally of till units of Wisconsin and questionable pre-Wisconsin or Early Wisconsin age (Harris and others, 1974). The upper part of the sequence is composed of lacustrine silts and clays associated with sedimentation in Glacial Lake Agassiz (Harris and others, 1974).

Methods of Study

Both during and upon completion of the drilling program, well cuttings were examined with a binocular microscope. Geophysical logs, run upon completion of the drilling program, were used to check lithologic changes observed in well sample studies. Thin sections prepared from selected core samples were described and classified according to rock type. Sedimentary rock thin sections were classified using Folk's (1968) classifications for carbonate rocks and sandstones.

Clay mineralogy of shales was determined using standard techniques for mineral identification such as those described by Parham (1970, p. 26-27). Relative abundances of clay-mineral species in individual samples were ascertained by comparing peak heights of the first basal (001) reflections of the clays present. This method, although not a precise measure of the amount of clay present in a given sample, is useful for demonstrating variations and trends in clay mineralogy in a stratigraphic section (Parham, 1970, p. 99ff).

The proportions of calcite and dolomite in carbonate rocks were determined by X-ray analysis of finely ground (<325 mesh) samples, using the method of fixed time counting of peak heights described by Royce and others (1971).

The Pleistocene till samples were analyzed by pipette to determine size-grade distribution and by grain counting of the sand-size fraction to determine lithologic variations.

DESCRIPTION OF WELLS

Graphic columns and geophysical logs for the two test wells are shown in Figures 3 and 4; lithic descriptions given in condensed form on these figures are discussed below.

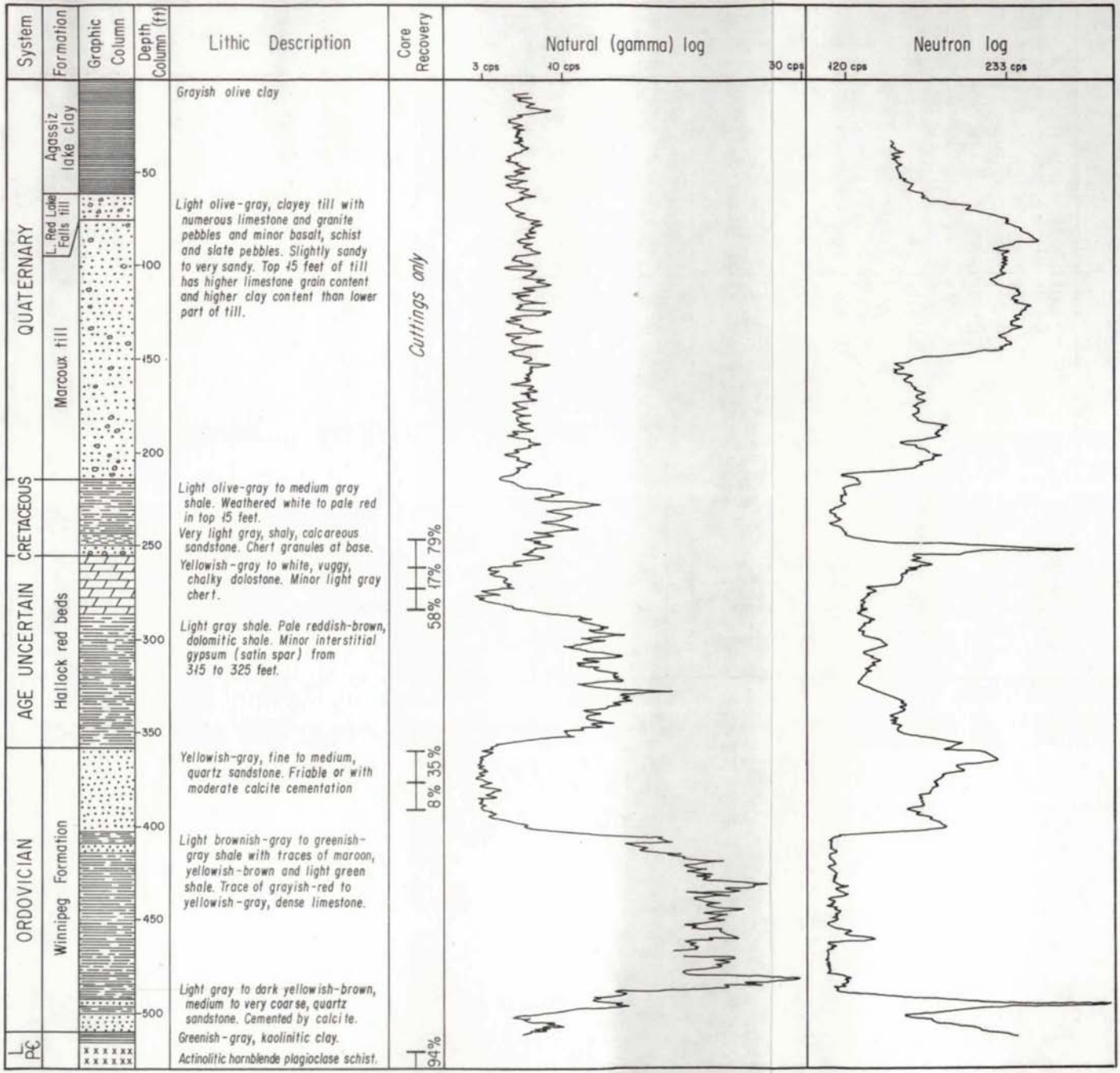

Figure 3 — Graphic column, core recovery, and geophysical logs for Well A, SE¼SE¼SW¼NW¼ sec. 13, T. 161 N., R. 49 W., Kittson County, Minnesota.
Surface elevation = 805±5 feet (245±1.5 m).

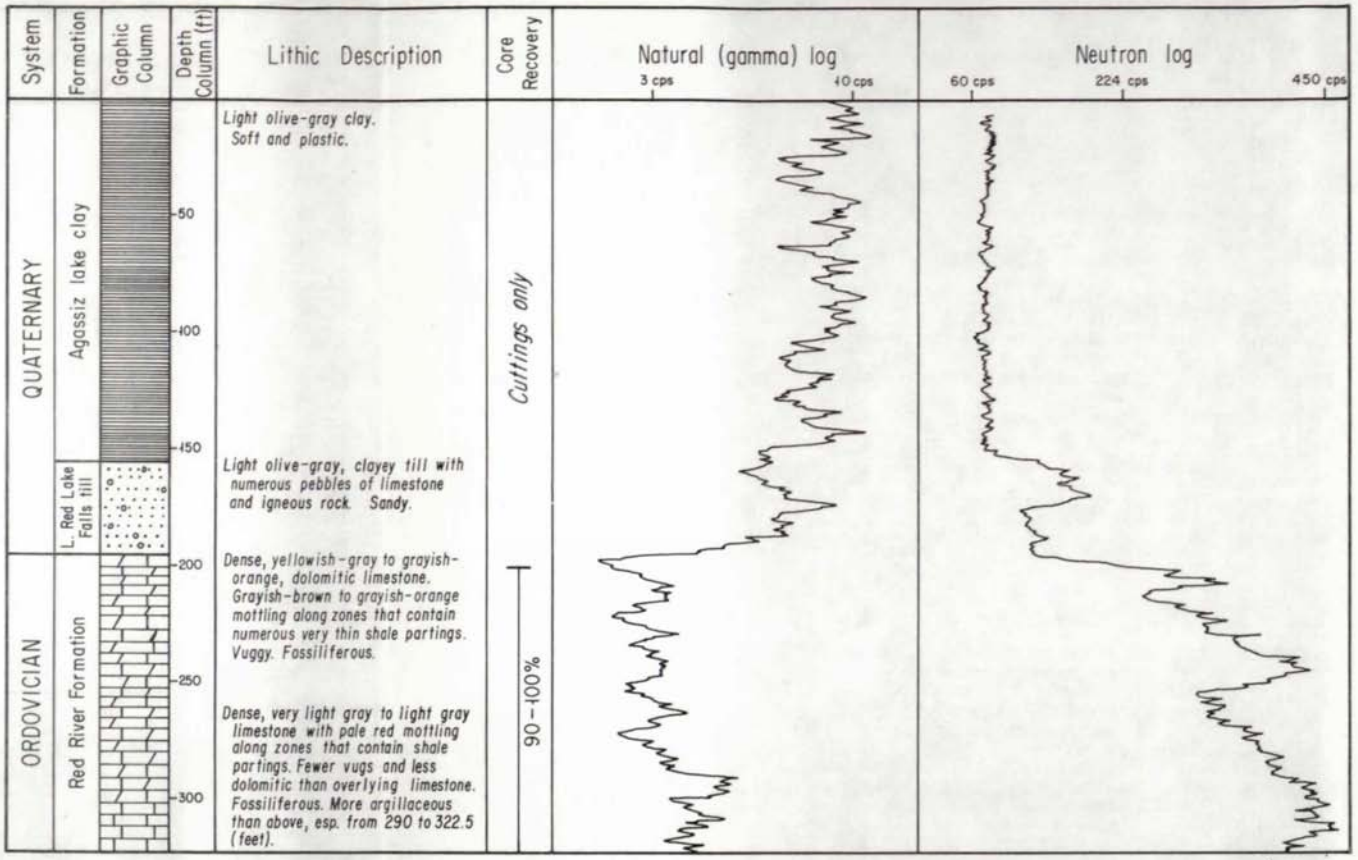

Figure 4 — Graphic column, core recovery, and geophysical logs for Well B, NE¼NE¼NE¼SE¼ sec. 20, T. 158 N., R. 50 W., Marshall County, Minnesota.
Surface elevation = 790±5 feet (241±1.5 m).

Well A, sec. 13, T. 161 N., R. 49 W., Kittson County

Test Well A was drilled to a total depth of 529 feet (161 m) (fig. 3). It penetrated 215 feet (66 m) of Pleistocene lake clay and till, 295 feet (90 m) of Paleozoic and Mesozoic sedimentary rock and 19 feet (6 m) of Precambrian metamorphic rock.

Pleistocene

The upper 62 feet (19 m) of Well A is Lake Agassiz lacustrine clay. The clay is grayish olive and is characterized by low content of sand- and silt-sized grains (tbl. 1). Till underlies the lake clay and extends from 62 to 215 feet (19 to 66 m) in depth. The till is light olive gray and is characterized by a high percentage of sand-sized grains and a large proportion of igneous rock fragments in the 1- to 2-mm size fraction (tbls. 1 and 2). An increase in clay content, as well as an increase in proportion of carbonate grains in the top 15 feet (5 m) of the till, indicates that two separate till units are present in the well (C. L. Matsch, oral commun.), and the top 15 feet (5 m) of till is considered to be a separate stratigraphic unit.

Table 1 — Textural analysis of Pleistocene till from Well A.*

Lithologic Unit	Sample Interval (feet)	Grain Size in Percent Sand	Silt	Clay
Lake Agassiz clay	60-63	4	9	87
Upper till--equiv. to lower unit of Red Lake Falls Fm.	65-70	23	27	50
	70-75	46	32	22
Average, upper till	65-75	34.5	29.5	36
Lower till--equiv. to Marcoux Fm.	80-85	69	16	15
	90-95	77	10	13
	100-105	78	11	11
	110-115	60	23	17
	120-125	67	21	12
	130-135	71	14	15
	140-145	78	11	11
	150-155	80	11	9
	160-165	56	24	20
	170-175	63	21	16
	180-185	73	16	11
	190-195	66	18	16
	200-205	66	16	18
	210-215	55	20	25
Average, lower till	80-215	68.5	16.6	14.9

*Data compiled by B. DeMarte

Table 2 — Lithology of 1- to 2-mm size fraction from Pleistocene till, Well A.*

Lithologic Unit	Sample Interval (feet)	Rock Type in Percent: Crystalline (igneous and metamorphic) Grains	Carbonate Grains	Others (incl. shale)
Lake Agassiz clay	60-63	50	46	4
Upper till--equiv. to lower unit of Red Lake Falls Fm.	65-70	59	40	1
	70-75	50	49	1
Average, upper till	65-75	54.5	44.5	1
Lower till--equiv. to Marcoux Fm.	80-85	70	30	
	90-95	82	18	
	100-105	81	19	
	110-115	84	16	
	120-125	91	9	
	130-135	89	11	
	140-145	88	12	
	150-155	94	6	
	160-165	92	8	
	170-175	91	9	
	180-185	91	9	
	190-195	93	7	
	200-205	87	13	
	210-215	83	17	
Average, lower till	80-215	86.9	13.1	

*Data compiled by B. DeMarte

Mesozoic

A 40-foot (12 m) interval of Cretaceous(?) shale underlies the Pleistocene interval. This unit is light olive-gray to medium gray fissile shale, which is weathered to white or pale reddish-brown in the top 15 feet (5 m). Pipette analysis of a sample from the lower part of the unit indicates that the shale is 1 percent sand, 15 percent silt, and 84 percent clay. Clay mineralogy of the shale is chiefly illite with minor (less than 10 percent) kaolinite (tbl. 3). Kaolinite content does not increase appreciably toward the top of the unit, indicating that the weathering, which probably produced the color changes at the top of the unit, was not intense enough to alter the clay mineralogy. Shale from a cored interval near the base of the Cretaceous(?) was 100 percent illite.

Table 3 — Clay mineral analyses of shales - Well A

Lithologic Unit	Depth (feet)	Mineralogy I	K	M
Cretaceous shale	215-220	9	1	
	220-225	9	1	
	225-230	9	1	
	230-235	9	1	present
	235-240	9.5	0.5	
	247-262	10	none	
Hallock red beds	273.5-285.5	10	none	
	290-295	10	trace	
	310-315	9	1	
	330-335	9	1	
	345-350	9	1	
	360-377	10	none	
Winnipeg shale	410-415	8.5-9	1-1.5	present
	435-440	9	1	
	460-465	5	5	
	485-490	6	4	
Possible Precambrian regolith	510-515	6	4	present

I = illite K = kaolinite M = montmorillonite
(Montmorillonite probably contamination from drilling fluid.)
Numbers in the kaolinite and illite columns refer to ratios of intensity of first order X-ray peaks for each mineral minus the background count. Ratio indicates, in general way, the relative abundance of each clay mineral (Parham, 1970, p. 99, 114).

Shale from the cored interval contains foraminiferids (Ammodiscus sp.) and ostracodes (Cytherella sp.). These fossils are long ranging forms that occur in rocks from Silurian to Recent age; therefore they cannot be used to determine the age of the unit (Harlan Bergquist, written commun.; F.M. Swain, written commun.). Provisional assignment to the Cretaceous is based upon lithologic similarities of the unit to rocks of known Cretaceous age elsewhere in Minnesota.

A 47-inch (119 cm) interval consisting of interbedded sandstone and sandy shale lies at the base of the Cretaceous. This unit is composed primarily of pelletoidal, fossiliferous intrasparite that has minor quartz sand. The fossil fragments have been replaced by calcite spar, and cannot be identified. The basal 2 or 3 inches (5 to 8 cm) is calcareous, conglomeratic orthoquartzite that contains chert fragments in the coarse-sand to granule range.

Beneath the Cretaceous(?) shale unit, there is a 102-foot (31 m) interval of dolomite, marl and red mudstone that was informally named the Hallock red bed by, Bayer (1959). The presence of a basal conglomeratic unit in overlying Cretaceous rock, as well as distinct lithologic differences between it and the Hallock red bed, indicates that they are separate

stratigraphic entities. The geologic age of the Hallock red bed is uncertain, as no fossils have been recovered from it.

The top 30 feet (9 m) of the red bed is very fine (micritic), faintly laminated dolostone and dolomitic marl with convoluted bedding. Light gray chert nodules occur in this interval. An interval of shale 72 feet (22 m) thick underlies the carbonate bed. The upper 6 feet (2 m) of shale is light gray; the rest is pale reddish brown. The reddish-brown shale interval contains numerous silt-sized, pink, euhedral rhombs of dolomite and minor satin spar gypsum that probably is interstitial. The primary clay mineral in this unit is illite, and traces of kaolinite also occur (tbl. 3).

Paleozoic

Comparison of the section of Winnipeg Formation present in Well A with descriptions of the unit in North Dakota (Anderson and Haraldson, 1968) and Manitoba (Andrichuk, 1959) indicates that a nearly complete section is present. In Well A, the formation is represented by a basal sandstone unit 10 feet (3 m) thick, a medial shale sequence containing thin sandstone stringers 97 feet (30 m) thick, and an upper sandstone unit 46 feet (14 m) thick. The upper sandstone is yellowish-gray, friable, fine to medium quartzose sandstone. Thin section examination indicates that it is calcareous orthoquartzite. The medial shale is greenish gray and variegated, and characterized by subequal amounts of illite and kaolinite in its lower part and predominance of illite in its upper part (tbl. 3). The basal sandstone is medium to coarse, quartzose sandstone that contains trace amounts of jasper and white, quartzitic siltstone granules.

Samples from this formation from another deep well (Bayer, 1959, p. 45-46) approximately a mile north of the drill site contained conodonts of Ordovician Black River age (Ethington and Furnish, 1960).

Precambrian

Fourteen feet (5 m) of Precambrian rock were drilled and cored in this well. In addition, a 5-foot (2 m) interval of greenish-gray, kaolinitic clay overlying the Precambrian and beneath the basal Winnipeg sandstone may possibly represent a weathering horizon at the top of the Precambrian, similar to the thin Precambrian weathered zone observed on schists near Lake Winnipeg in Manitoba (Baillie, 1952).

The Precambrian is interpreted to be a metamorphosed mafic tuffaceous sedimentary rock (R. W. Ojakangas, oral commun.) that has distinct bedding inclined at 50° to horizontal. The rock is actinolitic hornblende schist with albite, quartz, and accessory magnetite-ilmenite and clinozoisite. There is minor alteration of the magnetite and ilmenite to limonite and leucoxene, and of the feldspar to saussurite. The rock is transected by well developed kink bands and cut by quartz veins. Sims (1970) assigned it to the Lower Precambrian.

Well B, sec. 20, T. 158 N., R. 50 W., Marshall County

Test Well B was drilled to a total depth of 322.5 feet (98 m) (fig. 4). It penetrated 195 feet (59 m) of Pleistocene lake clay and till and 127.5 feet (39 m) of Paleozoic carbonate rock.

Pleistocene

Lake Agassiz lacustrine clay is 155 feet (47 m) thick in Well B. The clay is light olive gray to greenish gray, soft and plastic. It is underlain by 40 feet (12 m) of light olive-gray glacial till. The till resembles the upper till in Well A and is characterized by high clay content (tbl. 4) and predominance of carbonate grains in the sand fraction (tbl. 5).

Table 4 — Textural analysis of Pleistocene till from Well B.*

Lithologic Unit	Sample Interval (feet)	Grain Size in Percent		
		Sand	Silt	Clay
Upper till--equiv. to lower unit of Red Lake Falls Fm.	155-160	33	17	50
	165-170	42	22	36
	175-180	37	17	46
	185-190	35	18	47
	195-200	39	17	44
Average, upper till	155-200	37.2	18.2	44.6

* Data compiled by M. Willis

Table 5 — Lithology of 1- to 2-mm size fraction from Pleistocene till, Well B.*

Lithologic Unit	Sample Interval (feet)	Rock Type in Percent		
		Crystalline (igneous and metamorphic) Grains	Carbonate Grains	Others (incl. shale)
Upper till — equiv. to lower unit of Red Lake Falls Fm.	155-160	42	56	2
	165-170	39	60	1
	175-180	40	60	
	185-190	34	66	
	195-200	36	63	1
Average	155-200	38.2	61	0.8

*Data compiled by M. Willis

The Pleistocene is underlain by the Ordovician Red River Formation. A 127.5-foot (39 m) interval of this formation was drilled at Well B; the base of the formation was not reached in the test hole.

The Red River Formation is composed of fossiliferous dolostone classified as finely crystalline biogenic dolomite, and dolomitic limestone classified as dolomitized sparse biomicrite (Folk, 1968). The fossils include a variety of organisms, such as echinoderms, bryozoans, brachiopods, trilobites and ostracodes. Echinoderm fragments are the predominant fossil form in the upper part of the carbonate sequence, evidently because they were selectively preserved by preferential dolomitization of other skeletal grains.

Dolomitization is more intense in the upper part of the formation, the 195- to 260-foot (59 to 79 m) depth interval in the test hole, where dolomite may exceed 70 percent of total carbonate. Dolomite content decreases at the base of the formation to less than 10 percent of total carbonate (tbl. 6). The dolomite occurs as very fine to fine crystalline (0.05 to 0.065 mm) rhombs.

The Red River Formation contains numerous shale partings, particularly in its lower part, the 270- to 322.5-foot (82 to 98 m) depth interval in the test hole, and is intensely color mottled.

Table 6 — Dolomite content of Red River Formation, Well B expressed as a percentage of total carbonate in whole rock samples.*

Depth (feet)	Percent Dolomite
200	68
210	55
220	74
230	43
240	51
250	37
260	59
270	38
280	22
290	54
300	15
310	4
320	11

* Accurate to within $\pm$ 6%, 95% confidence interval (Royce and others, 1971).

COMPOSITE STRATIGRAPHIC SECTION, NORTHWESTERN MINNESOTA

A composite section for Phanerozoic rocks of the study area, shown in Figure 2, gives the age, generalized lithology, approximate maximum thickness, and stratigraphic sequence of units encountered in the subsurface.

Winnipeg Formation

The Winnipeg Formation of northwestern Minnesota resembles the Winnipeg in the subsurface of adjacent southeastern Manitoba. There, the formation has a thin (10 to 30 feet; 3 to 9 m), basal sandstone overlain by a thick shale sequence, which contains an east-west trending sandstone bar in its upper part that is as much as 90 feet (29 m) thick (Andrichuk, 1959).

A prominent medial limestone lentil that occurs in eastern North Dakota (Anderson and Haraldson, 1968) is not developed in the vicinity of Well A. The contact of the Winnipeg with the overlying Red River Formation was not encountered in the test wells, but where it has been encountered it is gradational and composed of argillaceous limestone and shale (Andrichuk, 1959).

Red River Formation

Because members of the Red River Formation identified in the outcrop area near Lake Winnipeg are difficult to recognize in the subsurface of southern Manitoba and adjoining areas, Andrichuk (1959) subdivided the formation into three informal lithologic units of variable thickness. The basal 50 to 150 feet (15 to 46 m) is partly dolomitized bioclastic limestone. The overlying 200 to 300 feet (61 to 91 m) is slightly dolomitic limestone, to interbedded limestone and dolomite, to pure secondary dolomite. All carbonates in the latter unit are bioclastic; even the pure dolomites contain relict crinoid and brachiopod fragments. The uppermost 100 to 150 feet (30 to 46 m) consists of lithographic to finely crystalline dolomite that sometimes contains thin interbeds of anhydrite, and is locally oolitic, pseudo-oolitic or bioclastic.

Lithologically, the Red River Formation in Well B most closely resembles the lower two units of the formation found in southern Manitoba. The uppermost evaporitic unit of the Red River of southern Manitoba may have been eroded from the vicinity of Well B.

Younger Paleozoic formations, the Stony Mountain Formation (Ordovician) and Stonewall Formation (Ordovician-?Silurian) have not been recognized in the subsurface of northwestern Minnesota and, if present, are probably present only in the extreme northwestern corner of the state.

Hallock Red Beds

The age and stratigraphic relationships of this unit to units in adjoining areas are uncertain because of the lack of precise paleontological control. Allison (1932, p. 101) considered the unit to be Paleozoic. In his discussion of two other possibilities, Bayer (1959, p. 51-53) favored the hypothesis that the unit is a thick regolith developed on the Paleozoic

formations. He interpreted its apparent high dolomite content and low clay content as resulting from weathering of Red River dolomite.

The alternative possibility discussed by Bayer is that the red beds are lateral equivalents of rock of Jurassic(?) age that subcrops beneath glacial drift in adjacent Manitoba (Bannatyne, 1959) and northeastern North Dakota (Blueme, 1973). This interpretation is supported by the composition of the clay minerals in the red beds, which are mostly illite with negligible (less than 10 percent) kaolinite. Authenticated sub-Cretaceous regoliths in Minnesota are characterized by a clay-mineral assemblage composed mainly of kaolinite (Parham, 1970). In addition, the dolomite in the Hallock red bed occurs as silt-sized euhedral crystals, whereas relict dolomite crystals from a weathered carbonate would be corroded and anhedral. The deposit is possibly a continuation of an outlier of Jurassic(?) in Manitoba, east of the Red River, that lies in a depression formed in front of an erosional escarpment composed of Ordovician and Silurian carbonates (Lambo, 1964; Bannatyne, 1959).

Cretaceous

Cretaceous shale and sandstone occur as a widespread, but thin and discontinuous unit over western Minnesota. Precise areal distribution is uncertain because of poor subsurface control.

As mentioned previously, a shale unit of questionable Cretaceous age was encountered in Well A. This age assignment is considered provisional because the fossils that occur in the shale are long-ranging forms.

Another feature that renders a Cretaceous age assignment uncertain is the clay mineralogy of the questionably Cretaceous shale and the underlying Hallock red bed. Elsewhere in the state, the basal Cretaceous overlies a regolith composed of kaolinite and the basal Cretaceous is itself highly kaolinitic (Parham, 1970). In Well A, however, the clay mineralogy of the shale sequence is mostly illite and little or no kaolinite is present. It is therefore possible, on the basis of the clay mineralogy, that the unit may predate the Cretaceous.

Pleistocene

Two glacial tills occur in Well A. The upper one, at the interval from 62 to 75 feet (19 to 23 m), is characterized by abundance of carbonate grains in 1- to 2-mm fraction (fig. 5), a large clay-size fraction (fig. 6), and absence of shale fragments. The lower till, at the interval from 75 to 215 feet (22 to 66 m), is characterized by abundant igneous and metamorphic grains in the 1- to 2-mm fraction (fig. 5), a smaller clay-size fraction than the upper till, and absence of shale fragments. The lithology of the till in Well B is similar to that of the upper till in Well A (C. L. Matsch, oral commun.).

Correlation of tills can be made by comparing petrologic and textural analyses with similar analyses from the area. C. L. Matsch correlates the lower till with the Marcoux till of the Red River Valley (Harris and others, 1974). He correlates the upper till with the lower Red Lake Falls till of the Red River Valley (Harris and others, 1974).

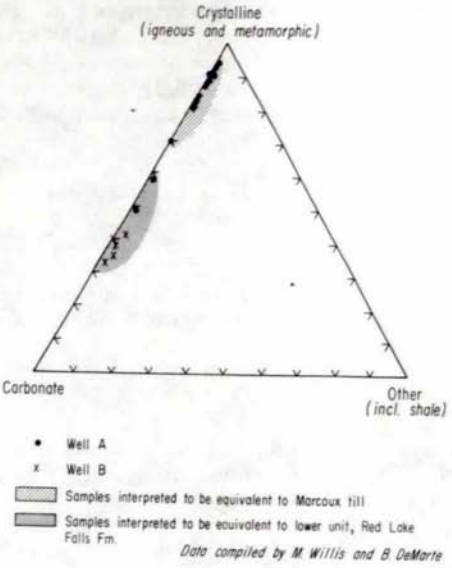

Figure 5 — Lithology of sand-size (1 - 2 mm) fraction of tills from northwestern Minnesota test wells.

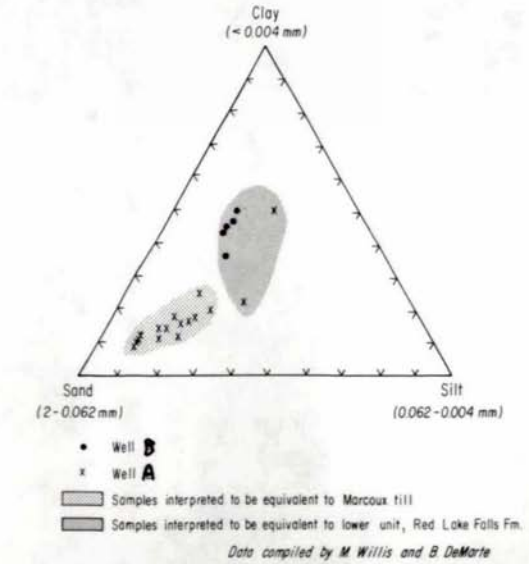

Figure 6 — Grain-size distribution in tills from northwestern Minnesota test wells.

The glacier that deposited the Marcoux till advanced from the northeast toward the southwest across Precambrian terrane and hence this till has a high content of igneous and metamorphic rock fragments. This glacier may have been pre-Wisconsin or Early Wisconsin. The glacier that deposited the lower Red Lake Falls till advanced southward from a more northerly direction than the earlier glacier during Wisconsin time (Harris and others, 1974). Because this glacier crossed the Paleozoic carbonate rocks that underlie much of the area in Manitoba directly north of the test drilling sites, its till contains a higher proportion of carbonate rock fragments.

The last Pleistocene event recorded in the wells is the deposition of a thick sequence of clay in Glacial Lake Agassiz during Late Wisconsin time.

ACKNOWLEDGMENTS

Brian DeMarte and Michael Willis, students at the University of Minnesota, Duluth, analyzed the glacial tills under the supervision of C. L. Matsch. F. M. Swain, University of Minnesota, and H. R. Bergquist, U. S. Geological Survey, examined foraminiferids and ostracodes from the Cretaceous in Well A. R.W. Ojakangas examined the Precambrian from Well A.

Funds for drilling the wells came chiefly from the Upper Great Lakes Regional Commission (Technical Assistance Project 10220071), with some supporting funds from the U. S. Geological Survey, the Minnesota Geological Survey, and private sources. Robert Graham, Warren, Minnesota, assisted in arranging for funds and drilling sites.

REFERENCES CITED

Allison, I. S., 1932, The geology and water resources of northwestern Minnesota: Minn. Geol. Survey Bull. 22, 245 p.

Anderson, S. B., and Haraldson, H. C., 1968, Cement rock possibilities in Paleozoic rocks of eastern North Dakota: N. Dak. Geol. Survey Rept. Inv. 48, 62 p.

Andrichuk, J. M., 1959, Ordovician and Silurian stratigraphy and sedimentation in southern Manitoba, Canada: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 2333-2398.

Arndt, B. M., 1975, Geology of Cavalier and Pembina Counties: N. Dak. Geol. Survey Bull. 62, part I, 68 p.

Baillie, A. W., 1952, Ordovician geology of Lake Winnipeg and adjacent areas, Manitoba: Manitoba Dept. of Mines and Natural Resources Pub. 51-6, 64 p.

Bannatyne, B. B., 1959, Gypsum-anhydrite deposits of Manitoba: Manitoba Dept. of Mines and Natural Resources Pub. 58-2, 46 p.

Bayer, T. N., 1959, The subsurface bedrock stratigraphy of northwestern Minnesota: Unpub. M.S. thesis, Univ. Minn.

Blueme, J. P., 1973, Geology of Nelson and Walsh Counties, North Dakota: N. Dak. Geol. Survey Bull. 57, part I, 70 p.

Carlson, C. G., and Anderson, S. B., 1965, Sedimentary and tectonic history of North Dakota part of Williston basin: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1833-1846.

Downey, J. S., 1971, Groundwater basic data, Nelson and Walsh Counties, North Dakota: N. Dak. Geol. Survey Bull. 57, part II, 459 p.

Ethington, R. L., and Furnish, W. M., 1960, Upper Ordovician conodonts from southern Manitoba: Jour. Paleontology, v. 34, p. 265-274.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's Book Store, 159 p.

Harris, K. L., Moran, S. R., and Clayton, Lee, 1974, Late Quaternary nomenclature, Red River Valley, North Dakota and Minnesota: N. Dak. Geol. Survey, Misc. Series 52, 47 p.

Lambo, W. A., 1964, Geology of the Silver Plains gypsum deposit: Unpub. M.S. thesis, Univ. Manitoba.

Minnesota Geological Survey, 1972, Report on Northwest Minnesota drilling program, Upper Great Lakes Regional Commission Technical Assistance Project No. 10220071: Minn. Geol. Survey file report, 11 p.

North Dakota Geological Survey, 1968, Results of gypsum-dolomite exploratory drilling project, Pembina County, North Dakota: N. Dak. Geol. Survey, Open-file report, 14 p.

Parham, W. E., 1970, Clay mineralogy and geology of Minnesota's kaolin clays: Minn. Geol. Survey Spec. Pub. 10, 142 p.

Royce, C. F., Wadell, J. S., and Petersen, L. E., 1971, X-ray determination of calcite-dolomite: an evaluation: Jour. Sed. Petrology, v. 41, p. 483-488.

Sims, P. K., 1970, Geologic map of Minnesota: Minn. Geol. Survey Misc. Map M-14.