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KAOLIN CLAY RESOURCES OF THE MINNESOTA RIVER VALLEY BROWN, REDWOOD & RENVILLE COUNTIES, A PRELIMINARY REPORT

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ABSTRACT

Kaolin clays of potential economic significance occur in the upper part of the thick regolith developed on Precambrian crystalline rocks and in overlying shales of late Cretaceous age in the Minnesota River valley, in Redwood, Brown, and Renville counties.

Preliminary tests indicate that the clays in the regolith warrant further testing for use as filler and coating clays in the paper industry and for the manufacture of refractories. Ball clays, previously unknown in Minnesota, and a few thin bentonite beds in Cretaceous strata appear to be of limited tonnage but should be investigated further.

INTRODUCTION

The kaolin clays of the Minnesota River valley in Brown, Redwood, and Renville counties are among the most promising clay deposits in the State for future commercial utilization. They are potential sources of filler and coating clays in the paper industry, raw materials for refractories and, to a lesser extent, ball clays. The clays occur in a regolith formed by deep weathering of Precambrian gneisses and in overlying Cretaceous shales, and are exposed sporadically in the valley walls and along tributary streams.

The clays in the Minnesota River valley were selected for study as the first phase of a detailed investigation and evaluation of clay and shale resources in Minnesota. Aside from a study of the State's bloating clays, shales, and slates (Prokopovich and Schwartz, 1957), little work has been performed on clay raw materials of the State since the early pioneering work by Grout and Soper (1914).

Kaolin clays of the type found in the Minnesota River valley are processed for use in a wide variety of industries, such as paper, refractories, ceramic, rubber, plastic, paint, cement, adhesive, cosmetic, printing ink, and medicine (Grim, 1962). Successful utilization of such clay deposits by industry, however, depends not only on the geology and mineralogy of the deposits but also on geographic, economic, and market conditions.

The purpose of this report is to present preliminary data on the geologic occurrence, mineralogy, and laboratory tests of clays of the Minnesota River valley and to point out possible uses for the kaolin clays. Field and laboratory studies of the materials are continuing.

FIELD AND LABORATORY WORK

The field work upon which this report is based was done by both writers during the fall of 1963. The area extending from Fort Ridgely on the southeast to Redwood Falls on the northwest (pl. 1) was examined systematically to determine the areal extent and locations of exposed clay-bearing rocks. Several sections were measured in outcrops and in pits and those containing favorable clay materials were sampled. Ten- to 15-pound channel samples were obtained for testing. The measured sections from which samples were taken are listed in appendix A; the sections that were described but not sampled are listed in appendix B.

The mineralogy and physical and chemical properties of the samples were determined in the laboratory by Parham, to provide preliminary data on potential industrial utilization of the clays. Mineralogy was determined by x-ray diffraction techniques and by the binocular microscope. Particle size analyses using the hydrometer method were made on selected samples. Kaolinite crystallinity determinations were made by x-ray. Test bars of eleven samples were fired at 2012°C and at 2200°C to determine fired color and firing behavior. Three samples were chemically bleached to determine whether their natural colors could be lightened.

Facilities of the Mines Experiment Station, University of Minnesota, were used for laboratory firing tests. R. E. Sloan of the Department of Geology and Geophysics contributed unpublished data on the geology of the region, and J. E. Stone of the Minnesota Geological Survey assisted in describing the glacial deposits.

GENERAL GEOLOGY

The kaolin clays described in this report occur in a regolith formed by deep weathering of the underlying Precambrian rocks and in overlying sedimentary strata of late Cretaceous age. They are exposed in the Minnesota River valley as a result of erosion that removed the overlying glacial drift and cut downward into the Precambrian basement rocks.

The kaolinitic regolith is inferred to extend over wide areas in western Minnesota. Exposures in the Minnesota River valley and in the Mississippi River valley near Bolus in Morrison County and near Richmond in Stearns County together with scattered water well data (Allison, 1932; Thiel, 1944, 1947) indicate that the kaolinitic regolith probably lies above Precambrian basement rocks in almost all western counties of the State. The inferred distribution is indicated on figure 1. Thicknesses of the weathered zone exceed 100 feet at many localities northward from Brown County. Except for scattered exposures in the Minnesota and Mississippi river valleys, the regolith is covered by glacial drift; the drift possibly exceeds 500 feet in eastern Mahnomen County (Allison, 1932).

In exposures in the Minnesota River and Mississippi River valleys as well as in drill cores from Otter Tail County the regolith is dominantly kaolinitic; presumably it is similar in composition throughout its areal extent. A classic study on the weathering near Redwood Falls in the Minnesota River valley was made earlier by Goldich (1938).

In the Minnesota River valley the regolith grades downward into the Morton Gneiss and associated crystalline rocks of Precambrian age (Goldich and others, 1961, p. 123-149). Presumably elsewhere in the area of its extent the regolith overlies various types of metamorphic and intrusive rocks, but details are lacking.

The regolith is overlain in the Minnesota River valley and presumably in adjacent areas by shales, sands, clays, and lignites of late Cretaceous age, which were deposited in an epicontinental sea that transgressed the area from the west. During transgression of the sea, the upper part of the regolith was eroded, reworked, and incorporated into the late Cretaceous sediments.

The weathering that produced the regolith has been interpreted from regional studies by R. E. Sloan (written communication, 1964) to have taken place in the interval between deposition of the youngest Devonian rocks and deposition of strata of late Cretaceous age. Sloan believes that the regolith formed mainly in early Cretaceous time; accordingly the regolith is indicated in this report as Cretaceous (?) in age.

The Pleistocene glacial drift that overlies the regolith on the uplands adjacent to the Minnesota River valley is as much as 130 feet

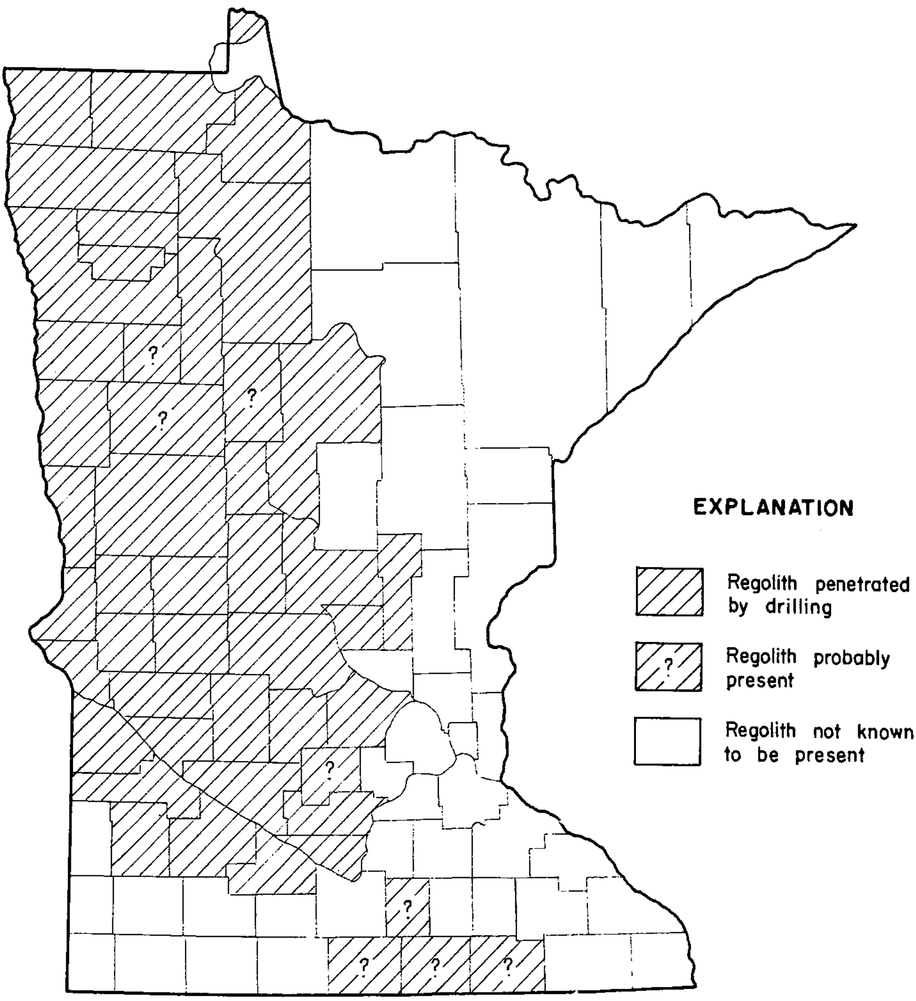

Figure 1. --Inferred distribution of kaolinitic clays developed on Precambrian crystalline rocks.

thick. It is primarily a gray, calcareous, clayey and silty till that contains substantial montmorillonite. Interspersed in the till are moderate amounts of sand and gravel as well as abundant fragments of Cretaceous shale. A succession of sand and gravel paved terraces, at altitudes of 845, 860, 890, and 990 feet, are exposed along the Minnesota River. The glacial drift forms unstable banks, and small-scale slumping and earth flowage occur during spring thaws and heavy rains.

CLAY DEPOSITS

Distribution and Lithology

The clay-bearing regolith and overlying Upper Cretaceous strata are exposed sporadically along the valley walls of the Minnesota River.

The principal exposures of the regolith are in canyons along the Redwood River between Redwood Falls and North Redwood Falls, in a few other tributaries of the Minnesota River, and in artificial cuts along benches of the Minnesota River valley (pl. 1). Elsewhere along the valley, the weathered zone is covered by slump material and other debris. The maximum thickness of the regolith is about 100 feet.

In general, the lithology of the regolith varies systematically but irregularly from its uppermost part downward into the underlying Precambrian bedrock. The upper part contains clay layers, mixed sand and clay, and cross-bedded sand lenses; these pass downward into partly decomposed gneiss that has a relict gneissic structure and contains angular quartz grains and altered feldspar. Some clays in the upper part of the regolith contain little or no quartz; they occur in beds composed dominantly of kaolinite, in somewhat pisolitic kaolinitic beds, and in an iron-stained pisolitic bed (fig. 2). The uppermost pisolitic bed, which tends to form benches in weathered exposures, appears to constitute the top of the regolith and formed the surface upon which the late Cretaceous sediments were deposited. It strikes N. 45° W., dips northeastward at 6 to 7 feet per mile, and generally is 3 to 5 feet thick but at locality 6 (pl. 1) is 15 feet thick. The other clay-rich beds appear to be discontinuous, variable in thickness, and irregularly distributed. Much additional data are needed, especially drilling, before the thickness, shape, extent, and purity of the clay bodies can be confidently predicted.

The Upper Cretaceous sedimentary rocks that overlie the regolith contain bentonite and ball clay beds. The bentonite beds are a few inches to 1 1/2 feet thick, occur at several stratigraphic positions within

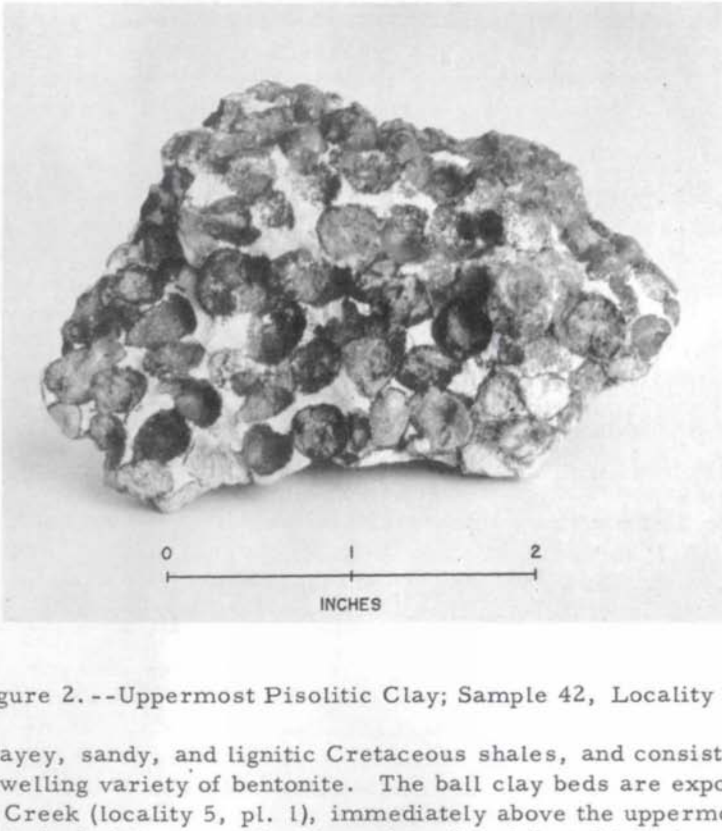

Figure 2.--Uppermost Pisolitic Clay; Sample 42, Locality 6.

the clayey, sandy, and lignitic Cretaceous shales, and consist of the non-swelling variety of bentonite. The ball clay beds are exposed in Crow Creek (locality 5, pl. 1), immediately above the uppermost pisolitic bed of the regolith. A section, 6 to 9 feet thick, is composed of one-half to 2-inch lignitic or lignitic-clay layers that alternate with 2-inch to 2-foot very fine-grained gray clay layers composed essentially of kaolinite and quartz.

Mineralogy

The clay-size fraction of the majority of samples other than bentonite is composed primarily of kaolinite, with lesser amounts of gibbsite, illite, and quartz; the fraction that is greater than 325 mesh is composed predominantly of quartz with lesser amounts of kaolinite, siderite, and limonite. The fine fraction of the bentonites is composed dominantly of calcium montmorillonite, and the coarser fraction is composed of calcium montmorillonite, biotite, and quartz.

Mineral analyses of many samples of dominant kaolinite composition and rich in the clay-size fraction suggests melting temperatures of approximately 1700°C. Precise determinations of fusion temperatures of these materials will be considered in future studies.

The mineralogy of 32 clay samples was determined by x-ray diffraction (table 1). The less than 2-micron fraction was prepared as oriented aggregates for x-ray analysis, whereas the greater than 325 mesh screen fraction was examined by binocular microscope and then ground for powder x-ray analysis. All oriented aggregates were placed overnight in an ethylene glycol atmosphere to facilitate identification of any expansible clay mineral component. Three samples containing montmorillonite were x-rayed under controlled humidity, a technique described by Milne and Warshaw (1956).

Table 1.--Mineralogy of clay samples

(Location of samples given on plate 1; T=trace; nd.=not determined; minerals listed in order of decreasing abundance)

Map location	Sample no.	Mineralogy	
		< 2 micron fraction	> 325 mesh fraction
1------	53	kaolinite	quartz, kaolinite, siderite
1------	54	kaolinite, illite (T)	quartz, kaolinite, limonite
2------	34	kaolinite	quartz, kaolinite
3------	33	calcium montmorillonite, kaolinite (T)	calcium montmorillonite, biotite
3------	55	kaolinite, illite (T)	nd.
3------	56	calcium montmorillonite, kaolinite (T)	calcium montmorillonite, quartz, biotite
3------	57	kaolinite, calcium montmorillonite, illite, quartz	nd.

Table 1 (continued)

Map location	Sample no.	Mineralogy	
		< 2 micron fraction	> 325 mesh fraction
4------	10	kaolinite	nd.
4------	11	kaolinite, gibbsite (T)	quartz, kaolinite, siderite, coal
4------	12	kaolinite, illite, montmorillonite	nd.
4------	13	kaolinite	nd.
4------	14	kaolinite, gibbsite	nd.
4------	15	calcium montmor-illonite, chlorite(?)	calcium montmor-illonite, biotite
5------	38	kaolinite	quartz, kaolinite (T), limonite
5------	39	kaolinite	kaolinite, quartz (T)
5------	40	kaolinite	kaolinite, quartz (T)
5------	41	kaolinite, gibbsite	nd.
5------	58	kaolinite, gibbsite (T)	coal, quartz, kaolin-ite, calcite (T), gibbsite (T)
5------	59	kaolinite, gibbsite (T), calcium mont-morillonite (T)	kaolinite, coal, quartz (T), calcite (T), potassium feldspar (T), gibbsite (T)
5------	60	kaolinite, gibbsite (T), mixed-layer clay (T)	quartz, kaolinite, coal, calcite (T)
6------	43	kaolinite	kaolinite, quartz, calcite (T)
7------	35	kaolinite	quartz, kaolinite, calcite (T)
8------	42	kaolinite	quartz, kaolinite
8------	52	kaolinite	quartz, siderite, limonite, kaolinite
9------	50	kaolinite	quartz, limonite, kaolinite

Table 1 (continued)

Map location	Sample no.	Mineralogy	
		< 2 micron fraction	> 325 mesh fraction
10-----	51	kaolinite	quartz, kaolinite, limonite, weathered rock fragments
11-----	37	kaolinite	nd.
12-----	46	kaolinite, montmorillonite, illite	nd.
12-----	47	kaolinite, illite, mixed-layer clays	nd.
12-----	48	illite, chlorite, mixed-layer clays, quartz (T), kaolinite (T?)	nd.
13-----	49	kaolinite, illite (T)	quartz, limonite, kaolinite
14-----	44	kaolinite	quartz, siderite, kaolinite

Kaolinite Crystallinity

The "crystallinity index" of kaolin samples from the Minnesota River valley was determined to compare the suitability of these clays with those from Georgia and South Carolina for possible use as paper filler or paper coating clays. The plate-like shape of fine kaolinite assists in developing a smooth, white, ink-receptive surface on processed paper.

Using a technique developed by Hinckley (1963), kaolinites from the Minnesota River valley have "crystallinity indices" ranging from 0.89 to 1.34 (table 2). Most samples fall in the well crystallized range. By comparison, Hinckley (1963) has shown that a wide variety of kaolinites from Georgia and South Carolina have "crystallinity indices" ranging from 0.25 (poorly crystallized) to 1.45 (well crystallized).

Kaolinite crystallinity is important in determining general uses and properties of untested kaolin clays for the paper industry. As shown in table 3, the degree of crystallinity is related directly to many physical and chemical properties that are important in the paper industry.

Table 2.--Kaolinite crystallinity indices of clays from the Minnesota River valley

(Larger numbers indicate better crystal perfection)

Sample No.	Crystallinity Index	Sample No.	Crystallinity Index
10--------	1.18	41--------	1.12
11--------	0.97	43--------	1.23
12--------	0.97	44--------	1.34
13--------	1.27	49--------	1.17
14--------	1.26	50--------	1.17
34--------	1.29	51--------	0.89
35--------	1.27	52--------	1.28
36--------	1.05	53--------	1.27
37--------	1.00	54--------	1.00
38--------	0.97	55--------	1.02
39--------	0.92	58--------	1.10
40--------	1.28	59--------	1.15
		60--------	1.16

Particle Size Analyses

Particle size analyses of 14 samples determined by the hydrometer method (ASTM, 1955) are tabulated in table 4. Samples 58, 59, and 60, classified as ball clay, have the greatest amount of fine clay-size material. They are stratigraphically above samples 38, 39, and 40,

Table 3.--Kaolinite crystallinity as related to its chemical and physical properties

(Source: Murray and Lyons, 1956; 1960)

Good crystallinity	Poor crystallinity
Forms suspensions of low viscosity	Forms suspensions of high viscosity
Small amount of dispersing agent needed for suspension of lowest viscosity	Larger amount of dispersing agent needed for suspension of lowest viscosity
High brightness on paper	Low brightness on paper
Low gloss on paper	High gloss on paper
Coarser particle size	Finer particle size
Smaller surface area/gm.	Larger surface area/gm.
Low cation exchange capacity	Higher cation exchange capacity
Low Fe_2O_3 and TiO_2 content	Higher Fe_2O_3 and TiO_2 content

which are considerably coarser in grain size. Samples 39 and 40 are difficult to crush and do not break down in water. Therefore, their particle size distribution is anomalous, reflecting only the amount of disaggregation. As the greater than 325 screen fraction also is composed chiefly of kaolinite, search should be made for a suitable wet grinding process to produce the required particle size fractions.

Firing Tests

Many samples from the Minnesota River valley appear to be suitable for use in ceramics. The firing colors of those samples tested are white or very light colored, as would be expected from their mineralogy. Except for sample 47 and ball clay sample 58, drying and firing shrinkage values are generally low. Plasticity on the other hand was poor for all samples except 47 and 58. Generally, drying and firing shrinkage values are low and plasticity is poor for kaolinite-rich clays other than ball clays. Most of the kaolinitic clays would

Table 4.--Particle size

Sample no.	1.5μ	2μ	4μ (in percent)	10μ	20μ	30μ
11	39	45	52	68	74	80
35	40	47	61	74	79	80
38	38	46	65	76	79	79
39	26	28	34	40	43	45
40	21	22	25	29	31	34
49	8	13	24	35	44	52
50	37	41	49	58	62	66
51	41	47	59	69	73	75
52	22	24	30	37	40	43
53	23	28	35	44	47	48
54	12	15	23	37	50	56
58	72	77	86	97	99	99+
59	72	77	87	99	100	--
60	61	67	77	91	94	96

have to be blended with more plastic clays if they were to be used in the manufacture of structural clay products.

Hand molded bars, 1 in. x 1 in. x 5 in. in size, were test fired in an electric furnace at 2012°F. and 2200°F. The amount of water required to develop sufficient plasticity in hand molding is greater and more variable than that needed in machine extrusion. Therefore, the firing and drying shrinkage values listed in table 5 are presented only to show general behavior of the clays.

Table 5.--Ceramic test data

Sample 35; map locality 7

Plasticity----------Poor

Linear drying shrinkage, in percent----------4.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	2.0	3.0
Total linear shrinkage, in percent	6.0	7.0
Fired color	White	White

Comments: Test bars developed numerous cracks on firing.

Sample 38; map locality 5

Plasticity----------Fair

Linear drying shrinkage, in percent----------4.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	0.0	2.0
Total linear shrinkage, in percent	4.0	6.0
Fired color	White	Pink

Sample 39 and 40; map locality 5

Samples 39 and 40 lacked sufficient plasticity to hand mold for firing tests; raw pieces of both were fired at 2012°F and 2200°F. The two samples fired to a white color and developed numerous small cracks at both firing temperatures.

Sample 47; map locality 12

Plasticity----------Good

Linear drying shrinkage, in percent----------7.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	4.0	Bloated
Total linear shrinkage, in percent	11.0	---
Fired color	Salmon	Brown

Sample 49; map locality 13

Plasticity----------Poor

Linear drying shrinkage, in percent----------2.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	0.0	1.0
Total linear shrinkage, in percent	2.0	3.0
Fired color	Pink	White

Sample 50; map locality 9

Plasticity----------Poor

Linear drying shrinkage, in percent----------3.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	1.0	3.0
Total linear shrinkage, in percent	4.0	6.0
Fired color	Pink	Tan

Sample 51; map locality 10		
Plasticity----------Very poor		
Linear drying shrinkage, in percent----------3.0		
Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	3.0	3.0
Total linear shrinkage, in percent	6.0	6.0
Fired color	Pink	Pink

Sample 52; map locality 8		
Plasticity----------Poor		
Linear drying shrinkage, in percent----------4.0		
Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	1.0	1.0
Total linear shrinkage, in percent	5.0	5.0
Fired color	Pink	Pink

Sample 53; map locality 1		
Plasticity----------Poor		
Linear drying shrinkage, in percent----------6.0		
Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	2.0	+2.0
Total linear shrinkage, in percent	8.0	4.0
Fired color	White	Pink

Sample 54; map locality 1

Plasticity----------Poor

Linear drying shrinkage, in percent----------4.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	1.0	1.0
Total linear shrinkage, in percent	5.0	5.0
Fired color	Buff	Buff

Sample 58; map locality 5

Plasticity----------Good

Linear drying shrinkage, in percent----------6.0

Firing temperature	2012°F	2200°F
Linear firing shrinkage, in percent	5.0	10.0
Total linear shrinkage, in percent	11.0	16.0
Fired color	White	White

Bleaching

Much of the kaolin clay used in the paper industry is bleached by industrial processes to increase its whiteness. Four samples--38, 39, 50 and 58--were subjected to chemical bleaching to determine if their color could be improved. Sample 38 has a natural color of light tan, 39 is cream, 50 is salmon, and 58 is gray. The first three samples responded to treatment with sulphuric acid and sodium hyposulfite and attained a white bleached color; sample 58 remained gray. Bleaching of gray kaolins has been generally unsatisfactory because of the presence of organic pigments (Grim, 1962). Standardized brightness and bleaching tests would be needed to properly assess the potential use of these clays in the paper industry. Nevertheless, the improvement in color of the three bleached samples is encouraging.

Ball Clays

Ball clays are fine-grained, sedimentary, white-burning, kaolinitic clays used primarily to add plasticity to china and stoneware clays and to increase green and dry strength in ware. Tennessee, Kentucky, Mississippi, and more recently Texas have been the only sources of ball clay in the United States.

Sample 58 from locality 5 along Crow Creek (pl. 1), which comprises approximately 6 feet of Cretaceous strata, can be classified as ball clay. The sample is very plastic, burns to a white color, has high firing and drying shrinkage, has very fine particle size (77 percent <2 microns), and is composed mainly of kaolinite and quartz. Bergquist[1/] reported that 9 feet of this material--in a Cretaceous section exposed along Crow Creek--is overlain by a 2-foot 3-inch bentonite bed, 1-foot of lignitic gray clay, and a maximum of 38 feet of glacial drift. To judge from his described section, the ball clay interval probably is more completely preserved locally than at the locality of sample 58. Clays above the hard, uppermost pisolitic layer should be examined carefully in the Crow Creek area as a potential source of ball clay.

Uppermost Pisolitic Clay as a Possible Source of Aluminum

The most aluminum-rich clay encountered in the Minnesota River valley is the uppermost pisolitic unit. It has been recognized at map localities 1, 5, 8, 9, 10, G, H, N, W, and Y, and can be traced throughout most of the region (pl. 1). Chemical analyses of five samples of this unit are listed in table 6.

Concentration of Al_2O_3 can be accomplished by either the Bayer process or an acid process. Raw materials used in the Bayer process must be low in SiO_2 for satisfactory results, whereas in the acid process they should be low in iron. It is evident from the chemical analyses that this clay in the Minnesota River valley is not wholly satisfactory as a source for aluminum in either process.

1/ Bergquist, H. R., 1943, Minnesota high alumina clays: unpublished manuscript in files of Minnesota Geological Survey.

Table 6.--Chemical analyses of uppermost pisolitic clay (in percent)
(Source: Bergquist, op. cit.)

Sample no.	SiO_2	Al_2O_3	Available*/ Al_2O_3	Fe_2O_3	TiO_2	Ignition loss	Total
I------	31.94	30.16	3.00	21.76	0.90	13.60	98.36
II -----	36.04	32.90	3.25	13.38	1.40	14.30	98.02
III-----	31.68	42.19	13.95	6.03	1.40	17.90	99.20
IV-----	34.52	40.26	10.45	6.62	1.40	16.80	99.60
V------	31.28	39.71	11.30	10.29	1.32	16.20	98.80

I. NW 1/4 SE 1/4 sec. 3, T. 112 N., R. 34 W. (Sample 42 shown in fig. 2)
II. NW 1/4 sec. 11, T. 112 N., R. 34 W.
III. SE 1/4 NW 1/4 NW 1/4 sec. 2, T. 112 N., R. 35 W.; along Crow Creek.
IV. SW 1/4 sec. 2, T. 112 N., R. 35 W.; along Crow Creek.
V. E 1/2 SW 1/4 sec. 2, T. 112 N., R. 35 W.; along Crow Creek.

*/ Available Al_2O_3 is that amount of Al_2O_3 that can be recovered by the Bayer process for use as a source of metallic aluminum.

Bentonite

Thin Cretaceous bentonites were recognized by Bergquist[2/] in exposures southwest of Morton along the south bluff of the Minnesota River. They range from a few inches to 1 1/2 feet in thickness and occur as distinct beds within the Cretaceous strata above the uppermost pisolitic clay. Samples 15, 33, and 56, taken from this area, are composed primarily of calcium montmorillonite and are the non-swelling variety of bentonites. Their colors range from a waxy dark-green and yellowish-green to dark gray.

2/ Bergquist, op. cit.

Samples 15 and 33 have a thin white zone at their base and have 96 percent material finer than two microns; sample 56 has 93 percent finer than two microns. The bentonites probably could be used effectively in correlating rock units in a core drilling program. The economic significance of the bentonites appear to be limited because of their thinness.

CONCLUSIONS AND RECOMMENDATIONS

Preliminary field and laboratory data indicate that the kaolin deposits in the area between Redwood Falls and Fort Ridgely are potential sources of clay for use in the paper industry and as refractories. Potentially valuable ball clays occur in and adjacent to Crow Creek. Additional geologic mapping and comprehensive laboratory study are needed, however, to fully evaluate tonnages and possible uses of the clays.

Selected samples worthy of further testing as potential industrial clays are listed in table 7. The results of more complete tests on some of these samples will be considered in future reports.

Table 7.--SUGGESTIONS FOR FURTHER TESTING OF SELECTED SAMPLES

	Sample numbers																			
	10	11	12	14	34	35	38	39-40	41	42	43	44	47	49	50	51	52	53	54	58
Refractories	X	X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
Paper coating	X			X	X	X	X				X	X			X	X				
Filler, paper	X	X		X	X	X	X				X	X		X	X	X	X	X	X	
Filler, rubber	X	X		X	X	X	X				X	X		X	X	X	X	X		
Filler, general		X		X	X	X	X				X			X		X	X	X	X	
White-ware	X	X		X	X	X	X	X			X	X			X	X	X	X		X
Paint	X			X	X	X	X	X			X	X			X	X	X	X		
Pottery	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X
Structural clay products			X										X							
Pozzolana	X	X		X	X	X	X	X			X	X			X	X	X	X		X

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APPENDIX A

Measured sections at localities sampled
Sample localities 1 through 14
(Locations shown on plate 1)

Locality 1

Redwood Co., SE 1/4 NW 1/4 NE 1/4 sec. 32, T. 113 N., R. 35 W., outcrop in northeast-southwest trending valley in south bluff of Minnesota River Valley

	ft	in
Pleistocene:		
Glacial drift	60	0
Cretaceous:		
Lignite streak		1-2
Cretaceous (?):		
Clay, iron-stained, hard, pisolitic (Sample 53)	5	0
Clay, sandy, tannish-yellow (Sample 53)	3	3
Clay, less sandy than above, cream colored (Sample 53)	2	6
Clay, sandy, tan (Sample 53)	1	6
Clay, very sandy, white (Sample 53)	2	0
Covered interval	7	6
Precambrian:		
Metamorphic rock, highly weathered, clayey, yellowish-brown (Sample 54)	6	0

Altitude of base of exposure is 915 ft. at creek level

Locality 2

Redwood Co., SW 1/4 SW 1/4 NW 1/4 sec. 33, T. 113 N., R. 35 W., old clay pit 450 feet south of farm house; 4 or 5 feet of clay poorly exposed west of road along creek (Sample 34). Section covered to top of hill; total cover 70 feet

Locality 3

Redwood Co., SE 1/4 SE 1/4 SE 1/4 sec. 34, T. 113 N., R. 35 W., section exposed on south side of U. S. Highway 19

	ft	in
Pleistocene:		
Glacial drift	60	0
Cretaceous:		
Shale, light-gray	1	0
Lignite	0	2
Clay, gray (Sample 57)	1	0
Covered interval	1	6
Clay, black, organic-rich	0	3
Clay, gray	1	0
Lignite	0	2
Clay, gray, shaly toward base	1	6
Clay, black, organic-rich	0	2
Clay, gray	1	4
Lignite	0	4
Clay, shaly, dark gray, grades downward to medium-gray clay with numerous lignite fragments. (Sample 56 from top 1'6")	3	0
Bentonite, yellowish-green, white streak at base; altitude 904' (Sample 33)	0	8
Shale, tannish-gray	1	3
Shale, dark gray to black	1	0
Lignite	0	8
Clay, light-gray, root traces present (Sample 55)	0	6
Clay, gray, lignite streaks throughout	1	6
Clay, grayish-green, lignite fragments at base	1	0
Cretaceous (?):		
Clay, sandy, iron-stained, hard, somewhat pisolitic toward top	1	4
Clay, light-gray to tan, poorly exposed	5	6

Locality 4

Redwood Co., SE 1/4 SW 1/4 sec. 35, T. 113 N., R. 35 W., "Morton" clay pit of Ochs Brick and Tile Company

	ft	in
Pleistocene:		
Glacial drift	45-50	
Cretaceous:		
Clay, black and gray, highly contorted from glacial overriding (Sample 12)	4-5	0
Bentonite, dark-green clay, altitude 941 feet (Sample 15)	0	8
Alternating layers of sand, lignite, lignitic-clay and light-gray clay (Sample 11)	8-10	0
Clay, white to buff, sandy, base at pit floor (Sample 10)	6	0
Cretaceous (?):		
Clay, light-buff, some quartz present, scattered pisolites; exposed in northeast corner of pit along small drainage (Sample 14)	5	6
Alternating layers of sand, sandy clay, and pisolitic clay; base is rust colored zone and very pisolitic (Sample 13); contains 2-3" angular quartz pebbles; base cuts into sediments below	5	6
Sandstone, white, cross-bedding, strike N 70° W, dip 10° NE. Sandstone rests on thin pisolitic, light colored clay zone that grades downward into iron-stained sandstone and white siltstone	5	0

Locality 5

Redwood Co., SW 1/4 NW 1/4 NW 1/4 sec. 2, T. 112 N., R. 35 W., outcrop high along west bank of Crow Creek

	ft	in
Pleistocene:		
Glacial drift	60	0

Locality 5 (continued)

	ft	in
Cretaceous:		
Clay, purplish-gray (Sample 60)	1	4
Lignite or lignitic clay	0	1
Clay, gray (Sample 59)	1	0
Lignite	0	2
Clay, gray, light-gray at top	1	0
Lignite streak	0	1/2
Clay, gray	2	0
Lignite or lignitic clay	0	1
Clay, gray	0	2
Lignite (Sample 58 includes section up to glacial drift)	0	1
Cretaceous (?):		
Clay, top iron-stained, hard, pisolitic (Sample 41)	3	0
Clay, hard, white, brecciated (Sample 40) grades downward to softer clay	2	0
Clay, softer than Sample 40, white, some limonite staining on joint surfaces (Sample 39)	4	6
Clay, tan, contains some sand (Sample 38)	3	0
(This part of section taken from Bergquist[3/] - now covered)		
Clay, tan to white, jointed and blocky throughout with iron stains along joints, very sandy in lower 5 feet	12	6
Clay, sandy to silty, white and buff; irregularly bedded with smooth clay lenses, latter somewhat pisolitic; large quartz fragments scattered in sandy portions and in some of the smoother clay	14	6
Sandy, medium- to fine-grained white and ferruginous; all somewhat argillaceous; stringers of white to pink plastic clay	3	0
Sandy, coarse angular white quartz	1	0

3/ Bergquist, op. cit.

	ft	in
Precambrian:		
Gneiss, decomposed greenish-gray to brown; kaolinized feldspar, quartz and biotite preserve texture, contains coarse quartz fragments up to 6 inches in length	28	0
Covered to level of Crow Creek	2	0

Note: The hard, iron-stained, pisolitic clay (Sample 41) crops out at several places along both sides of Crow Creek upstream from this section for about 3/4 mile at approximately the same elevation. It resists weathering, and thus stands out as ledges high on both valley walls. The section below the ledge is not well exposed at most other locations, but at junction of northwest-flowing tributary in SW 1/4 of sec. 2 approximately 20 feet of light bluish-green, highly altered metamorphic rock is exposed in the east bank just above creek level.

Locality 6

Redwood Co., NE 1/4 NW 1/4 NE 1/4 sec. 8, T. 112 N., R. 34 W., outcrop in east wall of valley at intersection of two small streams

	ft	in
Pleistocene:		
Glacial drift	70	0
Cretaceous (?):		
Clay, light-gray, pisolitic (Sample 43)	3	6
Covered interval	15	0
Clay, sandy, buff	2-3	0
Clay, sandy, conglomeratic, 1/4 inch quartz grains	0	6
Clay, buff	0	6
Sandstone, grayish-tan	0	6
Clay, iron-stained, sandy	1	6
Clay, light-gray to rust color, high sand content; contains angular quartz fragments up to 2 inch diameter	3	6
Clay, brown-stained, pisolitic	0	6
Clay, gray, sandy	0	3
Clayey sand, iron-stained	0	6
Clay, light-gray, contains large 1 inch to 2 inch quartz pebbles	1	0
Covered interval to creek level	6	0

Locality 7

Renville Co., SE 1/4 SE 1/4 SW 1/4 sec. 3, T. 112 N., R. 34 W., outcrop along north side of gravel road and below bridge at stream

	ft	in
Pleistocene:		
Glacial drift to top of bluff	137	0
Cretaceous:		
Clayey sand, white	6	0
Clay, light-gray (Sample 35)	6	0
Clayey sand, white, lignite fragments near top; contains 1" quartz pebbles	6	0
Covered interval	3	0
Cretaceous (?):		
Sand, rust colored, slightly pisolitic at top	5	0
Precambrian:		
Highly weathered gneissic rock, whitish-blue	4	0
Covered interval to creek level; elevation 840 feet at base	3	0

Locality 8

Renville Co., SE 1/4 NW 1/4 SE 1/4 sec. 3, T. 112 N., R. 34 W., south bank of creek below railroad grade

	ft	in
Pleistocene:		
Glacial drift	120	0
Cretaceous (?):		
Clay, hard, pisolitic, iron-stained, forms cliff; pisolites iron-coated, buff cores, up to 1 inch diameter (Sample 42)	15	0

	ft	in
Covered interval	4	0
Clay, tannish-gray, some pisolites present (Sample 52)	2	6
Clay, light-tan to buff, iron-stained toward top, slightly sandy (Sample 52)	4	0
Clay, grayish-tan, some iron-staining, slightly sandy (Sample 52)	2	6
Clay, sandy, mottled light-green	0	3
Clay and sand, alternating layers, tan, sand composed of 2 mm. rounded quartz grains, cross-bedded sand at base with strike N.21° E. dip 21° SE	4	0
Precambrian:		
Clay, bluish-green, altered metamorphic rock, base covered at creek level	1	0

Locality 9

Renville Co., SW 1/4 SE 1/4 NW 1/4 sec. 11, T. 112 N., R. 34 W., outcrop along north side of gravel road

	ft	in
Pleistocene:		
Glacial drift	110	0
Cretaceous (?):		
Clay, hard, light-buff, some scattered pisolites toward top (Sample 50)	2	0
Clay, sandy, red and buff, very red toward base (Sample 50) Altitude of road at base is 865 feet (This same section is exposed along road about 300 feet to the east)	8	6

Locality 10

Renville Co., SW 1/4 SE 1/4 NW 1/4 sec. 11, T. 112 N., R. 34 W., outcrop along north side of gravel road

Locality 10 (continued)

	ft	in
Pleistocene:		
Glacial drift to uplands	115	0
Cretaceous (?):		
Clay, hard, red, pisolitic	1	0
Clay, hard, buff, less pisolitic than above, amount of pisolites diminishes downward in section (Sample 51)	5	6
Clay, buff, softer than above (Sample 51)	1	0
Clay, buff, sandy at base (road); altitude 870 feet (Sample 51)	9	0

Locality 11

Renville Co., W 1/2 SW 1/4 NW 1/4 sec. 27, T. 112 N., R. 33 W.; outcrop along north side of gravel road. Same section is repeated east along road at SE 1/4 SW 1/4 NW 1/4 sec. 27, T. 112 N., R. 33 W.

	ft	in
Pleistocene:		
Glacial drift	150	0
Cretaceous:		
Clay or shale (?), dark-gray, weathered	1	3
Lignite, elevation 840 feet	0	2
Clay, very light-gray, contains root traces (Sample 37)	1	6
Clay, sandy, gray, some limonite staining, contains scattered lignite fragments, base at road level	1	6

Locality 12

Brown Co., NW 1/4 SE 1/4 SE 1/4 sec. 33, T. 112 N., R. 33 W.; outcrop in creek through farmyard south of gravel road

	ft	in
Pleistocene:		
Glacial drift	15	0
Cretaceous:		
Shale, buff to gray	2	0
Lignite	0	2
Clay, light-gray (Sample 48)	1	0
Laminated sand and clay; light colored laminae composed of quartz sand, dark colored laminae composed of clay; quantity of sand increases upward	8	0
Shale, dark-gray to black, scattered ironstone nodules toward top (Sample 47)	6	6
Laminated sand and clay, light colored laminae composed of quartz-rich sand, dark colored laminae composed of clay	3	0
Sandstone	0	2
Lignite	0	7
Clay, black, organic-rich (Sample 46) Base covered at 887' altitude at creek level	1	0

Locality 13

Brown Co., NE 1/4 NW 1/4 NW 1/4 sec. 3, T. 111 N., R. 33 W., section exposed in creek bank north and south of road

	ft	in
Pleistocene:		
Glacial drift	10	0
Cretaceous (?):		
Highly weathered material derived from alteration of metamorphic rocks; clay, light-yellow to white, much quartz exposed to creek level (Sample 49)	25	0

Locality 14

Renville Co., NE 1/4 SW 1/4 NE 1/4 sec. 31, T. 112 N., R. 32 W., outcrop on east side of Fort Ridgley Creek

Locality 14 (continued)

	ft	in
Pleistocene:		
Glacial drift	60	0
Cretaceous (?):		
Clay, white, quartz-rich (Sample 44)	2	0
Highly weathered material, mostly clay and quartz, alternating layers of 3 inch thick pink and white horizontal bands both consisting of about 1/3 to 1/2 quartz	10	6
Precambrian:		
Quartz, massive, contains numerous thin joint fillings of white clay, exposed to creek level; dominant joints strite N. 45° W., dip vertical	26	6

APPENDIX B

Described Sections
A through BB
(Locations shown on Plate 1)

Locality A

Redwood Co., in Alexander Ramsey City Park, SW 1/4 SW 1/4 NE 1/4 sec. 36, T. 113 N., R. 36 W., exposure SW of bituminous road, between 927 feet and 937 feet altitude

	ft	in
Pleistocene:		
Covered interval	75	0
Cretaceous (?):		
Buff colored, very clayey, altered material derived from metamorphic rock; somewhat iron stained; section covered to road level	10	0

Locality B

Redwood Co., in Alexander Ramsey City Park, SE 1/4 SW 1/4 NE 1/4 sec. 36, T. 113 N., R. 36 W., entire bluff exposed on north side of Redwood River, base of outcrop at river level; 862 feet altitude

	ft	in
Pleistocene:		
Glacial drift	2	0
Precambrian:		
Tan to pale green, highly altered metamorphic rock; quartz present mostly in 2 mm size range	74	0

Locality C

Redwood Co., SW 1/4 NE 1/4 SW 1/4 sec. 30, T. 113 N., R. 35 W., high bluff along Redwood River; base of outcrop at river level, altitude 845 ft.

	ft	in
Pleistocene:		
Glacial drift	53	0
Precambrian:		
Weathered metamorphic rock, yellow to buff color in middle and upper part, greenish brown near base; abundant muscovite and iron minerals in lower portion, some apparent foliation preserved in soft, altered rock near river level	98	0

Locality D

Redwood Co., SW 1/4 NW 1/4 SW 1/4 sec. 29, T. 113 N., R. 35 W., exposure along bituminous road south of North Redwood Falls; base of described section in ditch at fork in road

	ft	in
Pleistocene:		
Glacial drift	5	0
Cretaceous (?):		
Clay-shale, very sandy, limonite stained, some poor 1 to 3 in. bedding	8	0
Clay, slightly sandy	2	0
Clay, some sand in upper part, becomes pisolitic toward base; altitude of base 940 ft.	4	0
Precambrian:		
Gneiss, highly weathered, pale green; gneissic texture preserved; contains some unaltered K-feldspars; section becomes more mafic with		

	ft	in
more biotite toward base; whole interval clayey and sandy	47	0

Locality E

Redwood Co., NW 1/4 NW 1/4 NE 1/4 sec. 32, T. 113 N., R. 35 W., outcrop along unimproved road

	ft	in
Pleistocene:		
Glacial drift; altitude 1000 feet at top	75	0
Cretaceous (?):		
Clay, mostly float, white, pisolitic, some sand present; gray toward base; section covered to base of hill	10	0

Locality F

Redwood Co., SW 1/4 SW 1/4 NW 1/4 sec. 33, T. 113 N., R. 35 W., outcrop along unimproved road

	ft	in
Pleistocene:		
Glacial drift	57	0
Precambrian:		
Highly weathered metamorphic rock; much clay and sand; tan and limonite stained; base of outcrop in farm yard	28	0

Locality G

Renville Co., NW 1/4 NW 1/4 NW 1/4 sec. 4, T. 112 N., R. 34 W., outcrop along State Highway 19

Locality G (continued)

	ft	in
Pleistocene:		
Glacial drift; altitude of base 892 feet	118	0
Cretaceous (?):		
Clay, pisolitic, hard, limonite stained; forms ledge; base covered	2	0

Locality H

Renville Co., NE 1/4 NE 1/4 SE 1/4 sec. 4, T. 112 N., R. 34 W., outcrop along gravel road; section measured down from railroad right of way

	ft	in
Pleistocene:		
Alluvium and glacial drift; altitude of base 875 ft	20	0
Cretaceous (?):		
Clay, hard, pisolitic, limonite stained; forms ledge, base covered	2-3	0

Locality I

Redwood Co., SW 1/4 NW 1/4 SE 1/4 sec. 9, T. 112 N., R. 34 W., along creek below cemetery

	ft	in
Pleistocene:		
Glacial drift	50	0
Precambrian:		
Highly weathered gneiss; better preservation of gneissic texture in lower 3 feet 6 inches of section; sandy toward Pleistocene contact	19	0

Locality J

Redwood Co., NW 1/4 NW 1/4 NW 1/4 sec. 15, T. 112 N., R. 34 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift; altitude of top 969 ft	44	0
Cretaceous:		
Black, organic shale	0	6
Alternating thin layers of tan sandstone and lignite	3	0
Clay, very light gray, sandy in lower part	2	0
Sandstone, white to pale buff; clayey throughout; altitude of base 914 ft	5	6

Locality K

Redwood Co., SW 1/4 SE 1/4 NW 1/4 sec. 15, T. 112 N., R. 34 W., outcrop in creek bank below farm yard

	ft	in
Pleistocene:		
Glacial drift	27	0
Cretaceous (?):		
Clay, sandy, white to light blue, grades downward to buff; base covered at altitude 920 ft	2-3	0

Locality L

Renville Co., 1,900 feet south of northwest corner, sec. 11, T. 112 N., R. 34 W., outcrop along gravel road

	ft	in
Cretaceous:		
Sandstone, white, grades downward to orange color at road level	6	0

Locality M

Renville Co., SW 1/4 SW 1/4 NW 1/4 sec. 11, T. 112 N., R. 34 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift	4	0
Cretaceous (?):		
Alternating layers of red and yellow sandstone and clayey sandstone; base covered at road level	8	0

Locality N

Renville Co., SE 1/4 SE 1/4 NW 1/4 sec. 11, T. 112 N., R. 34 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift; altitude of base 884 ft	5	0
Cretaceous (?):		
Clay, top 1 foot hard, pisolitic, limonite stained, grades downward to buff color clay with few pisolites; road level at base of section	5	0

Locality O

Renville Co., SW 1/4 NW 1/4 SE 1/4 sec. 18, T. 112 N., R. 33 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift; altitude of base 853 ft	147	0
Precambrian:		
Weathered metamorphic rock, buff colored; some fresh, pink K-feldspar phenocrysts present; base of section at road	7	0

Locality P

Renville Co., NE 1/4 SE 1/4 sec. 18, T. 112 N., R. 33 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift	144	0
Precambrian:		
Deeply weathered, dark, mafic igneous rock; many calcite filled fractures; base at road level, altitude 844 feet	10-12	

Locality Q

Renville Co., NW 1/4 NW 1/4 NW 1/4 sec. 20, T. 112 N., R. 33 W., outcrop on east side of creek

	ft	in
Pleistocene:		
Glacial drift	30	0
Precambrian:		
Highly weathered metamorphic rock; clayey with large amounts of quartz, yellow-buff color, red staining toward top; base at creek level, altitude 875 feet	14	0

Locality R

Brown Co., SE 1/4 NW 1/4 NW 1/4 sec. 30, T. 112 N., R. 33 W., outcrop behind barn south of road

	ft	in
Precambrian:		
Weathered gneiss, yellowish-brown; base of outcrop altitude 855 feet	5	0

Locality S

Brown Co., NW corner NE 1/4 SW 1/4 NW 1/4 sec. 30, T. 112 N., R. 33 W., outcrop in farm yard at junction of road and creek

	ft	in
Precambrian:		
Highly weathered, punky, rust colored gneiss	9	0

Locality T

Brown Co., SE 1/4 NW 1/4 SW 1/4 sec. 29, T. 112 N., R. 33 W., exposure in small pit

	ft	in
Pleistocene:		
Glacial drift	15	0
Precambrian:		
Weathered gneiss, clayey, yellow	2	0

Locality U

Brown Co., SW 1/4 NE 1/4 SW 1/4 sec. 29, T. 112 N., R. 33 W., outcrop in back of farm house

Precambrian:

Small exposure of weathered gneiss, yellow, clayey

Locality V

Brown Co., SE 1/4 NW 1/4 SW 1/4 sec. 29, T. 112 N., R. 33 W., outcrop along creek bank

	ft	in
Precambrian:		
Weathered metamorphic rock; yellow, clayey; elevation of base at creek level 870 ft	14	0

Locality W

Brown Co., NW 1/4 SW 1/4 SE 1/4 sec. 29, T. 112 N., R. 33 W., outcrop along road up hill opposite farm house

	ft	in
Pleistocene:		
Glacial sand; altitude of base 880 ft	6	0
Cretaceous (?)		
Clay, hard pisolitic, iron stained; base covered	2	0

Locality X

Renville Co., NW 1/4 NW 1/4 SW 1/4 sec. 21, T. 112 N., R. 33 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift	15-20	
Glacial sand	1	0
Cretaceous (?):		
Sand and clayey sand; buff color; altitude of base 851 ft	15	0

Locality Y

Renville Co., SE 1/4 SW 1/4 SE 1/4 sec. 27, T. 112 N., R. 33 W., outcrop at driveway of farm house

Locality Y (continued)

	ft	in
Pleistocene:		
Glacial drift	15	0
Cretaceous (?):		
Clay, hard, pisolitic, buff, limonite stained toward top; altitude of base at gravel road level 860 feet	5	0

Locality Z

Renville Co., SW 1/4 SE 1/4 SE 1/4 sec. 35, T. 112 N., R. 33 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift	15	0
Cretaceous (?):		
Clay, pisolitic, very sandy, contains rounded quartz pebbles up to 1 inch in diameter	6	0
Clay, very sandy	5	6
Sandstone, limonite cement	1	6
Covered interval to road level altitude 860 feet	10	0

Locality AA

Nicollet Co., NW 1/4 NE 1/4 NW 1/4 sec. 1, T. 111 N., R. 33 W., outcrop along gravel road

	ft	in
Pleistocene:		
Glacial drift; altitude of base 850 feet	10	0

	ft	in
Cretaceous (?):		
Clay, limonite stained at top; gray and sandy in middle portion; red staining toward base; lower portion clay, sandy and gray; base of outcrop at road level	5	0

Locality BB

Brown Co., NE 1/4 NW 1/4 SW 1/4 sec. 8, T. 111 N., R. 32 W., outcrop along creek bank

	ft	in
Pleistocene:		
Glacial drift	30	0
Cretaceous (?):		
Very coarse-grained quartz sandstone	5	0
Covered interval to creek level	10	0