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Clay Mineralogy and Geology of Minnesota's Kaolin Clays

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ABSTRACT

Humid tropical weathering during the latter part of the Mesozoic Era, probably during early Late Cretaceous time, produced a thick kaolinitic residuum (unit 1) over much of Minnesota, mainly from Precambrian metamorphic and igneous rocks. The weathered zone is now covered by younger Cretaceous sedimentary rocks and Pleistocene glacial deposits except locally along the Minnesota River Valley in southwestern Minnesota and between St. Cloud and Little Falls in the central part of the state. As much as 100 feet of residuum is exposed along a 45-mile long section of the Minnesota River Valley between Granite Falls and Fort Ridgley State Park; marginal to the valley, the residuum is overlain by 40 or more feet of clays and shales, and glacial deposits.

The clay minerals of the residuum—unit 1 of this report—that were formed from weathering of felsic rock types are composed primarily of kaolinite. In the least weathered parts of the profile, the kaolinite has an irregular platy form. Tubular halloysite is present in minor amounts, especially in the lower part of the weathering profile. Mafic rock types weathered first to montmorillonite and under progressively more intense weathering to kaolinite.

Two Upper Cretaceous units of kaolinitic sedimentary rocks (units 2 and 3) overlie the residuum. The lowermost of these (unit 2), which was derived from erosion of the weathered residuum and which also underwent tropical weathering, has a maximum observed thickness of 45 feet, and is composed of varying proportions of kaolinite and quartz, with trace amounts of halloysite. A three- to five-foot, generally iron-rich, kaolinitic, pisolitic clay that contains small amounts of gibbsite and boehmite lies at the top of unit 2. Sedimentary rocks of unit 3 disconformably overlie unit 2, and consist of gray to black, organic-rich clays and shales, thin beds of lignite, and at least one thin bed of bentonite. Kaolinite is abundant in the basal part of unit 3 but gives way upward progressively to montmorillonite and illite, suggesting that the humid tropical climate under which units 1 and 2 had formed had been replaced by more temperate conditions by unit 3 time.

Some of the kaolinitic clays of units 1 and 2 are potentially important as raw material for paper coating and filler. However, the presence of minor amounts of halloysite in some of these kaolin clays might adversely affect the flow properties of clay-water suspensions during paper-coating operations by increasing the suspensions' viscosity; some kaolinite having an irregular particle form may also produce a similar effect. It may be difficult to improve the whiteness and brightness of some of the clays of unit 1 if their natural color is pale green; the clays of unit 2, on the other

hand, generally respond better to chemical bleaching. In addition, some of the kaolin clays present in all three stratigraphic units may be satisfactory for use in the ceramics and refractories industries. Ball clays of unit 3, which are very plastic and burn white, could be mixed with less plastic kaolin clays of units 1 and 2 for the production of a variety of refractory products. Most of the kaolin clays of the three units when fired become tan, pink, or white and could be used in common types of light-colored ceramic products.

INTRODUCTION

Kaolin is a general term for natural clays consisting mostly of kaolinite and/or halloysite with lesser amounts of quartz and/or feldspar. Such clays generally are a valuable and useful industrial mineral. The clay-sized fraction (less-than-two-micron) is used as filler in paper and also as a coating on paper surfaces, producing a white glossy paper used commonly in many of today's magazines. Paper of this type is composed of approximately one-third clay, thus indicating in a general way the immensity of kaolin-clay production for the paper industry alone. Most kaolin clays presently used by the paper industry are produced in southeastern United States and are transported into the upper Midwest by rail. Kaolin clays are also a basic ingredient in many ceramic and refractory products and in the plastics, paint, and rubber industries. Other less common but nevertheless significant uses of kaolin clays are in cement, adhesives, printing ink, and pharmaceutical products. Today, in various parts of the United States, pilot-plant studies which are aimed at economic extraction of aluminum from clays and shales are being carried on. Even though extraction of aluminum from these materials is not economically competitive as yet compared with aluminum production from bauxite, the future potential of these kaolin clays for such use should not be overlooked.

A deeply weathered residuum, formed on Precambrian igneous and metamorphic rocks, is present beneath Pleistocene glacial deposits and Upper Cretaceous sedimentary rocks in much of the western half of Minnesota. The residuum is rich in kaolinite and quartz, and the relative proportion of each mineral is directly related to the composition of the underlying parent rock. Reworking of the upper part of the residuum by running water during Late Cretaceous time produced kaolinitic quartz sands and sandy kaolinitic clays as well as relatively pure kaolinitic clays. Subsequent erosion of a part of the basal Upper Cretaceous sedimentary and residual kaolins resulted in redeposition of kaolinite in the lower few tens of feet in the overlying organic-rich Upper Cretaceous sediments. It is this succession of rocks, that is, the residuum, the overlying sedimentary kaolin clays, and the lowermost kaolinitic part of the organic-rich Upper Cretaceous sediments that is the focus of this study.

Sporadic interest in the kaolin clays of Minnesota has been shown over the years by various individuals and industries who have attempted to use them as a raw material in the production of paint, bricks, refractories, lightweight-aggregate, bonding clay, and aluminum, and for coating and filling paper. However, to the present time (1970), the kaolin clays in Minnesota have been used successfully for any appreciable length of time only in the production of brick. Over the past several years attention has again been focused on these clays as an undeveloped resource of potential value to the paper industry, and as a result exploratory drilling and detailed laboratory testing of the clays have been undertaken by several companies. It is likely that certain kaolin clays of Minnesota may be suitable for use in the paper industry.

The purpose of this report is twofold: (1) to assemble all pertinent published and unpublished data relating to the kaolin clays of Minnesota and to integrate this with new mineralogical and geological data in order to clarify the origin of the kaolins, and (2) to present information that will assist the kaolin clay industries in exploration and development of this clay resource.

Field Work and Acknowledgments

Field work begun in the fall of 1963 resulted in a preliminary report on the kaolin clays of the Minnesota River Valley (Parham and Hogberg, 1964). A part of each succeeding summer through 1968 was spent in obtaining additional clay samples from this region as well as from other scattered localities in the state where kaolinitic sediments are exposed. Descriptions of individual kaolin clay exposures are listed in Appendix B.

Field work consisted primarily of locating and describing occurrences of deeply weathered Precambrian rocks and associated kaolinitic sediments, and sampling the various lithologic units for laboratory study. Because exposures of the kaolin clays are uncommon throughout Minnesota, no attempt has been made to construct a detailed geologic map of these rocks. Rather an attempt has been made here to synthesize available geologic information relating to the kaolin clays in order to show the broad regional aspects of paleogeography during the time of their formation.

Additional samples of kaolin clays from drill cores and cuttings collected by other state agencies were made available to the Minnesota Geological Survey and are included in this report. Twenty-nine other sets of hand-augered samples which were collected by K. F. Bickford and D. Price[1] for the Minnesota Geological Survey in 1947 are also included here.

Funds for electron microscopy were made available by the Mines Experiment Station of the University of Minnesota. Mrs. Hannalore Hagan, former electron microscopist of the School of Mines and Metallurgical Engineering, University of Minnesota, prepared and photographed the kaolin samples for this report. Photographs in Figures 4, 9, 12, and 35 were taken by Tom Bastien, and the drafting was done by Richard Darling.

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[1] Bickford, K. F., and Price, D., 1947, Report on work done on clays in summer, 1947: Unpublished open-file manuscript of the Minnesota Geological Survey.

Previous Investigations

Over the years numerous geologists of the Minnesota Geological Survey have reported on their studies of various aspects of Minnesota's kaolin clays. These reports, which are in part only open-file data, are reviewed historically here to indicate periods of interest and to point up the diverse views that have been expressed on the distribution, occurrence, and genesis of kaolin clays.

Kaolinitic residuum that forms the near-vertical valley walls near the Redwood River-Minnesota River confluence was described first by William Keating in 1823 as fine white sandstone, a description he published in 1825 (Winchell, 1893). N. H. Winchell visited the same area in 1873, and concluded that the material was not sandstone but rather an alteration product of the underlying granitic rocks composed primarily of kaolin clay and quartz. Winchell attributed the alteration of the granitic rocks to action of the Cretaceous sea, for he noted that Cretaceous sedimentary rocks overlie these residual kaolins in many exposures. In observing additional outcrops along the valley walls a few miles downstream from Redwood Falls, Winchell noted a rock type of peculiar appearance that formed beds as much as 18 feet thick. He (1893, p. 197-198) described the rock as . . . "A concretionary marl, or apparently limy earth, of white color . . . The surfaces of these pieces show a great number of round or oval spots, or rings, which seem to be formed by the sections of concretions enclosed in the mass. It is rather hard when dry, and nearly white. . . . At a point a little further up this creek appears a heavy deposit of concretionary, rusty marl, or ferro-calcareous substance, the exact composition and proper name of which it is impossible to give, before it has been chemically examined. It is in heavy beds, that fall off in large fragments, like rock. The first impression is that the bluff is composed of ferruginous conglomerate but there is not a foreign pebble in it. Every little round mass has a thin shell which is easily broken, revealing either a cavity or a loose, dry earth. These concretions are generally not more than one-quarter or one-half inch in diameter." A specimen of this rock type is shown in Figure 6.

Winchell (1893) also described Cretaceous organic-rich shales, clays, and lignites exposed at numerous places above the altered Precambrian rocks. Many attempts were made to mine thin beds of lignite and cannel coal in the vicinity of Redwood Falls around 1871, but the coals proved to be too thin and too impure to sustain active interest.

The United States Geological Survey, in cooperation with the Minnesota Geological Survey, published a report after World War I (Grout and Soper, 1919) on the clays and shales of Minnesota that includes comments on the kaolin clays of the Minnesota River Valley. The "concretionary marl", first described by Winchell, was chemically analyzed and found to contain alumina in excess of that in pure kaolinite; for this reason the clay was thought to contain bauxite, and Grout referred to it as a concretionary bauxitic clay.

Exploratory churn drilling for kaolin clay was carried out during 1933 by Butler Brothers Mining Company on land just north of Fort Ridgley

State Park, and cuttings of decomposed gneiss and kaolin were taken from six holes. In one additional hole, the drill penetrated directly from glacial drift into fresh Precambrian gneiss.

S. S. Goldich's doctoral dissertation at the University of Minnesota in 1936, entitled "A study in rock weathering," which was published two years later (Goldich, 1938), served as a basis for comparing chemical changes that took place during the weathering of various igneous and metamorphic rock types selected from several areas of the United States. Six samples of residual kaolin clays from the Redwood Falls-Morton area of Minnesota were compared chemically and mineralogically with fresh Morton Gneiss, their probable parent material. Goldich noted that in the sequence of alteration, mica and the more calcium-rich plagioclase feldspars altered to kaolinite while the potassium-rich feldspars remained fresh. Only under the most advanced stages of weathering was the potassium feldspar destroyed. Goldich stated that chemical analyses of one sample suggested the presence of an aluminous hydrate in addition to the kaolin.

A study of outcrop samples of kaolin clays taken in 1941 from exposures between Redwood Falls and Fort Ridgley State Park was undertaken by Lynn Gardner[2] to determine the potential usefulness of kaolin as filler and coating clay for the paper industry. Selected for detailed investigation were samples from three localities each having a low iron content. The samples were washed and screened, a mechanical analysis of each was made, and the natural color of the beneficiated fraction was determined. Gardner concluded that the locality most worthy of further investigation was the area along Fort Ridgley Creek just north of Fort Ridgley State Park. He cautioned, however, that because of extreme variability in composition of the weathered rocks in the immediate area, detailed drilling would be necessary to obtain sufficient subsurface material to properly evaluate the resources. He also stated that some of the kaolinite he examined might be mistaken for muscovite because of the very pale green color of the kaolinite and its pearly luster, but that it could easily be identified by x-ray analysis.

A Minnesota Geological Survey Bulletin (Emmons and Grout, 1943, p. 136) that describes the mineral resources of Minnesota contains a table of chemical analyses, one of which is of a pisolitic clay exposed in a roadcut east of Morton. A footnote to this analysis states that J. W. Gruner identified some gibbsite in this sample by x-ray diffraction. This finding paralleled Goldich's earlier suggestion that some of these clays might contain aluminous hydrates.

The first compilation of available information on kaolin clays of Minnesota was completed by H. R. Bergquist[3] in 1943. His report contains descriptions of measured geologic sections of sedimentary kaolins and of the kaolinitic residuum developed on Precambrian rocks in the Redwood Falls

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[2] Gardner, Lynn, 1941, Clay-prospects and testing: Unpublished open-file manuscript of the Minnesota Geological Survey.

[3] Bergquist, H. R., 1943, Minnesota high alumina clays: Unpublished open-file manuscript of the Minnesota Geological Survey.

area and also in Morrison and Stearns Counties. The presence of halloysite in the pisolitic clay is first mentioned in this report. Gibbsite was identified again in the pisolitic clay at several localities, suggesting to Bergquist that some of the clays might serve as possible aluminum ores. During World War II, some of these gibbsite-bearing clays were tested by aluminum companies because of the shortage of aluminum in the United States. Bergquist stated that, based on mineral and chemical analyses from both industry and the U. S. Bureau of Mines, the pisolitic clays were composed largely of iron minerals, kaolinite, and minor amounts of gibbsite. Percentages of alumina and silica in the clays range from 30 to 42 and 31 to 44 respectively. He reported 11 to 14 percent available alumina in the bauxitic clay in Crow Creek southwest of Morton, but generally only 2 to 3 percent of available alumina for samples collected elsewhere. (Available alumina is that amount of Al_2O_3 that can be recovered from bauxite by the Bayer process.) He classified only one clay sample as bauxite; chemical analysis showed that the three and one-half-foot-thick bed from which the sample was taken contained 22.60 percent silica and 50.09 percent alumina, 36.20 percent of which was available alumina. He concluded that because industry was showing a decreased interest in low-grade bauxite and bauxitic clay as an aluminum ore, it seemed inadvisable for the Minnesota Geological Survey to continue work on these materials at that time.

In 1947, K. F. Bickford and D. Price hand-augered kaolin clays and weathered Precambrian metamorphic rocks at 26 localities extending from Redwood Falls to Fort Ridgley State Park along the Minnesota River Valley, and at two additional localities in Stearns and Morrison Counties, to add further detail to information on the distribution and character of Minnesota's kaolin clays. In all, 257 samples were collected, and many of these were used in a later study by the Minnesota Geological Survey on the state's bloating clay resources. I have x-rayed all these samples for the clay mineral identification for this report and the results are listed in Appendix D.

A petrographic study by E. Bradley[1], completed in 1941, to categorize several groups of Minnesota clays, included four samples of residual kaolins from weathered Precambrian rocks and seven other samples of Cretaceous sediments. He concluded that the residual kaolins were composed mainly of kaolinite and quartz and that Cretaceous sediments from the pit of Ochs Brick and Tile Company at Springfield were composed predominantly of quartz and halloysite.

Later, Prokopovich and Schwartz (1957) tested numerous clays from Minnesota to determine their suitability as bloating clays for expanded aggregate production. Among these samples were 131 residual kaolins formed from Precambrian rocks and basal Upper Cretaceous kaolinitic clays of the Granite Falls-Fort Ridgley State Park segment of the Minnesota River Valley. All the kaolin clays tested were found to be non-bloating.

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[1] Bradley, E., 1949, Physical and mineralogical properties of several groups of Minnesota clays: Unpublished master's thesis, University of Minnesota.

R. E. Sloan (1964) compiled the first comprehensive report on the Cretaceous System of Minnesota. He placed the time of kaolin formation as Late Jurassic and Early Cretaceous, and suggested that the intense weathering period that formed the kaolin may have been limited to a span of one to five million years. His interpretation of a weathering interval in Late Jurassic and Early Cretaceous time was based partly on his belief that the kaolinitic regolith is interbedded with Cretaceous sediments at nearly all localities and partly on the expected climatic effect that would be produced by the proximity of a Late Jurassic to Early Cretaceous epicontinental sea just west of Minnesota. Because of the scattered outcrops and poor exposure, he acknowledged that detailed age relationships and stratigraphic correlation of these rocks would have to await the availability of much additional information.

A preliminary report on the geologic occurrence, mineralogy, and physical properties of both residual and sedimentary kaolin clays from the Minnesota River Valley in Brown, Redwood, and Renville Counties, by Parham and Hogberg (1964), indicated that some of the clays examined probably could be used satisfactorily as raw material for coating and filler clays for the paper industry and also for refractory products. A few qualitative bleaching tests on various colored kaolins showed that the whiteness of the clay could be improved substantially. Whiteness is an important quality in consideration of a kaolin clay for use as a paper coating clay. Ball clay, a very plastic, white-burning kaolin clay used in most refractory products, was reported in the lower part of the organic-rich, Upper Cretaceous sediments along Crow Creek. Fired test bars made of the raw clays indicated that these clays might serve as suitable raw material for refractory uses.

GENERALIZED STRATIGRAPHY

Regional Relations and General Character

The kaolin clays of Minnesota can be divided for the purpose of this report into three general stratigraphic units. The lower unit (unit 1) is a light silver-green or buff kaolinitic residuum that formed during Cretaceous time on pre-Cretaceous bedrock, generally Precambrian gneisses and granites. The overlying unit (unit 2) consists of kaolinitic sandstones, white, buff, or yellow sedimentary kaolin clays, and pisolitic kaolin clay, all of Late Cretaceous age. The uppermost unit (unit 3), which lies directly on unit 2, is composed of gray to black organic-rich sedimentary kaolin clays of younger Late Cretaceous age. Each of the three kaolin-bearing units is separated from the adjacent unit by an unconformity, and accordingly each varies in thickness from place to place. A few tens of feet to 500 or 600 feet of overburden generally covers the kaolinitic units in Minnesota. On a regional basis, the overburden is thinnest in the St. Cloud region and thickest in western Minnesota. The generalized regional relations of the three kaolinite-bearing units are shown in Figure 1.

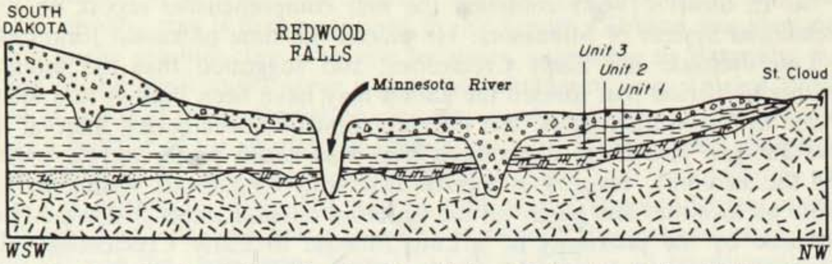


Figure 1. Generalized geologic section from the vicinity of St. Cloud to Redwood Falls and westward along the Minnesota River to the South Dakota border.

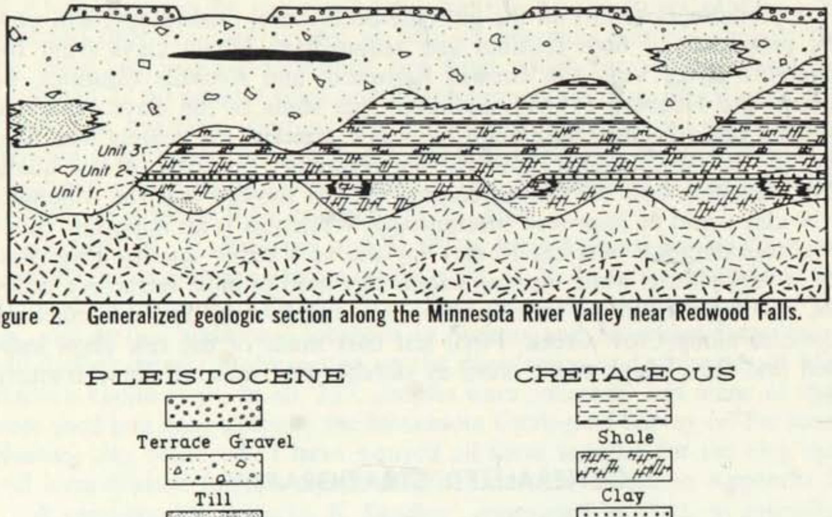
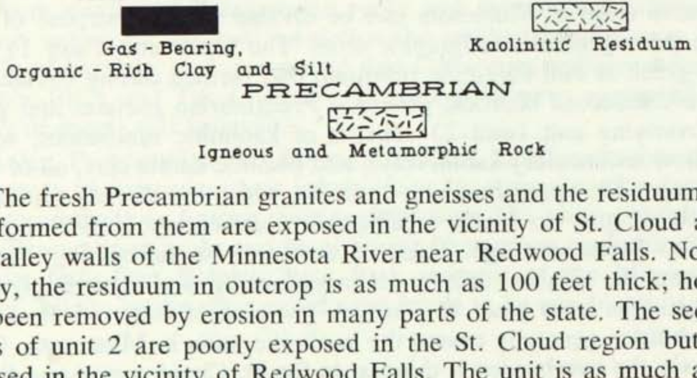


Figure 2. Generalized geologic section along the Minnesota River Valley near Redwood Falls.



The fresh Precambrian granites and gneisses and the residuum (unit 1) that formed from them are exposed in the vicinity of St. Cloud and along the valley walls of the Minnesota River near Redwood Falls. Not uncommonly, the residuum in outcrop is as much as 100 feet thick; however, it has been removed by erosion in many parts of the state. The sedimentary rocks of unit 2 are poorly exposed in the St. Cloud region but are well exposed in the vicinity of Redwood Falls. The unit is as much as 45 feet thick but has been removed by erosion in many areas. Farther to the southwest in Minnesota, the sedimentary kaolin clays and kaolinitic sandstones of the unit grade laterally into the Upper Cretaceous Dakota Sandstone. Unit 3, the kaolinitic basal part of the overlying organic-rich clays and shales, is exposed in approximately the same areas as units 1 and 2. The stratigraphic relationships of the units in the vicinity of Redwood Falls within the Minnesota River Valley are shown in Figure 2. Correlation of the three kaolin-bearing units from area to area is difficult because exposures are discontinuous over long distances in the state and reliable subsurface data are scarce.

Paleontologic and stratigraphic studies show that all the kaolin-bearing units in Minnesota are most probably Late Cretaceous in age. Sloan (1964) attempted to correlate the Cretaceous sedimentary rocks throughout Minnesota, but established only tentative stratigraphic correlations within the state and with strata farther west because of limited exposures, lack of drill cores and reliable waterwell cuttings, and sparseness of paleontological data. He believed that the three kaolinitic units were interbedded with one another at nearly all localities rather than being separated by unconformities, and thus considered all to be of the same approximate age. Though paleontological data are scarce, John Hall (written communication, 1969), Department of Botany, University of Minnesota, has identified pollen from a thin organic-rich clay or shale (sample 338) below a 15-foot thick bed of pisolitic kaolinite at locality 8 as being diagnostic of Cenomanian time (early Late Cretaceous). Hall identified the following pollen forms: *Bacubivesiculites inchoatus, Clavabivesiculites pannosus, Retibivesiculites planus, Rugubivesiculites convolutus, Rugubivesiculites reductus, Verrumonocolpites conspicuus, Punctamultivesiculites inchoatus, Granamultivesiculites inchoatus, Cingutriletes congruens,* and *Retitriletes pluricellus.* Other paleobotanical studies (Lesquereux, 1893; Chaney, 1954; Bolin, 1956; Zangerl and Sloan, 1960; Hall and others, 1968) have shown that the pre-Pleistocene sedimentary rocks stratigraphically above the pisolitic kaolinite layer in Minnesota also are Late Cretaceous in age. Accordingly, the paleontologic data indicate that the weathering interval in Minnesota, which produced abundant kaolin clays, probably began in early Late Cretaceous time and ended sometime later in Cenomanian time.

In the sections below, a discussion of the generalized stratigraphy of the kaolin-bearing succession is followed by descriptions of kaolin-bearing clays in three areas that are isolated from the main area. Because of uncertainties of correlations between the strata in these areas and the main area, it seems appropriate to discuss them separately. In turn, this is followed by a brief description of the glacial deposits of Pleistocene age along the Minnesota River Valley that generally cover the Cretaceous strata.

Residuum—Unit 1

The deeply weathered residuum formed from a wide variety of pre-Cretaceous igneous and metamorphic rock types. Exposures that show both fresh parent rock and the complete transition into the overlying thick residuum are rare, for generally either the weathered material has been completely removed by erosion, exposing the fresh parent rock, or the residuum is exposed and completely covers the parent rock. Accordingly, it can be difficult to determine the relationships of the weathering product to the parent rock.

The residuum (unit 1) varies both vertically and laterally in thickness, mineral composition, color, and density. These differences are related to a combination of factors but primarily to differences in past erosional cycles, the lithology of parent rocks, and the intensity of chemical weathering.

On a regional basis, the thickness of the residuum is greater in the western part of the state and thinnest in the eastern part. Thicknesses on the order of 100 feet are common in the western half of the state and as much as 200 feet has been reported by water-well drillers at a few localities. The thinner residuum in the eastern part of the state probably has resulted from removal of substantial amounts of material by erosion.

The non-clay mineral composition of the residuum varies with differences in rock type and with stratigraphic position in the weathering profile. That original rock type has a marked influence on the non-clay mineral fraction in the residuum is indicated by contrasts in the weathering of felsic and mafic rock types. Granitic rocks, including the widespread Morton Gneiss, yield abundant quartz and potassium feldspar to the residuum as non-clay mineral constituents upon weathering, whereas mafic rocks, such as the basalt that occurs as local dikes in the Precambrian crystalline rocks, break down to a soft, punky, dark red or green clayey material that lacks quartz and potassium feldspar. Differences in the non-clay mineral assemblages related to positions in the weathering profile can be illustrated by the residuum developed on the Morton Gneiss. Typically, the lower part of the residuum on this rock type contains both quartz and potassium feldspar whereas the upper part consists entirely of quartz. The transition from weathered material downward into the fresh rock generally is gradational, as for example along Birch Coulee (fig. 3, locality 74), where the transitional zone is 25 feet thick. Sharp transitions, however, are observed at some places, as in the east face of the Cold Spring Crystal quarry (locality 89) in Stearns County. At this locality, the residuum is rich in kaolinite, and the transition takes place over an interval of less than a foot. Stratigraphic variations in the clay-mineral assemblages of unit 1 are discussed in the following section.

Particle-size distribution in the residuum varies considerably, and is a function of intensity of chemical weathering, parent rock type, and eluviation of clay material. For any given parent rock type, particle sizes are greater in the lower part of the residuum than in the upper part, because weathering is more intense near the surface. The grain size of the parent rock also influences the particle size of its weathered equivalent. Schist, for example, weathers to a residuum having a finer particle size than does granite. Another factor affecting the particle size of the residuum is the removal of minerals from the rock by solution during weathering, providing open-

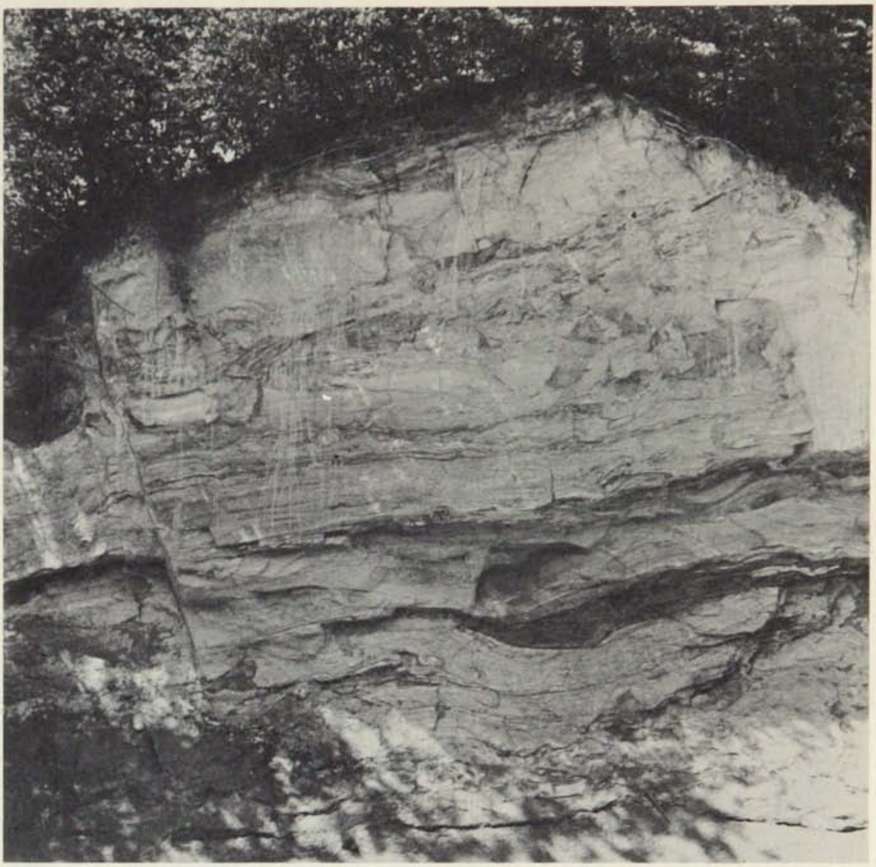


Figure 3. **Weathered Precambrian Morton quartz monzonite gneiss exposed in stream cut along Birch Coulee, Renville County, locality 74. The exposed section is 25 feet thick. Original structures are preserved although most feldspars have weathered to kaolinite and halloysite. Quartz and some partly altered K-feldspars are present.**

ings for downward-percolating waters to move finer particles to lower parts of the profile.

In interpreting particle-size data in weathered profiles, the method of sample preparation must also be taken into account. For example, some of the sedimentary kaolin clays of unit 2 will not disaggregate naturally in water and therefore must be wet-ground during sample preparation. The resulting particle-size distribution is most probably merely a function of grinding time. The number of variables inherent in sample preparation and size analysis, particularly of the finer-sized fractions, leaves the analyses open to question. Boswell (1961) stated ". . . . mechanical analysis today has, in a very broad way, its uses; the best that can be said for it is that it is better than nothing." It seems that a percentage range which brackets the variation in abundance of clay-sized material in the residuum is more significant than data on specific samples. The less-than-two-micron fraction of the residuum varies in amount from 13 to 33 percent in the samples examined.

The residuum in outcrop generally ranges in color from silver-green to light buff or rusty-red, whereas wet samples taken from drill holes commonly are silver-blue or light silver-green. Certain surface exposures where sporadic slumping continually exposes unoxidized material also are silver-blue or light silver-green. The blue and green colors of the wet material generally change to white or pale green upon drying.

Upper Cretaceous Sedimentary Rocks

The Upper Cretaceous sedimentary rocks that overlie the residuum can be divided into two stratigraphic subdivisions. The lower subdivision (unit 2) is defined to include all sedimentary rocks stratigraphically below and including the pisolitic kaolinite layer, and the upper subdivision (unit 3) to include the basal succession of kaolinitic sedimentary rocks stratigraphically above the pisolitic layer. The rocks in unit 2 generally are characterized by white, buff, orange, and less commonly red colors, whereas those in unit 3 are generally gray or black and commonly organic-rich.

Rocks of unit 2

The general succession of rocks in unit 2 from the base upward is: (a) kaolinitic sandstone or sandy kaolinitic clay, (b) white kaolinitic clay, (c) grayish-white, pisolitic, kaolinitic clay, and (d) iron-stained, hard, pisolitic clay. Contacts between the four lithologies generally are transitional. The succession has a maximum observed thickness of approximately 45 feet (locality 5), but commonly is much thinner. Its overall color depends upon the amount of oxidized iron present, which increases in abundance upward in the section, and manganese, which discolors the clays or sandstones to various shades of light purple, red, and black.

Both the kaolinitic sandstone which is cross-bedded (fig. 4), and the sandy kaolinitic clay of the basal part of unit 2, are composed predominantly of quartz sand and kaolinite. The quartz grains are angular and are in the medium to coarse size range. Large pieces of angular quartz as much as 5 inches in dimension are scattered throughout one such sandstone in the extreme northeast corner of the Ochs Brick and Tile Company pit near Morton (locality 4). The sandstones and sandy clay seem to grade into one another both laterally and vertically. The white or buff sandy clays vary in hardness; some of them will not slake readily in water. Some of the softer clays have at least 40 to 45 percent of their particles in the less-than-two-micron fraction.

Conglomerate is not commonly seen at the base of the succession, but thicknesses of as much as one or two feet were recorded during augering at locality 5 (map B). The conglomerate generally is composed of more resistant rock fragments of the residuum below, and most of the weathered fragments are less than six inches in diameter.

The white, kaolinitic clay of unit 2 generally overlies the more sandy lower rocks. The clay has a blocky fracture, is of varying hardness (the harder varieties will not slake in water), and commonly lacks quartz. It consists mainly of kaolinite and trace amounts of halloysite (figs. 27 and 28). Iron-oxide stain, where present, occurs along joint planes.

An uncommon breccia was observed in part of an exposure of a hard white clay at locality 5. The sample shown in Figure 5 was sawed and stained to bring out the texture. It has many finely divided cracks and contains pieces of a finer-grained clay in a coarser clay matrix. The brecciated texture of the white, kaolinitic clay was not noted elsewhere in the state.

The white kaolinitic clay grades upward into a white, grayish-white, or buff, hard pisolitic clay. The clay has a blocky fracture, and pisolites in it are more numerous in its upper part. Quartz sand is generally absent.

The uppermost part of unit 2 is the iron-stained, hard, pisolitic clay (fig. 6). Generally it is three to five feet thick, regardless of whether it formed directly on the residuum or on sedimentary clays and sandy clays. Its maximum observed thickness is 15 feet (locality 8, Renville County). Texturally this rock type is the most distinctive in the sedimentary succession of unit 2 in that it resembles many bauxites. The matrix surrounding

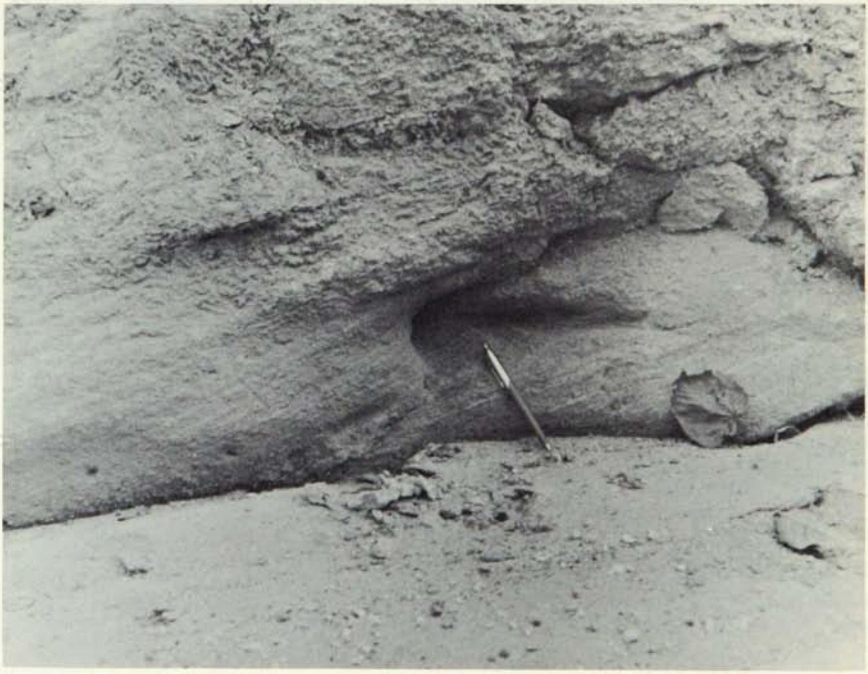


Figure 4. **Upper Cretaceous kaolinitic, cross-bedded, quartz sandstone exposed in a drainage ditch in the extreme northwest corner of Ochs Brick and Tile Company clay pit near Morton, Redwood County, locality 4. Cross-bedding direction is N. 20° E.; dip, 10° SE.**

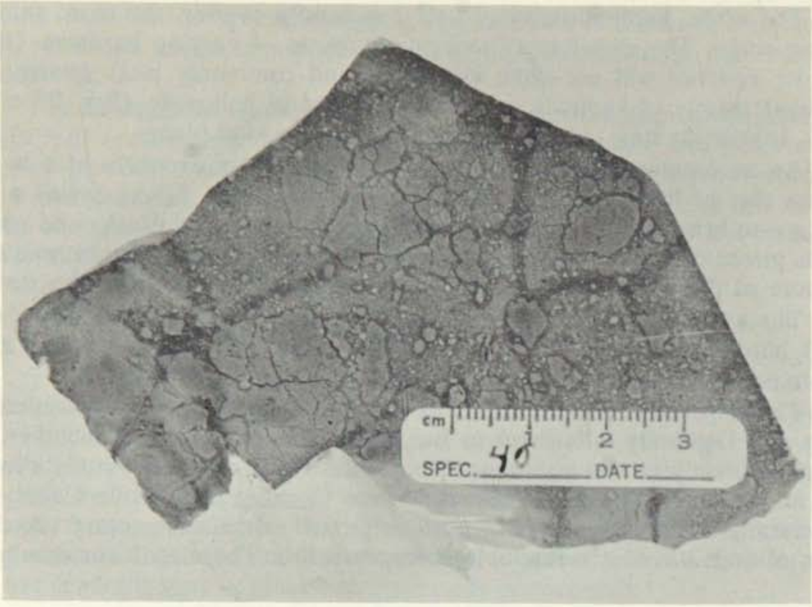


Figure 5. Stained, sawed section of Upper Cretaceous white, brecciated, kaolinite clay, Redwood County, locality 5, sample 40.

Figure 6. Iron-rich, hard, pisolitic kaolinite of Late Cretaceous age from sedimentary rock unit 2 (sample 42, locality 8). White matrix is poorly crystalline kaolinite and the clay fraction within pisolites is mainly poorly crystalline kaolinite with lesser amounts of gibbsite and boehmite.

the pisolites is a light gray or white clay and may have a translucent appearance. The pisolites are generally spherical, are iron-rich toward their outer surface and generally lack the iron-rich shell toward the base. Hematite, goethite, and possibly maghemite are present in the shell. Kaolinite occurs both in the matrix and within the pisolites; gibbsite is present within some pisolites and as surface coatings on others (fig. 7), and boehmite occurs less commonly within the pisolites. Pisolites having a diameter of as much as one and one-half inches have been observed, but most have diameters of one-half to one-quarter inch. Small pisolites enclosed in larger ones are common.

The iron-stained, hard pisolitic clay has been observed in the field or recognized in drill holes from Stearns and Morrison Counties in central Minnesota to Blue Earth County in the southeast, westward through Brown, Renville, Redwood, Yellow Medicine, and Lyon Counties, and north to Ottertail County[5]. It is resistant to erosion and forms ledges in outcrop (fig. 8), whereas the sedimentary rocks beneath it are softer and

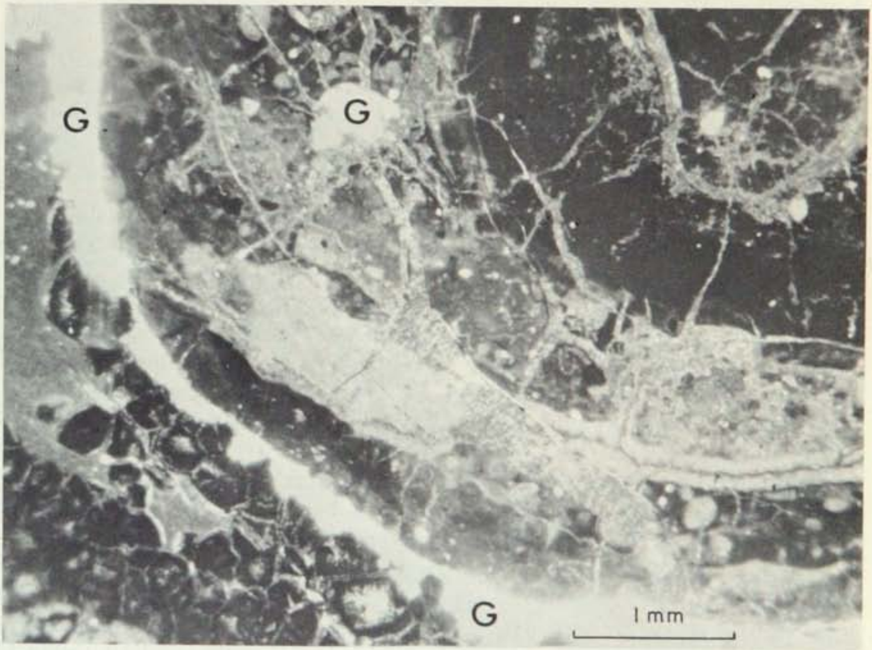


Figure 7. Photomicrograph of a thin-section of an Upper Cretaceous hard, iron-rich, pisolitic kaolinite clay (sample 42) showing pisolite structure. Gibbsite surrounds outer pisolite surface and occurs as scattered patches within. Photograph taken under crossed nichols. G=gibbsite.

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[5] Anderson, E. E., 1957, Petrography and petrology of some bedrock types in Becker and Ottertail counties, Minnesota: Unpublished Master's thesis, Univ. of Minnesota.

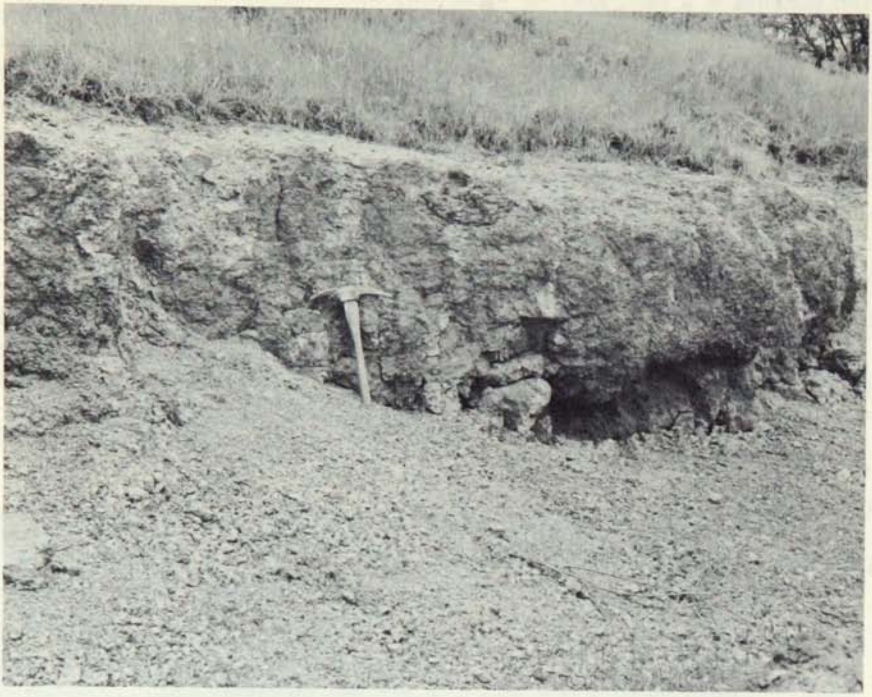

Figure 8. Upper Cretaceous hard, iron-rich, pisolitic kaolinite clay; forms ledges along valley walls of the Minnesota River and its tributaries, Renville County, locality 22. Pick length is 17 inches.

slump more easily. Pre-Pleistocene erosion and Pleistocene glacial scouring removed much of the overlying soft shales and clays. Commonly, glacial till lies directly on the hard pisolitic clay. The faults in the clay shown in Figure 9 are attributed to stresses resulting from glacial overriding; erosion of the upper surface of the bed is slight.

An incipient development of a pisolitic texture has been noted at a few localities in the clays and sandy clays that lie beneath the pisolitic clay. The pisolitic zones in this stratigraphic interval are thin and seem to be discontinuous laterally, however, and generally the pisolites are as soft as the enclosing material. Some of the pisolitic zones have a pale green color, but most have a white or buff matrix with iron stain outlining soft pisolites. It is not difficult to distinguish the lower poorly developed pisolitic units from the iron-stained hard one that caps the sedimentary rocks of unit 2.

Rocks of unit 3

The Upper Cretaceous organic-rich clays and shales (unit 3) lie disconformably on the pisolitic clay or less commonly on lower sedimentary strata of unit 2 (fig. 10). The lowermost sedimentary rocks of unit 3 are rich in kaolinite, but the upper stratigraphic part contains only minor kaolinite. The discussion here will be limited generally to the more kaolinitic parts of the sedimentary sequence.

Purplish gray or dark gray clay of very fine particle size generally comprises the basal part of the sedimentary rocks of unit 3. It probably does not exceed ten feet in thickness. It is well exposed along Crow Creek in Redwood County and as far north as locality 90 in Stearns County. Where bedding is lacking, the clay has the physical properties characteristic of ball clay, but where bedding or fissility is more prominent the clay lacks these properties. Ball clay is a gray, fine-grained, sedimentary, white-burning, plastic, kaolinitic clay. Sample 58 from locality 5 contains 77 percent less-than-two-micron material (Parham and Hogberg, 1964), a particle-size distribution typical of ball clays.

Lignites, as much as six inches thick, and lignitic clays occur as streaks or very thin beds in the lower part of unit 3. The detailed succession and thicknesses of the gray clays, lignitic clays and lignites, and gray shales differ locally as do their comparative contents of quartz sand. Figure 11 shows a typical sequence of the organic-rich sedimentary rocks and their lithologic succession in the lower part of unit 3.

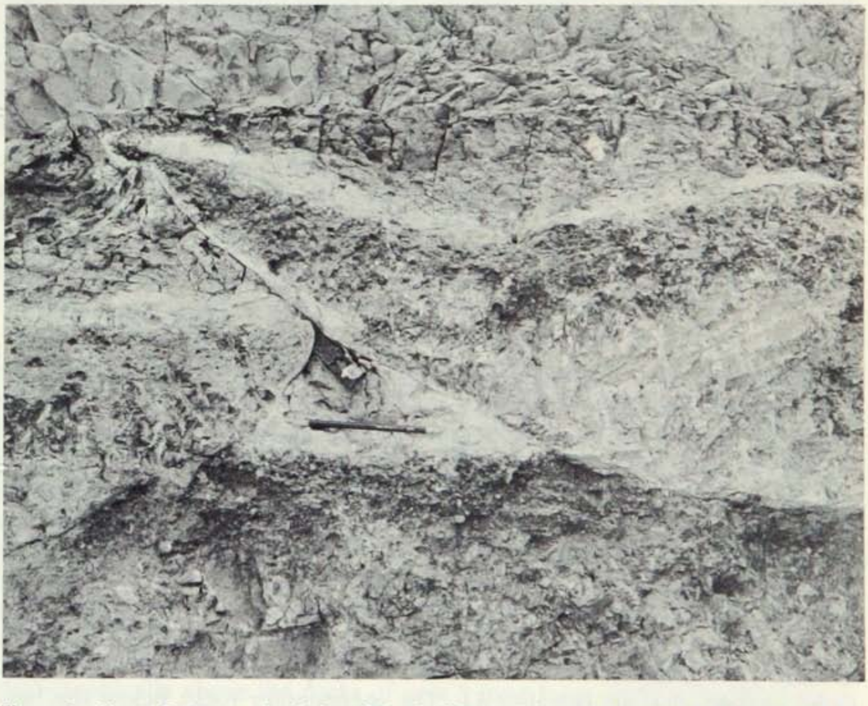

Figure 9. Upper Cretaceous hard, iron-rich, pisolitic kaolinite clay showing faulting caused by glacial overriding, Redwood County, locality 51. Upper Cretaceous bentonite, one-inch thick, rests on pisolitic kaolinite surface.

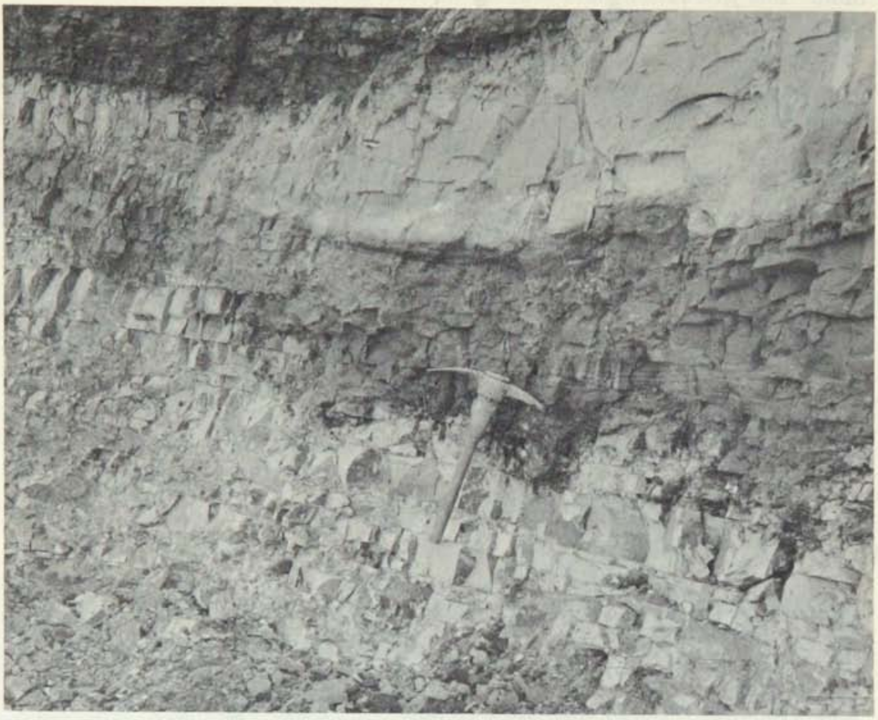

Figure 10. Disconformity between dark sedimentary rocks (unit 3) above and white block sedimentary kaolin clay (unit 2) below. Both are Late Cretaceous in age. Approximately seven feet of the sediments of unit 2 have been removed here by erosion, Redwood County, locality 4, along east wall of clay pit. Further north along east wall unit 3 sedimentary rocks rest directly on the hard, iron-rich, pisolitic kaolinite clay of unit 2 without a pronounced unconformity. Pick length is 17 inches.

At least one thin bentonite, reported to be as much as eight inches thick (Bergquist,[6]), has been observed in the lower part of unit 3 at localities 4 (fig. 11), 3, and 51. Possibly it is correlative also with the bentonite bed in the Ochs Brick and Tile Company clay pit southwest of Springfield in Brown County (locality 81). Test drilling of clay reserves by this company in the vicinity of their other clay pit near Morton has shown the presence of a thin bentonite at approximately the same stratigraphic position as those mentioned above. The bentonite beds range in color from a waxy dark green to yellowish green. As a consequence of glacial overriding, the clays, shales, and lignites above the bentonite layers are sheared and faulted, at least locally, as can be seen in some fresh cuts in the south face of the Ochs Morton clay pit (locality 4). The sedimentary rocks below the bentonite are generally undisturbed, suggesting that the bentonite behaved as

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[6] Bergquist, op. cit.

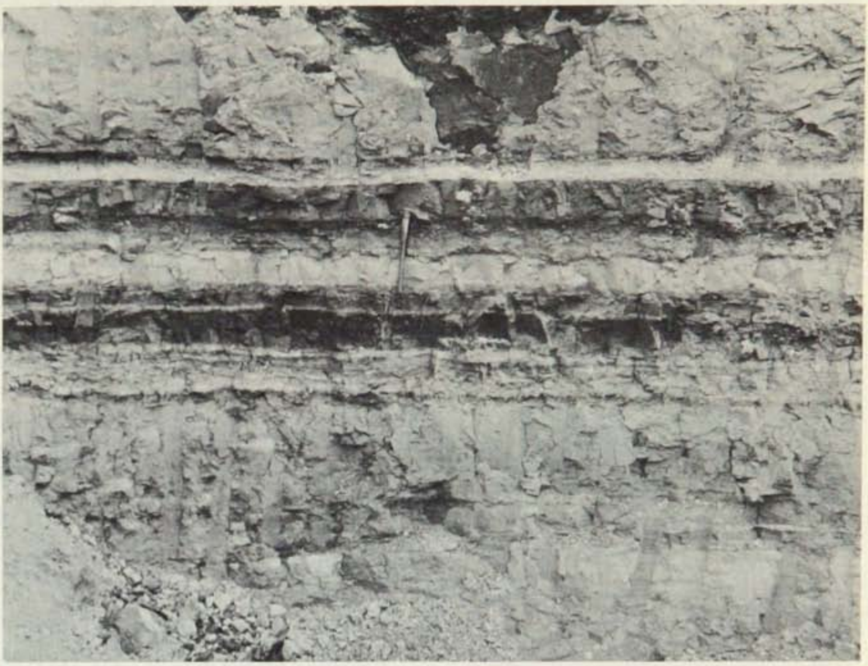

Figure 11. Upper Cretaceous sedimentary rocks of unit 3 exposed in south face of clay pit, locality 4, Redwood County. Bedding above white clay layer across center of photo has been disturbed by glacial overriding. A thin bentonite is present on the white clay band and directly below disturbed sediments. Pick length is 17 inches.

a shear surface. Deformation of the bentonite during shearing resulted in thickening and thinning of the bed.

The sedimentary units stratigraphically above the bentonite are characterized by alternating shale and laminated sand and clay, as exemplified at locality 81 (fig. 12) and locality 12. Well preserved fossil leaves of Upper Cretaceous plants were found in samples taken from the interval above the bentonite at three localities. The leaves were found in sample 76 from locality 50, sample 106 from locality 38, and a few in shale at locality 12. Macroscopic fossil plant fragments are common throughout other parts of the Upper Cretaceous shales and sandstones in Minnesota. A few thin lignites and underclays are present in the sedimentary sequence above the bentonite, but seem to be less common or even absent in younger Upper Cretaceous sedimentary rocks in the state.

Montmorillonite-rich, gray or gray-green marine shales are present stratigraphically above the rocks of unit 3 over large parts of southwestern, western, and northwestern Minnesota, but little is known of the mineralogy, paleontology, and stratigraphy of these rocks. Marine shales are known to exist also in north-central Minnesota, where they have been exposed in walls of several open-pit mines (Sloan, 1964). Sample 30, a composite of a 75-foot section of Upper Cretaceous marine shale in Itasca County (SE¼ SE¼ sec. 24, T. 57 N., R. 22 W.), contains pyrite concretions, and the clay mineral fraction is composed of montmorillonite, illite, and chlorite. Pyrite is present in the marine shales in southwestern Minnesota. Here the uppermost shales have clay mineral assemblages consisting mainly of montmorillonite and illite with lesser amounts of chlorite and kaolinite (personal communication, G. S. Austin, 1968).

Clays of the New Ulm Area

Upper Cretaceous sedimentary rocks in the vicinity of New Ulm consist of two lithologies: (1) red and green siltstones, shales, and clay-shales

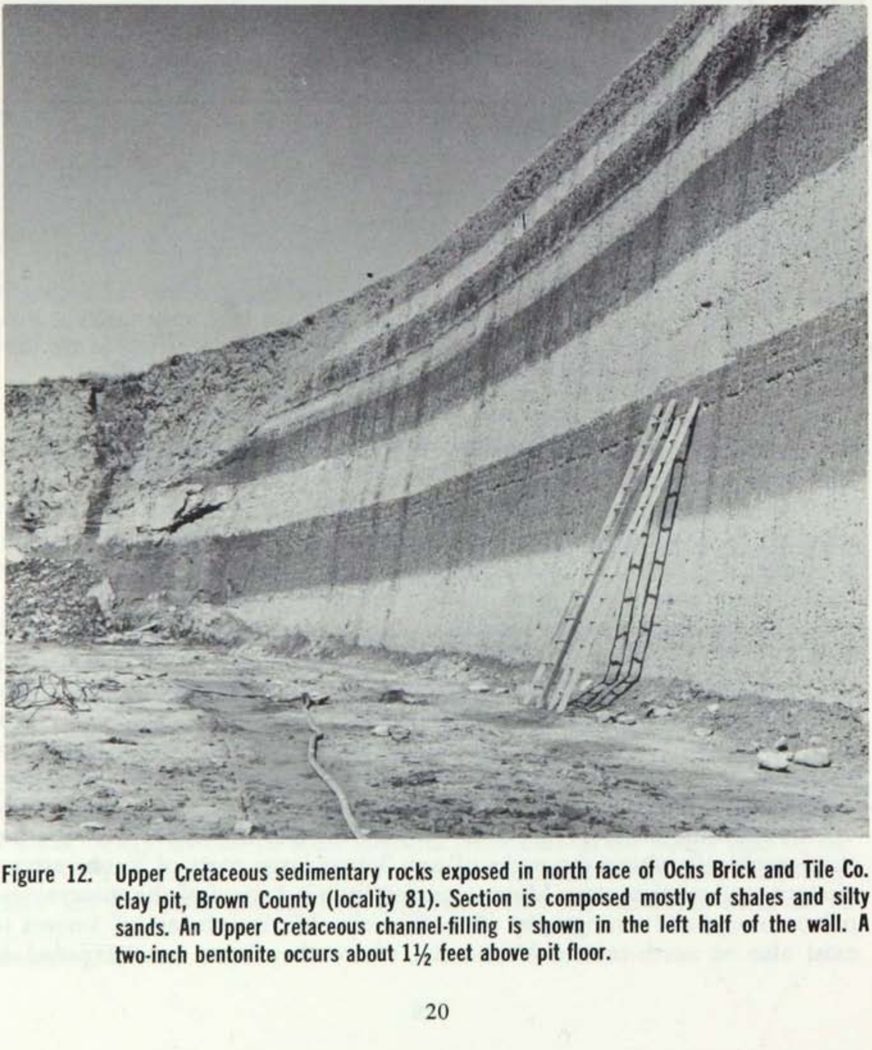

Figure 12. Upper Cretaceous sedimentary rocks exposed in north face of Ochs Brick and Tile Co. clay pit, Brown County (locality 81). Section is composed mostly of shales and silty sands. An Upper Cretaceous channel-filling is shown in the left half of the wall. A two-inch bentonite occurs about 1½ feet above pit floor.

that are interbedded with thin beds of nodular limestone (SW¼ NW¼ NW¼ sec. 35, T. 110 N., R. 35 W., Nicollet County), and (2) cross-bedded quartz sandstones (cen. NE¼ NE¼ sec. 4, T. 109 N., R. 30 W., Brown County).

The red and green argillaceous rocks have an exposed total thickness of about 15 feet, and are overlain directly by glacial drift. Individual limestone beds within the shales have maximum thicknesses of one to one and one-half feet, and are buff to light green. The red (sample 143) and green (samples 142 and 323) shales have essentially similar clay mineralogies; both are composed of illite and montmorillonite, with illite being slightly more abundant.

The clay mineralogy of thin clay seams associated with the cross-bedded quartz sandstones, on the other hand, is quite different from that of the red and green argillaceous rocks. A thin seam of light gray clay taken from sandstone (sample 144) is composed mostly of kaolinite with traces of illite and montmorillonite. A thin lignitic clay (sample 145), also from the cross-bedded sandstone, is composed mostly of kaolinite and lesser amounts of illite and montmorillonite.

Clays of the Goodhue-Wabasha Area

The Upper Cretaceous sedimentary rocks of the Goodhue-Wabasha County area were not well exposed during my studies, but have been exposed from time to time in the past in small shallow pits. The clays have been described as occurring as lenses within orange terrestrial sands of Late Cretaceous age (Austin, 1963). They are gray to white, some containing sand and having a clay mineral assemblage dominated by kaolinite but containing also substantial amounts of illite (samples 20, 21, and 289). To judge from a soft white clay (sample 289) that was uncovered in 1966 during shallow pipeline trenching in Wabasha County, it seems probable that other patches of Upper Cretaceous kaolinitic clays may be found at shallow depths further to the southeast of the old clay mining district.

Clays of similar occurrence and mineralogy to those of the Goodhue-Wabasha County area, which probably are also of Late Cretaceous age, occur as isolated patches beneath Pleistocene glacial drift in the vicinity of Hersey, Wisconsin, about 60 miles east of Minneapolis-St. Paul (Buckley, 1901). The clays were mined during the late 1800's and early 1900's for use in paper manufacture. The clay fraction was reported to be composed primarily of kaolinite.

Clays of the Austin Area

Thin discontinuous Cretaceous sedimentary clays that lie at shallow depths occur in Mower County in the vicinity of Austin. The clays fill depressions in the Devonian Cedar Valley Formation, and are generally rust-red in color but may be mottled with pale green and white. A few one-or two-inch beds of clean quartz sand are present in the clays. Generally, the clays are slightly richer in kaolinite than illite. The presence of a cover of glacial drift together with the fact that the clays are discontinuous makes detailed geological study of them difficult. Clay mineral analyses of Cretaceous clay samples from this area are listed under Mower County in Appendix C.

Pleistocene Glacial Sediments

Glacial till, sand, gravel, and organic accumulations of Pleistocene age overlie most Precambrian and Cretaceous rocks in Minnesota. The maximum recorded thickness of Pleistocene deposits in the Redwood Falls area, 263 feet, occurs in the deepest part of a buried pre-Pleistocene bedrock valley at NW¼ NW¼ SE¼ sec. 13, T. 112 N., R. 36 W. (Schiner and Schneider, 1964) that is marginal to the Minnesota River Valley. The glacial deposits in the buried valley lie directly on fresh Precambrian rock. Within the Minnesota River Valley and some of its tributaries, the glacial deposits have been largely removed, exposing either fresh or partly weathered Precambrian rocks, which now occur as irregular patches on the floor of the valley. Highly weathered bedrock is poorly preserved within the valley because of its low resistance to erosion by running water. Potholes, generally a foot or two in diameter and in depth are developed in fresh gneiss and granite and occur along the length of the valley floor.

Some of the bedrock knobs that stand above the generally flat valley floor have acted as natural sediment traps, and on their downstream side beds of coarse boulders, gravel, and sand have been deposited. One such deposit west of Morton was mined until recently as an aggregate source by the Morton Aggregates Company at NW¼ NW¼ NW¼ sec. 36, T. 113 N., R. 35 W. (fig. 13). Aerial photographs show a feature with similar surface expression at the small oval-shaped rise just to the north, in SW¼ SW¼ SW¼ sec. 25, T. 113 N., R. 35 W. Both of these localities are on the downstream side of an irregular Precambrian bedrock knob that is half a mile wide. Maximum altitude of the bedrock high is 920 feet, whereas both the downstream boulder deposits have relatively flat tops at an altitude of 880 feet. Both upstream and downstream from this locality similar flat-topped features are present on the downstream sides of other bedrock highs, and should be considered potential sources of coarse aggregates within the valley proper. The locations of four such areas are:

1) Redwood County, SW¼ NW¼ sec. 29, T. 114 N., R. 36 W.
2) Redwood County, SE¼ sec. 19, T. 113 N., R. 35 W.
3) Redwood County, SW¼ sec. 14, T. 112 N., R. 34 W.
4) Redwood County, NW¼ NE¼ sec. 23, T. 112 N., R. 34 W.

The coarse sediments were deposited by a precursor of the present-day Minnesota River, glacial River Warren, once a powerful river formed by the outflow of water from glacial Lake Agassiz, which had occupied large parts of western and northwestern Minnesota. Erosion by River Warren

Figure 13. Water-deposited Pleistocene boulders, gravel, and sand exposed in pit, Renville County (locality 65). The sediments were deposited by glacial River Warren.

cut through older valley sediments that had been deposited at higher altitudes along what is now the Minnesota River. Some of the older sands and gravels now cap terraces which are developed on the older glacial till cover of the uplands (fig. 14). Two examples of well developed terraces occur along the south bluff of the Minnesota River, along the south boundary of the Lower Sioux Indian Community, and along the bluff top between Delhi and Redwood Falls. These terraces occur at an altitude of about 980 feet. The Lower Sioux Indian Community itself is situated on a slightly higher terrace having an altitude of about 1000 feet. Remnants of other terraces occur at altitudes of 900 feet (cen. E½ sec. 10, T. 113 N., R. 36 W.) and 860 feet (S½ sec. 11, T. 113 N., R. 36 W.).

Numerous small, inactive gravel pits are scattered along the edge of the bluff in the vicinity of the Lower Sioux Indian Community at the 1000-foot level. The coarse fraction of these sediments commonly contains many fragments of a gray to gray-green, hard, fissile, montmorillonitic shale. The shale fragments do not resemble any other Cretaceous shale thus far encountered in Minnesota. The clay-sized fraction of the shale contains a substantial amount of disordered cristobalite, the type described by Schultz (1964), which also serves to distinguish them from Minnesota's analyzed Upper Cretaceous shales. Lithologic and mineralogic descriptions of the

Figure 14. Pleistocene terrace gravels along the south side of the Minnesota River Valley near Morton, NE¼ NE¼ sec. 22, T. 112 N., R. 34 W., Redwood County.

Pierre Shale (Schultz, 1964, 1965) of South Dakota and adjacent areas suggest that the shale pieces were derived from the Pierre Shale.

The thickest section of terrace gravel observed during this study—55 feet—occurs on the east side of Crow Creek (locality 47). The gravel serves as a source for ground water supply for farm wells. Information from local water-well drillers and data from Schiner and Schneider (1964) indicate that most water obtained from the Pleistocene sediments is hard, whereas water from wells completed in the weathered Precambrian rocks is soft. Wells in the Pleistocene sands and gravels, however, yield larger water supplies than do those in the residuum.

Deposits of tufa, a spongy, white, porous limestone, are present along many tributaries of the Minnesota River in the Redwood Falls-Morton area. The tufa was formed by evaporation of calcium carbonate-bearing spring water along the contact between permeable glacial deposits and various underlying impermeable bedrock types in the valley walls. The tufa occurs as a thin deposit, as much as a foot thick, just below spring outlets.

Beneath the terrace gravels and covering the uplands north and south of the Minnesota River are alternating units of montmorillonitic till and silts, sands, and gravels. Pleistocene sections along the north bluff of the Minnesota River south of Franklin at NW¼ NW¼ SW¼ sec. 12, T. 112 N., R. 34 W. consist of a calcareous till approximately 50 feet thick that is buff colored in the upper oxidized part and blue-gray in the lower unoxidized part. The till lies on approximately 50 feet of cross-bedded silty-sands (fig. 15) and cemented gravels. The top twenty feet of a brown to gray calcareous till is exposed here beneath the sands and gravels. By contrast, the Pleistocene section exposed in the south face of the Ochs Brick and Tile Company clay pit southwest of Morton (locality 4) is 46 feet thick and consists of several alternating units of calcareous till and silty-sand. The thickest till unit is ten feet; the thickest sand unit five and one-half feet. The beds of till in the upper part of the section are buff to brown and those below are gray. No attempt has been made in this study to correlate stratigraphic units of the glacial deposits throughout the region. The Pleistocene sections described above merely serve as examples of the degree of variation in the lithologic sequence that can be expected in the glacial drift of this area. Recognition of such lithologic variations is an important factor in planning for successful open-pit mining of the underlying kaolin clays. Ease of removal of overburden, stability of pit walls, and water content of the sands and gravels would be related to lithologic variations of the glacial deposits.

Water-well drillers working in the region of Olivia in Renville County and south to the Minnesota River Valley report that glacial-drift gas is common within the Pleistocene sediments. It is not unusual for pieces of Pleistocene age wood to be recovered during drilling operations in the Redwood Falls-Morton area, from depths 85 to 90 feet below the level of the upland surface. Glacial-drift gas is generally considered to be derived from decomposition of buried organic-rich materials such as wood, peat,

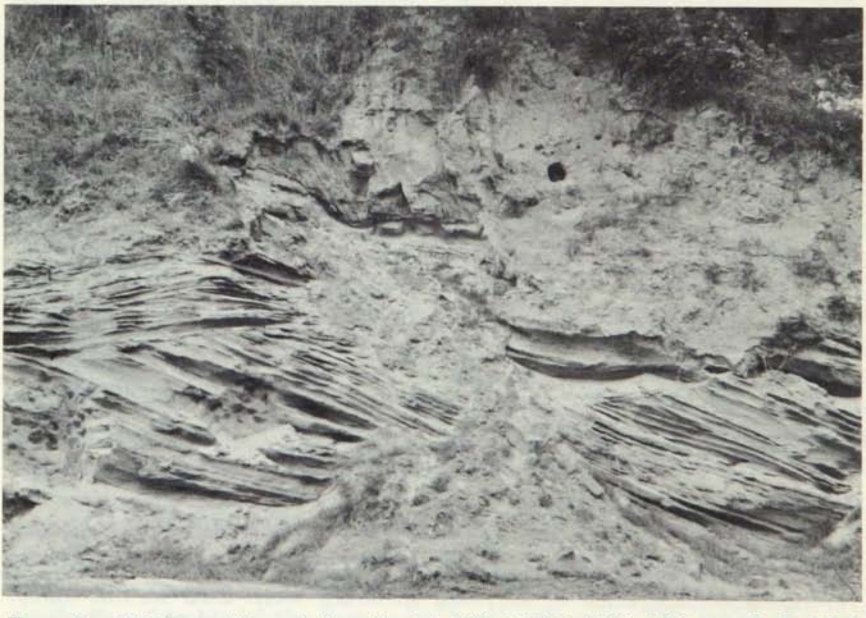

Figure 15. Pleistocene silty-sands beneath glacial till at NW¼ NW¼ SW¼ sec. 12, T. 112 N., R. 34 W., Renville County.

or organic-rich silts. Meents (1960) studied numerous occurrences of glacial-drift gas in Illinois and found the gas primarily composed of methane and lesser amounts of nitrogen. He stated: "The gas is believed to be derived from buried soil zones and from organic matter in deep buried valleys. The glacial end moraines control the accumulation of drift gas by providing a cover of glacial till thick enough to prevent escape of gas."

It is not known whether the glacial-drift gas in this part of Minnesota has accumulated only under the terminal moraines of low relief, or has accumulated over a wider area and is trapped by thick overlying till sheets.

CLAY MINERALOGY

Sample Preparation for X-ray Analysis

Clay-mineral oriented aggregates were prepared on glass slides from the less-than-two-micron fraction e.s.d. (estimated spherical diameter) of each sample. Each raw sample was disaggregated, dispersed in distilled water and allowed to stand for ten minutes, after which an eyedropper was touched to the surface of the dispersion and enough of the suspension was removed to completely cover the glass slide. The slides were then air dried. A part of the same clay-water suspension was collected for examination with the electron microscope, to determine the morphology of the clay minerals and to determine whether the decanted clay fraction was in fact representative of the less-than-two-micron-size fraction. In those samples in which the clay minerals were essentially equidimensional plates, the large diameters of most of the particles grouped around 1.5 to 2.0 microns, and only small amounts of coarser fractions were present. The estimated spherical diameter of samples containing lath or tube-shaped clay particles, however, is difficult to evaluate.

The clay slides were x-rayed from 2° to 32° 2θ and then rerun from 2° to 15° 2θ after the slide had been subjected to a warm ethylene glycol atmosphere for approximately 24 hours. Certain samples containing montmorillonite or abundant mixed-layer clay material were x-rayed under controlled conditions of high and low humidity as outlined by Milne and Warshaw (1956). X-ray diffraction records of powder mounts were made on selected samples. X-ray machine settings used for both oriented-aggregate slides and powder mounts were 40 KV and 20 ma, and goniometer speeds ranged from ¼° 2θ per minute to 2° 2θ per minute. Diffraction peaks on each x-ray record were recorded on a linear scale and Ni filtered copper $K\alpha$ radiation was used throughout the study.

Sample Preparation for Electron Microscopy

Electron micrographs, both of replicas of fractured rock surfaces and grid-mounted-dispersions of clay-size material, were used in this study. Direct-carbon replicas of fractured clay surfaces were satisfactory for producing good quality electron micrographs. The clays were dispersed in distilled water and a drop of the dilute suspension was mounted on a collodion substrate covering an electron microscope grid. Electron micrographs were taken of portions of the less-than-two-micron clay taken from selected suspensions at the time of preparation of x-ray slides. Certain samples were shadowed with carbon and/or palladium on a rotating stage. A Norelco Phillips 100-A electron microscope was used throughout the study with accelerating voltages of 80 KV.

Problems of Clay Mineral Identification

Halloysite is sometimes difficult to identify using x-ray techniques. It may be present in a sample in the fully hydrated state, halloysite·$4H_2O$, but most commonly in the samples studied it is in the form halloysite·$2H_2O$. The presence of substantial amounts of halloysite·$2H_2O$ in a sample may be partly or completely masked during x-ray analysis by the presence of kaolinite because kaolinite and the dehydrated form of halloysite have a basal spacing of approximately 7 Å as well as other similar diffraction peaks. The fully hydrated form, on the other hand, has an approximate basal spacing of 10 Å and can be readily distinguished from kaolinite by x-ray diffraction techniques, and can be differentiated from other 10 Å minerals, muscovite and illite, by heat treatment at relatively low temperatures. The 10 Å peak of hydrated halloysite, after being heated to 300° C. for one hour, collapses to about 7 Å, whereas the 10 Å peak of muscovite and illite is not affected. Halloysite·$2H_2O$, which gives broad diffraction maxima similar to poorly crystalline kaolinite, is difficult to identify when mixed with poorly crystalline kaolinite, and identification is even more difficult when halloysite is present in small amounts (Brindley and others, 1963). Small amounts of halloysite are readily distinguished from plate-shaped, pseudohexagonal kaolinite flakes with the electron microscope.

Samples collected from widely scattered localities were studied with the electron microscope to determine general vertical and lateral variations of the kaolin minerals and their morphology throughout the residuum. The absence of halloysite from many samples listed in Appendix C and Appendix D does not preclude its presence, because a substantial number of samples were not examined with the electron microscope, and x-ray diffraction alone is inadequate for identification of small amounts of halloysite·$2H_2O$ where kaolinite is abundant.

Clay-size muscovite and illite are generally present in partly weathered granite gneisses and other similar weathered rock types. Differentiation of muscovite from illite in this report is based on a combination of x-ray peak height and peak sharpness of the first order basal reflection of x-ray diffraction records. X-ray peaks of the 10 Å clay mineral from the least weathered rocks are generally narrow and intense and most closely resemble the diffraction records of muscovite. The 10 Å material in the more weathered zones gives weak, broad diffraction maxima and may show asymmetry on the low 2θ side of the first order basal reflection. The latter clay material is referred to here as illite. It is very probable that there is a complete gradation between muscovite and illite as characterized here, and this is to be expected; the weak, broad, asymmetric peaks are a result of a more advanced stage in the breakdown of muscovite due to weathering.

Kaolinite Crystallinity, and Kaolinite and Halloysite Particle Shape

The morphology of the clay platelets may be related in some cases to kaolinite crystallinity, as measured by x-ray diffraction, that is, the more crystalline the kaolinite, the more regular the shape of the pseudohexagonal kaolinite platelets; sometimes, however, this relationship does not hold true (Robertson, Brindley, and MacKenzie, 1954; O'Brien and Orlopp, 1964). Variations in the crystallinity of kaolinite from Minnesota were measured (Parham and Hogberg, 1964) using the x-ray technique of Hinckley (1963). Considerable variation in kaolinite crystallinity was noted using this technique; however, at that time none of the samples had been examined with the electron microscope. Even though some samples contain only small amounts of halloysite, it is likely that such crystallinity values may be more a function of halloysite content than a true measure of kaolinite crystallinity.

Residuum—Unit 1

General discussion

Kaolinite comprises the major part of the clay-size fraction (less-than-two-micron) of the residuum. Halloysite, montmorillonite, muscovite, and illite are common minerals that occur in small amounts in some samples.

Kaolinite and halloysite are closely associated in their formation with weathered feldspars in the residuum. Kaolinite and halloysite in some cases have formed on different cleavage surfaces of the same partly weathered feldspar crystal. The clay minerals and feldspars are discussed together in the following pages to emphasize their close association. In order to determine the relationships among the three minerals, crystals of partly weathered K-feldspar were examined in detail with the electron microscope. In addition, the clay-sized fraction of a number of samples taken from the residuum at various localities was examined with the electron microscope. The general morphology of some of the kaolinite and halloysite crystals in these samples is illustrated in the following pages.

Halloysite, kaolinite and weathered feldspar

Partly weathered feldspar crystals, one to two inches in diameter, are present in the weathered Morton Gneiss at locality 74 along Birch Coulee, Renville County. The feldspars have a bleached white color and can be broken easily with the fingers, yet maintain some of the outward form of the fresh mineral. Powder x-ray diffraction data indicate that these crystals are composed of microcline feldspar and lesser amounts of kaolinite. Most of the potassium feldspars of the fresh gneiss are microcline perthite (J. A. Grant, personal communication, 1968).

Small pieces of some of the larger partly weathered feldspar crystals were broken and electron micrographs of replicas of the (001) cleavage surface and the probable (010) and (100) cleavage surfaces were prepared. Precise determination of the (100) and (010) surfaces was difficult because of the degree of alteration of the feldspar.

Kaolinite is present in several forms in the residuum. It is generally irregular in outline in the least weathered parts of the residuum, but more commonly forms lath-shaped platelets upward in the section. The laths may have straight edges or may have a saw-tooth appearance. The saw-tooth edges result from overlap of small pseudohexagonal plates among the laths' edges. Upward in the residuum, much of the kaolinite commonly occurs as two varieties of pseudohexagonal plates. The first is plate-like but its overall outline is irregular. The irregular plates, one to two microns in diameter seem to consist of a mosaic of smaller pseudohexagonal platelets (fig. 16).

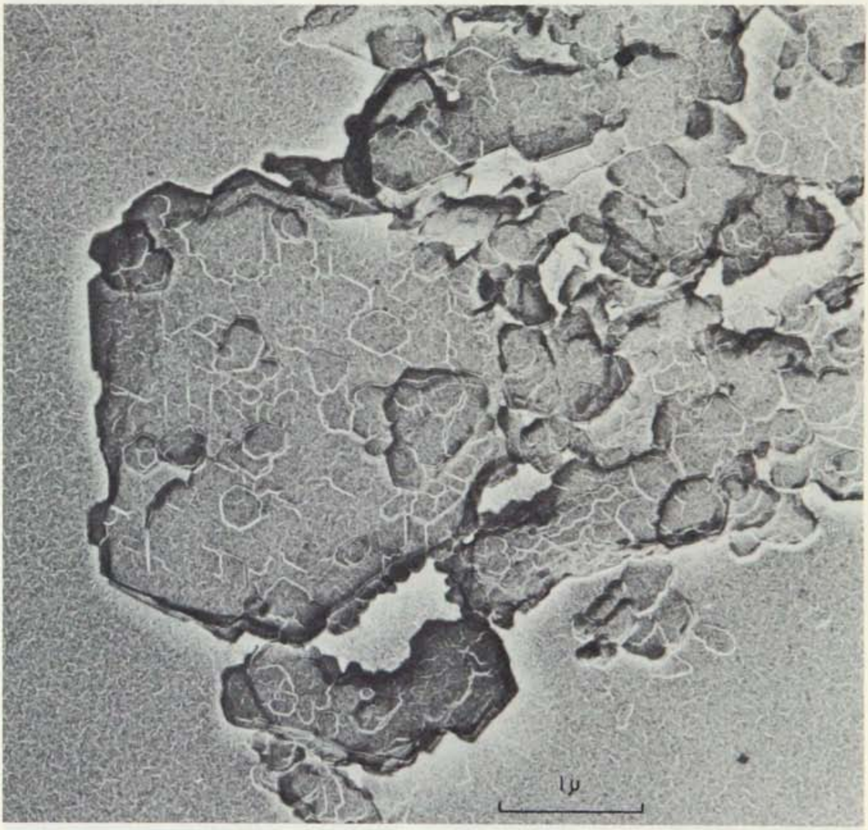

Figure 16. Electron micrograph of kaolinite from weathered gneiss, Redwood County, sample 104, locality 52. Larger kaolinite plates exhibit mosaic or alligator-skin texture. Clay dispersion Pt-Pd and C coated.

The smaller flakes form segments of the larger crystal, lending a broken outline to the appearance of the larger flakes. The second variety occurs as regularly shaped, pseudohexagonal plates which may occur in thick stacks. Kaolinite exhibiting this form (figs. 17, 18, and 19) is more common in the upper parts of the residuum. The kaolinite shown in Figures 17, 18, and 19 most probably formed from the weathering of granite gneiss.

Replicas of the (001) surface of partly weathered K-feldspar generally show flat-lying pseudohexagonal kaolinite plates (fig. 20), however, in some cases tubular halloysite may be admixed. Halloysite shows no preferred orientation here, and where halloysite is present it is always subordinate in amount to kaolinite. Replicas made from some of the inferred (010) surfaces (fig. 21) show randomly oriented assemblages of tubular halloysite with small amounts of platy kaolinite. The halloysite tubes may have been dislodged from the feldspar surface when the feldspar was

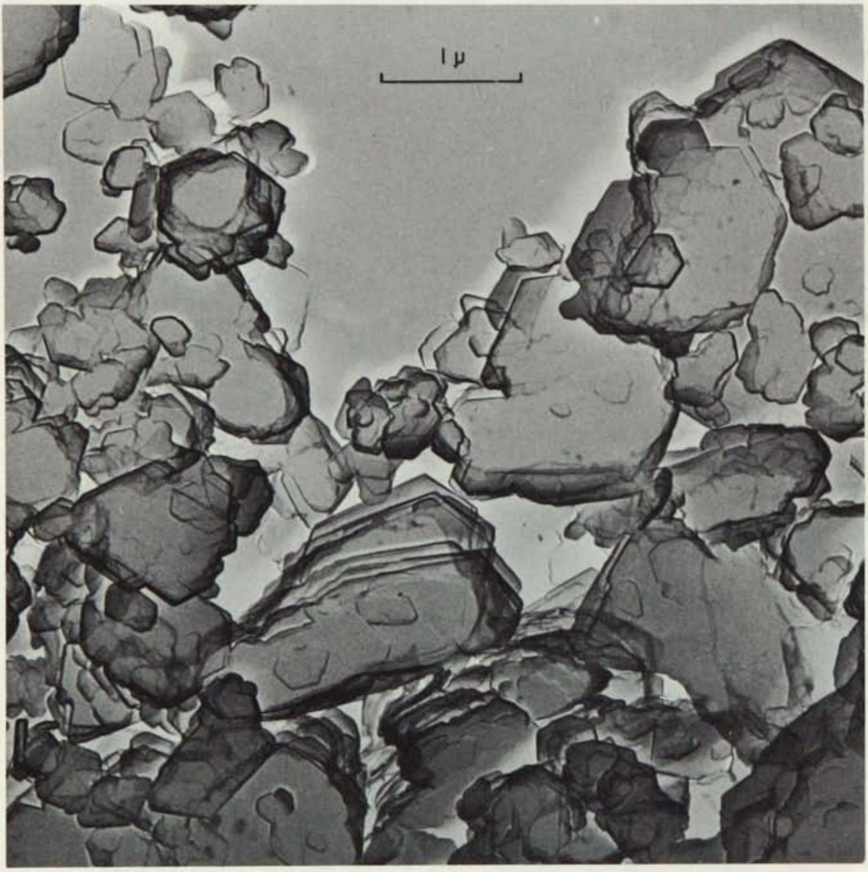

Figure 17. Electron micrograph of well-formed pseudohexagonal kaolinite, Renville County, sample 44, locality 14. Clay dispersion C coated.

Figure 18. Electron micrograph of pseudohexagonal kaolinite from weathered gneiss, Brown County, sample 49, locality 13. Clay dispersion C coated.

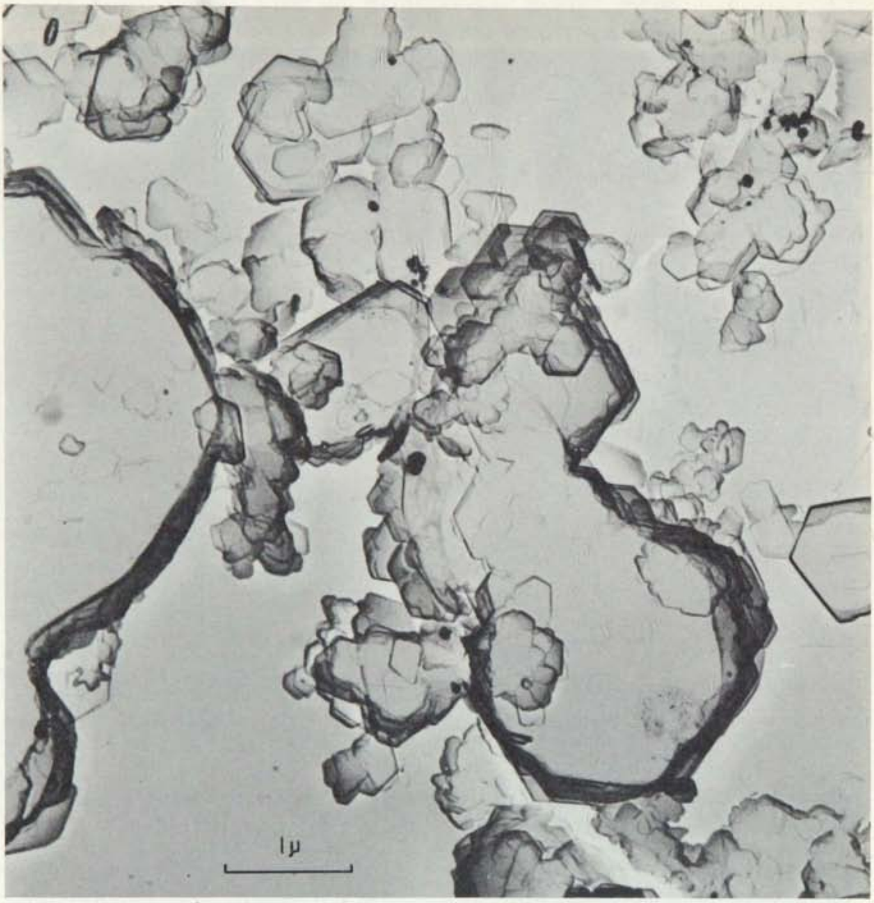

Figure 19. Pseudohexagonal kaolinite, Yellow Medicine County, sample 263, locality 87. Clay dispersion C coated.

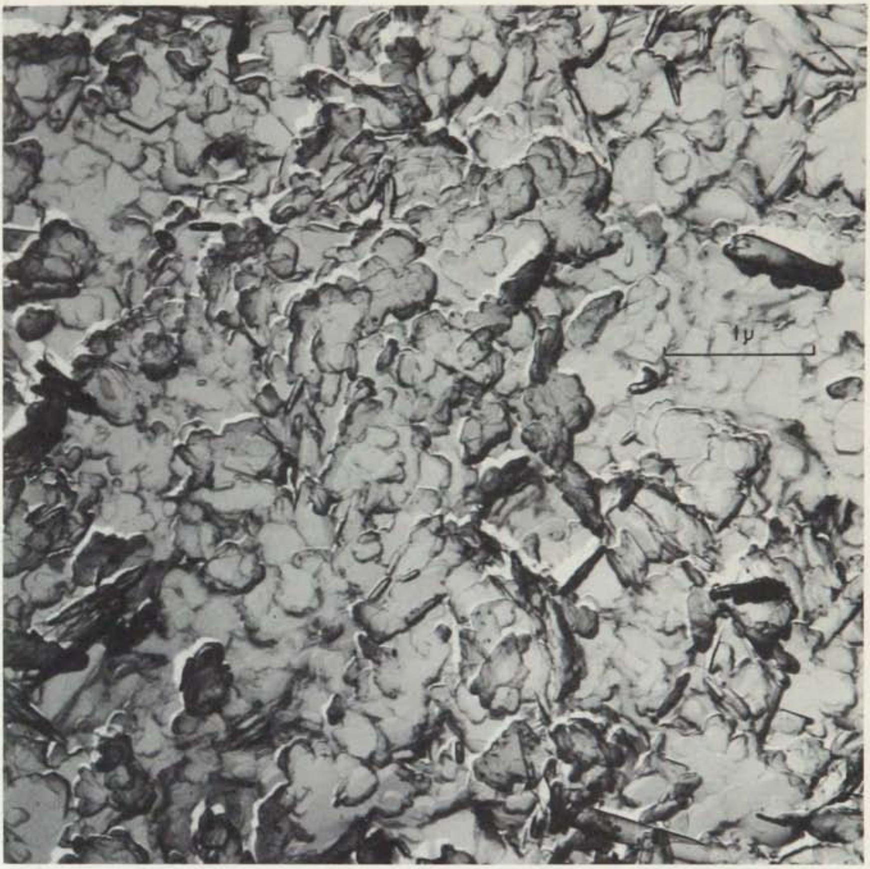

Figure 20. Carbon replica of a cleavage surface parallel to (001) of weathered microcline, Renville County, locality 74. Surface covered mostly with pseudohexagonal kaolinite plates.

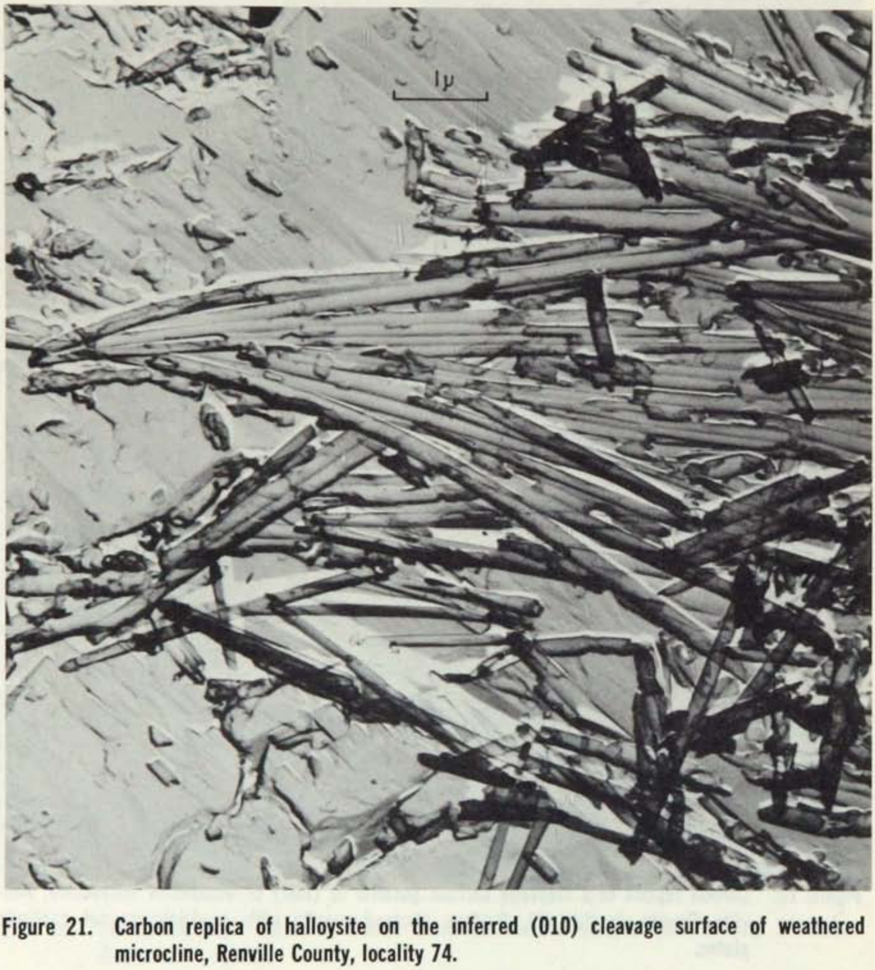

Figure 21. Carbon replica of halloysite on the inferred (010) cleavage surface of weathered microcline, Renville County, locality 74.

cleaved. This interpretation is supported by the fact that other replicas of the (010) feldspar surface commonly show preferred orientation of halloysite tubes (fig. 22). There is a definite tendency for the long axes of halloysite to lie parallel to the intersection of the (001) and (010) cleavage planes. If the ends of the halloysite tubes intersect the (100) cleavage plane, replicas of the (100) surface should show endwise views of the tubes. No replicas showing such relationships were observed; however, it is possible that good surface expression of the (100) surface was not obtained. In addition, preferred orientation of halloysite is not obvious on replicas which show a substantial thickness of clay alteration and where little feldspar is visible in the background.

Halloysite occurs as long prismatic crystals of polygonal cross-section (fig. 23). Halloysite tubes may reach lengths of as much as 20 microns in the residuum, and tube widths vary from 0.03 to 0.27 microns. The length-

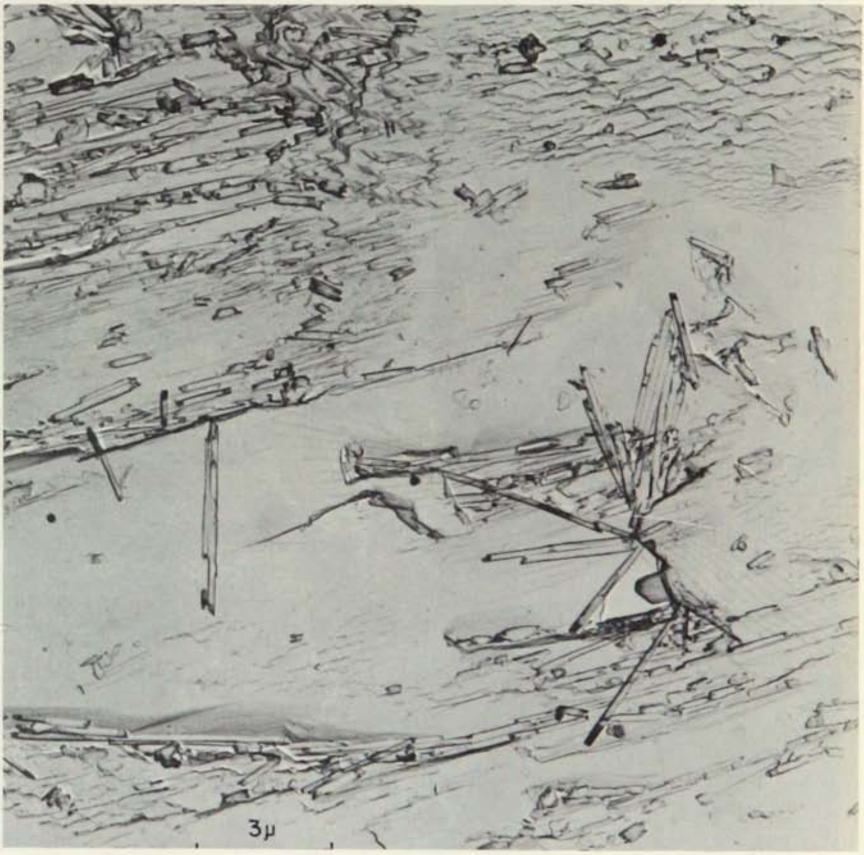

Figure 22. Carbon replica of halloysite developed on inferred (010) cleavage surface of weathered microcline, Renville County, locality 74.

to-width ratio for halloysite tubes prepared from clay dispersions is generally 4:1. This ratio is very likely merely related to halloysite tube-breakage during sample preparation.

Trace amounts of halloysite resembling a "wheel and axle" (figs. 24 and 25) are present in the residuum. This form has not been identified as halloysite by x-ray diffraction because of the small amount present, but it does resemble the tube-within-tube form characteristic of some halloysite crystals, and therefore it is included here with halloysite.

Kaolinite is the clay mineral commonly formed from highly weathered mafic rocks of the residuum. A highly weathered amphibolitic facies of the Morton Gneiss (fig. 3) contains well formed, pseudohexagonal, kaolinite platelets approximately ¼ micron in diameter (fig. 26). Whether this morphology is characteristic of kaolinite formed from mafic rocks in general is not known; very few occurrences of weathered mafic rocks were found.

Figure 23. Carbon replica of halloysite developed on weathered microcline. Halloysite crystals have a prismatic form and a polygonal cross-section. Renville County, locality 74.

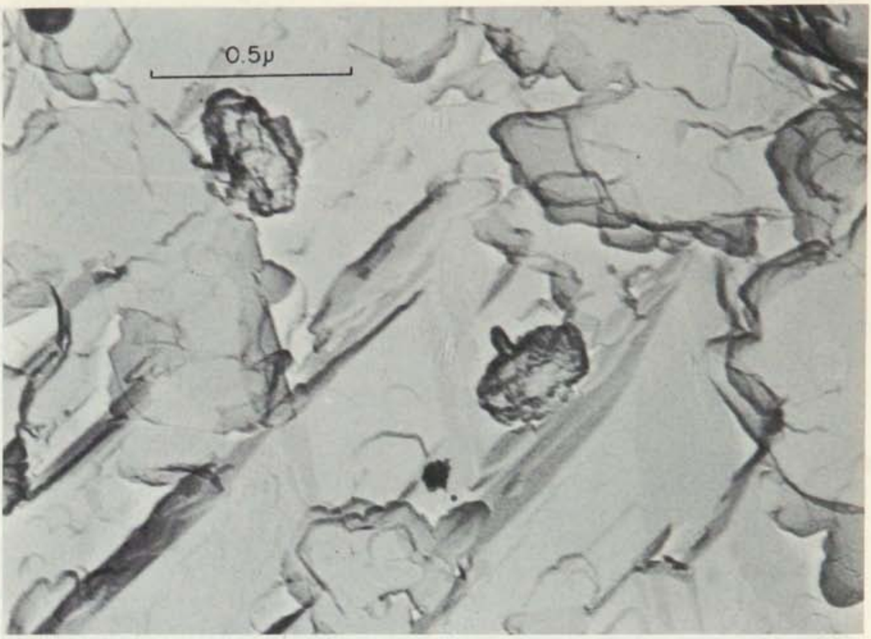

Figure 24. Carbon replica of "wheel and axle" halloysite(?) formed on the (001) cleavage of weathered microcline, Renville County, locality 74.

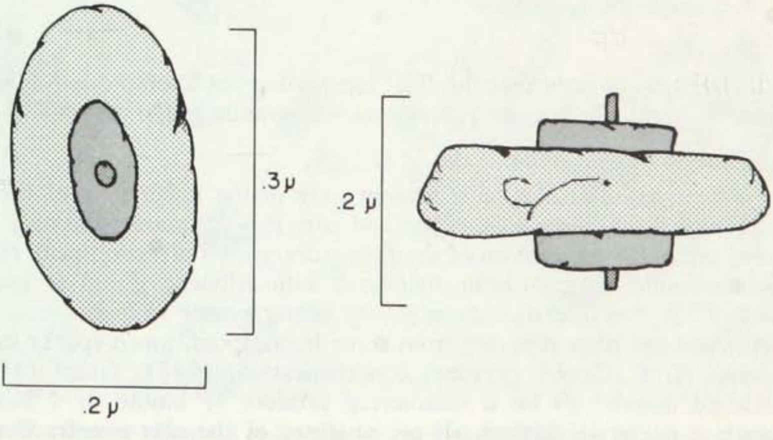

Figure 25. "Wheel and axle" form of halloysite (?).

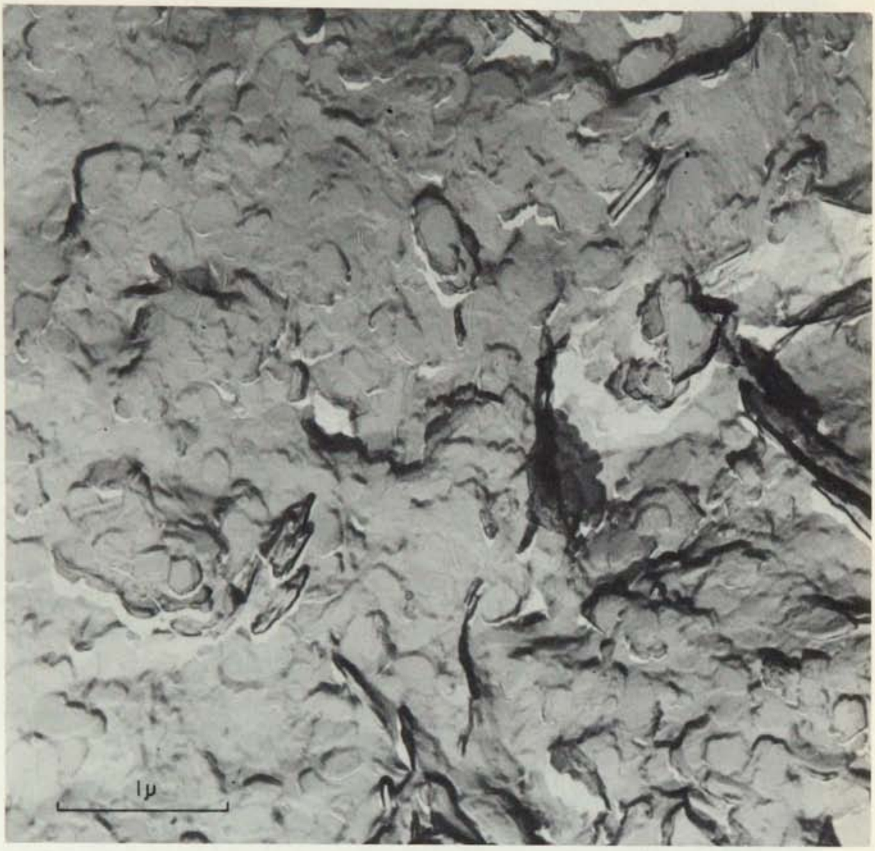

Figure 26. Carbon replica of a fractured surface of weathered amphibolite, Renville County, sample 324, locality 74.

It does suggest, though, that the final morphology of kaolinite is not significantly different whether the parent rock was granite gneiss or amphibolite.

Montmorillonite and amesite

Calcium montmorillonite is present only in the lower part of the residuum near fresh mafic rock types, and here it is commonly the only clay mineral present. The position of the first order x-ray diffraction peak of the montmorillonite after 24-hour treatment with ethylene glycol is usually close to 17 Å, but in certain cases it may center nearer 16.5 Å.

Amesite has been reported from some handpicked, green specks in the residuum (I. E. Odom, personal communication, 1968). Grant (1964) considered amesite to be a weathering product of biotite in a biotite-plagioclase gneiss in Georgia. X-ray analyses of the clay-size fraction of samples of Minnesota's residuum did not show the presence of amesite;

however, Grant (1964) noted in his Georgia study that because the x-ray diffraction peaks are similar for amesite and kaolinite, small amounts of amesite may be masked by kaolinite. Examination of the less-than-two-micron fraction of pale green samples of the residuum with both x-ray diffraction and the electron microscope failed to provide definite evidence of the presence of amesite. Amesite may occur as irregular flakes or as dense rod-like crystals when observed with the electron microscope (Beutelspacher and van der Marel, 1968). It is possible, therefore, that small amounts of amesite could be mistaken for poorly formed kaolinite or tubular halloysite in the clay-size fraction. It is unlikely though that amesite is present in many samples which have pale green colors and in which only well-formed pseudohexagonal plates were seen.

Sedimentary Rocks of Unit 2

The sedimentary rocks of unit 2 have a clay mineral composition of kaolinite and halloysite. Small amounts of the non-clay minerals gibbsite ($Al_2O_3 \cdot 3H_2O$) and boehmite ($Al_2O_3 \cdot H_2O$) are confined to the pisolitic kaolinite layer that marks the top of the rock sequence.

Kaolinite from these sedimentary clays generally has a fair to good pseudohexagonal outline (fig. 27). Fragments of halloysite tubes, shown also in Figure 27, are present in very small amounts. Replicas of freshly broken surfaces of unit 2 kaolinite-rich sediments show that the kaolinite plates have preferred orientation within small domains, but that the domains

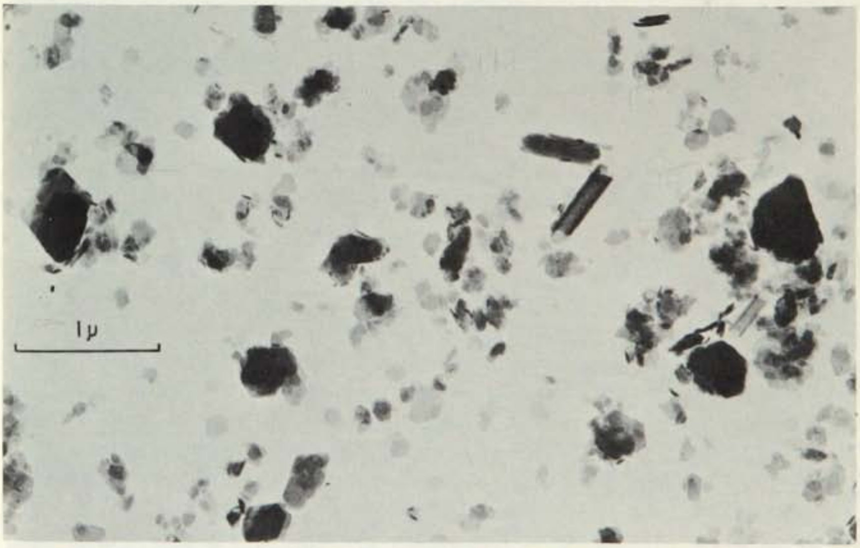

Figure 27. Electron micrograph of the clay fraction from kaolinitic clay of unit 2, sample 38, locality 5, Redwood County. The hexagonal plates are kaolinite and the scattered tube fragments are halloysite.

have random orientations with respect to one another. A part of one such domain is shown in Figure 28. The pseudohexagonal outline of kaolinite in the sedimentary clays generally appears less perfect than in the residuum (unit 1). Some edges of the kaolinite plates from unit 2 are slightly irregular, suggesting that the kaolinite crystals have undergone some abrasion during transport.

X-ray diffraction patterns of the clay-size fractions of the pisolitic kaolinite clay are characterized by poorly crystalline kaolinite, minor amounts of gibbsite, and trace amounts of boehmite. The most diagnostic x-ray peaks for the latter two minerals are 4.85 Å at 18.3° 2θ (gibbsite), and 6.11 Å at 14.5° 2θ (boehmite). Poorly crystalline kaolinite forms the white to pale blue-white matrix surrounding individual pisolites. It also predominates over gibbsite and boehmite within the pisolites. The ragged outline

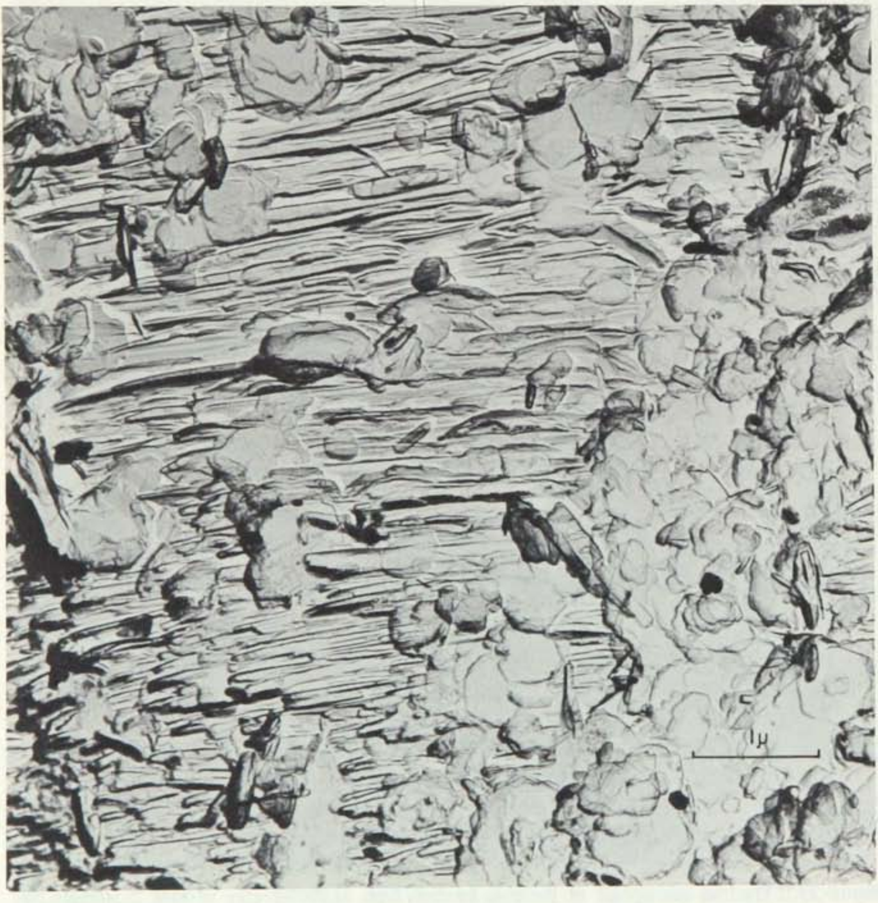

Figure 28. **Carbon replica of a fractured surface of a unit 2 kaolinitic clay, Redwood County, sample 10, locality 4. Kaolinite occurs in stacked domains.**

Figure 29. Carbon replica of poorly crystalline kaolinite matrix surrounding individual pisolites. Note lack of any well-defined pseudohexagonal outlines. Renville County, sample 42, locality 8.

of the poorly crystalline kaolinite of the matrix is shown in Figure 29. Few if any kaolinite plates showing pseudohexagonal outlines are present.

Halloysite in the sedimentary rocks of unit 2 occurs as detrital fragments. It is present in minor quantities, and is more common in lower stratigraphic units than in the pisolitic kaolinite layer. Hollow spheres of halloysite were recognized in a thin poorly developed pisolitic kaolinite near Granite Falls (sample 247, locality 82). The spheres are approximately 0.2 microns in diameter and make up only a small part of the clay-mineral fraction. Kaolinite has the most regular pseudohexagonal form in the lower part of unit 2, is more irregular upward in the rock sequence, and lacks any regular outline in the pisolitic kaolinite layer.

Sedimentary Rocks of Unit 3

The clay mineralogy of the sedimentary rocks of unit 3 varies vertically in a relatively orderly manner. The stratigraphically lower part of the Upper Cretaceous sediments is mostly non-marine, and those higher in the section are mostly marine. Kaolinite is abundant in the lower part and decreases upward, whereas montmorillonite has a reverse distribution. Illite is absent in the lowermost part of the rocks of unit 3, but increases in abundance upward and becomes common in the stratigraphically higher Upper Cretaceous rocks. Chlorite, like illite, is also absent in the basal part of unit 3 but becomes more common in the upper stratigraphic parts. The first occurrence of chlorite in these sedimentary rocks is always stratigraphically above the first occurrence of illite.

One or possibly two bentonites have been recognized thus far in Minnesota in the Upper Cretaceous sedimentary rocks of unit 3; the bentonites differ substantially in clay mineralogy from the adjacent strata. The clay-mineral fraction of the bentonite samples is composed of montmorillonite, which may be either sodium or calcium saturated. Various coarse and fine fractions were examined by x-ray to determine if cristobalite were present in the non-clay mineral fraction; no definite identification of cristobalite was made. Euhedral biotite is the most common heavy mineral in the bentonite.

An unusual form of halloysite is found in two separate clays of unit 3. The halloysite appears as hollow spheres, generally less than one micron in diameter, made up of small plates which lend a somewhat polygonal cross-section to the spheres. The spherical, platy halloysite (figs. 30 and 31) occurs in a white clay band about two inches thick (sample 69, locality 4) that lies directly beneath an Upper Cretaceous bentonite exposed in the Ochs Brick and Tile Company clay pit near Morton. The same form of halloysite occurs in an Upper Cretaceous underclay (sample 55, locality 3). Only a small number of Upper Cretaceous sedimentary rocks of unit 3 were examined with the electron microscope, and accordingly it is not known whether this form of halloysite is common. X-ray diffraction traces of both samples 55 and 69 are shown in Figure 32. The x-ray traces, as indicated by the general 7 Å basal spacing, show that most of the material is present in the form of halloysite$\cdot 2H_2O$; however, sample 55 shows a weak 10 Å peak that collapses approximately to 7 Å when heated to 300° C., indicating the presence of fully hydrated halloysite. The diffraction maxima between 20° and 23 ° 2θ are characteristic of halloysite or of poorly crystalline kaolinite. Similar spherical forms of halloysite have been described by Birrell and others (1955), Sudo and Takahashi (1956), Sudo (1959), Nakamura and Sherman (1965), and Professor Chukhrov (1967, personal communication). Nakamura and Sherman (1965) concluded from their weathering study in Hawaii that halloysite formed as a residual weathering product has a general tubular morphology, whereas halloysite formed as a precipitation product is generally spherical in form and has curled edges on its outer surface. Halloysite, in the form of hollow spherical shells, was also

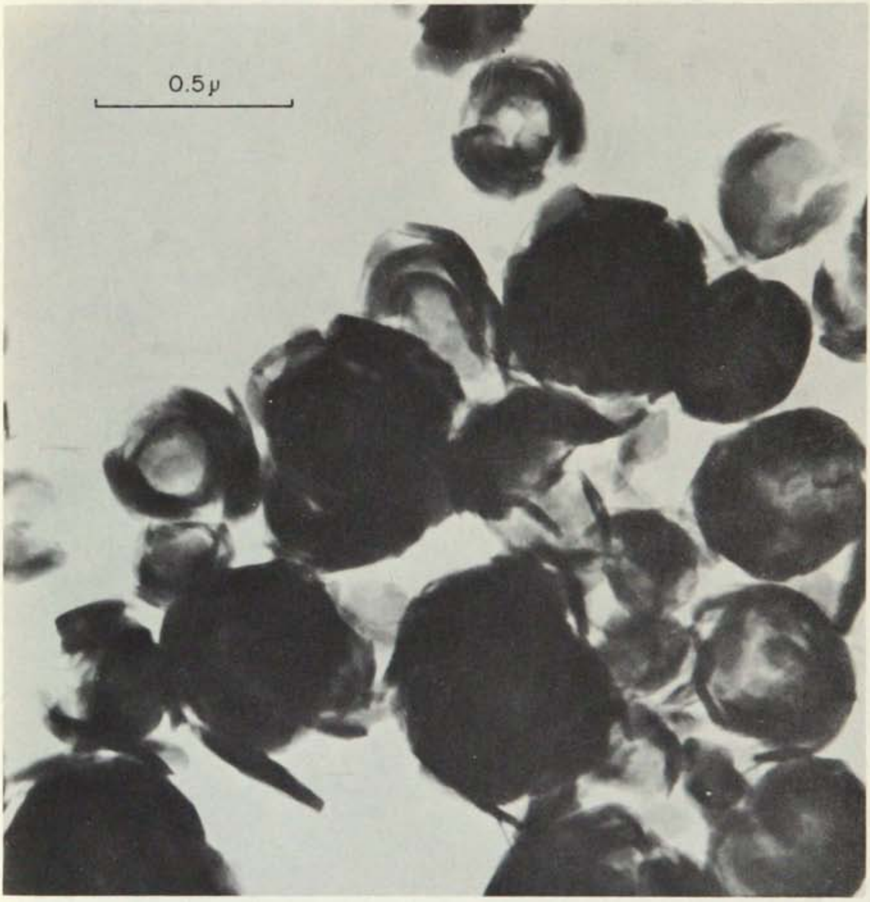

Figure 30. Electron micrograph of spherical, platy halloysite from thin white clay band of unit 3 beneath bentonite in clay pit, Redwood County, sample 69, locality 4.

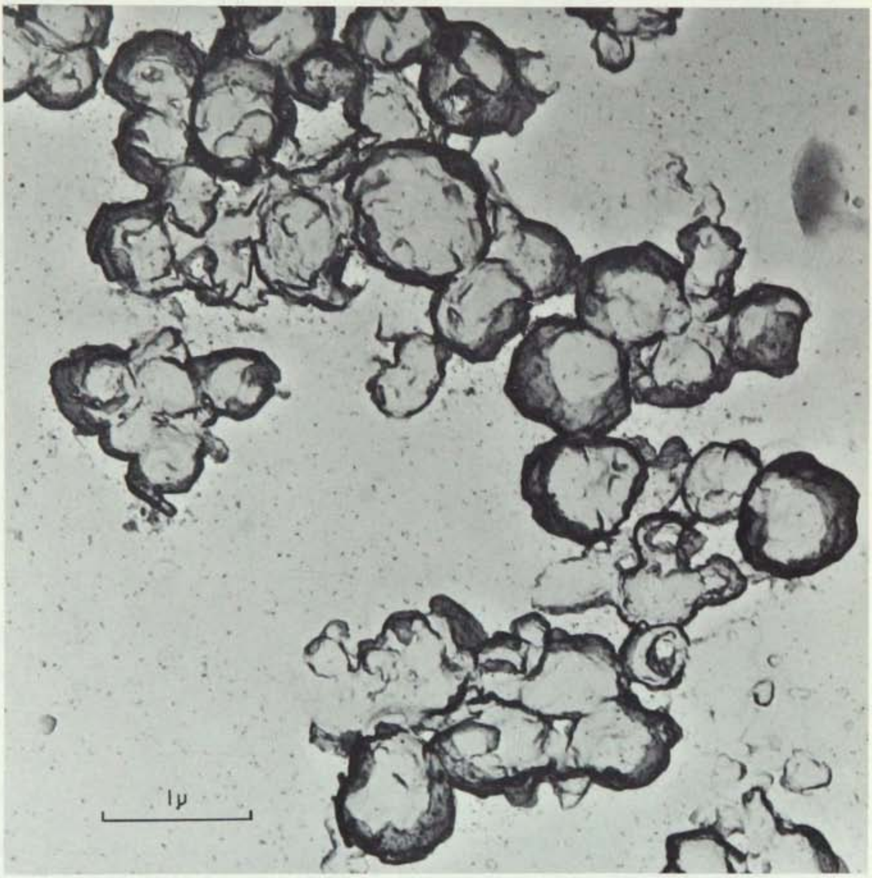

Figure 31. Carbon replica of spherical, platy halloysite from a thin white clay band beneath a unit 3 bentonite in clay pit, Redwood County, sample 69, locality 4.

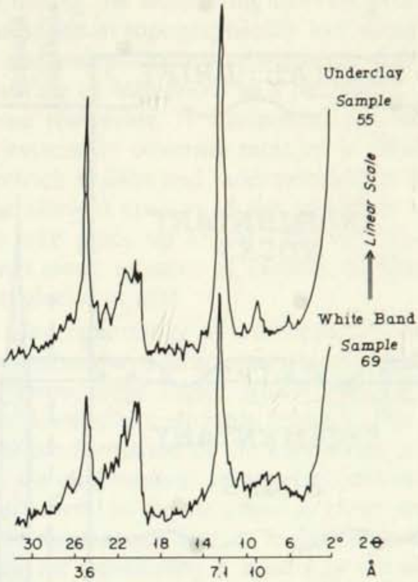

Figure 32. **X-ray diffraction traces of the less-than-two-micron fraction of spherical, platy halloysite, Redwood County, unit 3, sample 55, locality 3, and unit 3, sample 69, locality 4.**

found by Birrell and others (1955) in a volcanic ash soil in an advanced stage of weathering in New Zealand. Sudo and Takahashi (1956) and Sudo (1959) proposed that reorganization and crystallization of allophane leads to the formation of rounded halloysite·$4H_2O$ ("chestnut-shell-like shaped particles"), and this form in turn transforms into tubular halloysite·$4H_2O$. Sudo noted that, in numerous cases, both the rounded and the tubular forms of halloysite were present together in soil developed on volcanic glass. If, as Sudo and Takahashi suggest, there is a progressive alteration from the spherical to the tubular form, it would seem from the abundance of the spherical form in samples 55 and 69 that spherical halloysite may exist in a metastable form for long periods of time. The residual weathering products in Minnesota, as in Hawaii (Nakamura and Sherman 1965), are characterized by tubular halloysite morphology. The spherical form is limited to sedimentary rocks of units 2 and 3 in Minnesota. Whether the spherical form of halloysite has developed as a precipitation product, as suggested by Nakamura and Sherman, is not known. It is believed, though, that the nature of the sediments in which the spherical type occurs in Minnesota does suggest an aqueous environment in which the rate of sediment accumulation was slow.

The changes in clay mineral assemblages that occur from the base of the residuum to the top of the exposed Upper Cretaceous sedimentary rocks in Minnesota are summarized graphically in Figure 33. The illustration is based primarily on information gathered from the southwestern part of

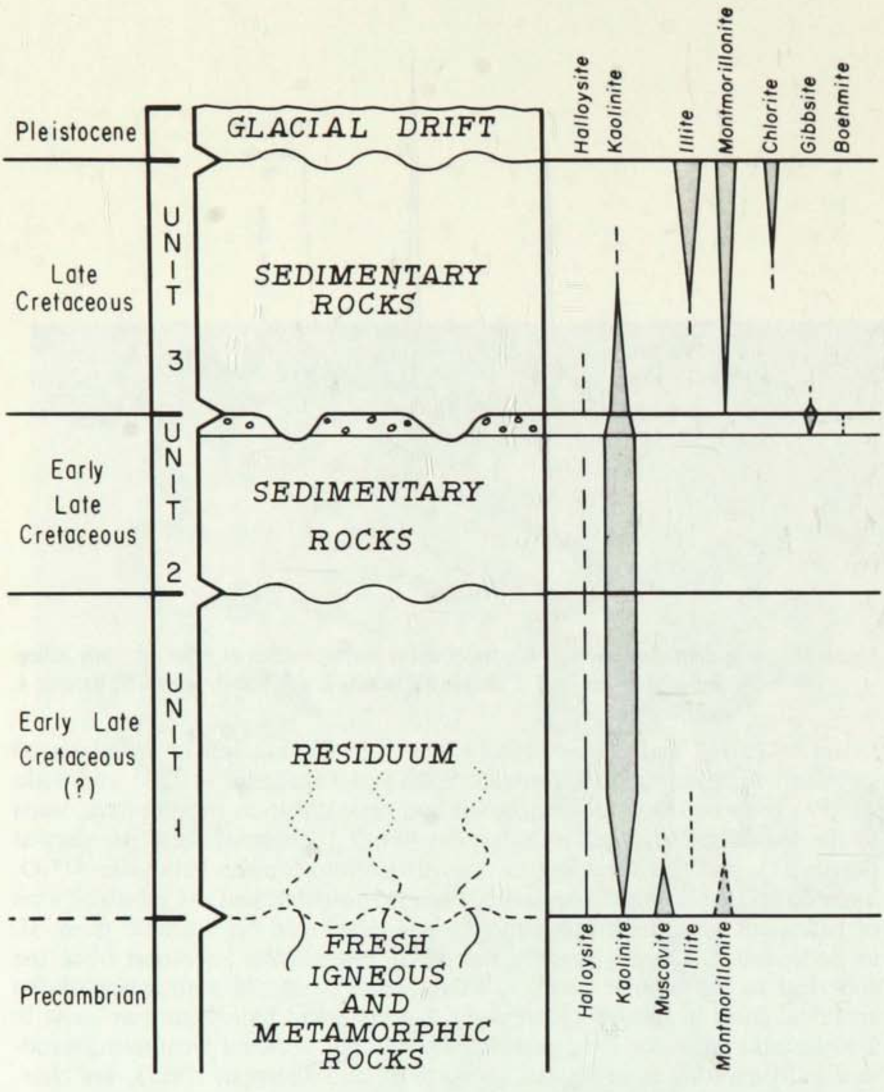

Figure 33. Vertical variations in the clay mineral assemblages of the weathered residuum and of the Upper Cretaceous sedimentary rocks of Minnesota.

Minnesota along the Minnesota River, but mineralogical data from related scattered outcrops in other parts of the state follow the same general pattern.

WEATHERING HISTORY

Weathering of Precambrian crystalline rocks in Minnesota during early Late Cretaceous time under a humid tropical climate produced a thick, kaolinitic residuum throughout much of the state. Subsequent erosion of part of the residuum during the weathering interval produced a thin series of kaolinitic clays and sands in topographically low areas. The processes of weathering, erosion, and redeposition of the parent rock and the residuum in time reduced the surface of Minnesota to a peneplain. The climate of the area then became more temperate. A Cretaceous sea encroached onto the state from the west, eventually covering most of it. Marine sediments deposited in that sea are rich in illite and montmorillonite and poor in kaolinite. Retreat of the sea allowed erosion of the residuum and overlying Cretaceous sediments to take place up to the time of Pleistocene glacial deposition. An additional small amount of erosion of Cretaceous rocks has occurred since the last glacial retreat.

Variations in the clay mineralogy of weathered Precambrian rocks and of Upper Cretaceous sedimentary strata are a useful geological parameter for considering the environment under which Minnesota's kaolinitic residuum and associated kaolinitic sediments formed. The inferred sequence of events necessary for the formation of the kaolin clay materials in Minnesota is based not only on clay-mineral studies but also on the interrelationships of geologic observations in the state and in other areas. The synthesis of geologic data on the Cretaceous System in Minnesota by Sloan (1964) provided a framework for developing a relatively detailed picture of the weathering history and formation of Minnesota's kaolin clays. However, at our present state of knowledge evidence supporting certain points is sparse and certain information is somewhat conflicting. The areas of conflict are worthy of further detailed study, which could add substantially to our understanding of the geologic history of Minnesota and the processes involved in the formation of kaolin clays.

According to Sloan's interpretation (1964), a widespread epicontinental sea existed in Minnesota and the states to the west, probably no earlier than Late Jurassic time, and definitely during Early Cretaceous time. The sea had a warming effect on the land and served as the source for rainfall necessary for the formation of a thick chemically weathered zone, which is preserved today mainly on Precambrian igneous and metamorphic rocks in the western half of Minnesota (fig. 34). The deeply weathered residuum probably extended further eastward over the state but was largely removed by Tertiary erosion, subsequent Pleistocene glaciation, and post-glacial erosion.

The kaolinitic residuum has been penetrated by drilling beneath a cover of Cretaceous sediments in the easternmost counties of North Dakota, that is, Grand Forks, Traill, Cass, and Richland (Kelly, 1968; Jensen, 1967; Klausing, 1966; and Paulson, 1953), and in two other of the easternmost counties of South Dakota, that is, Deuel, and Brookings (open file data from the South Dakota Geological Survey). Paulson (1953) identified the clay minerals in one sample of the residuum as mostly kaolinite with a small amount of halloysite. It seems very likely that the equivalent weathered zone should occur to the north of Minnesota in Manitoba also.

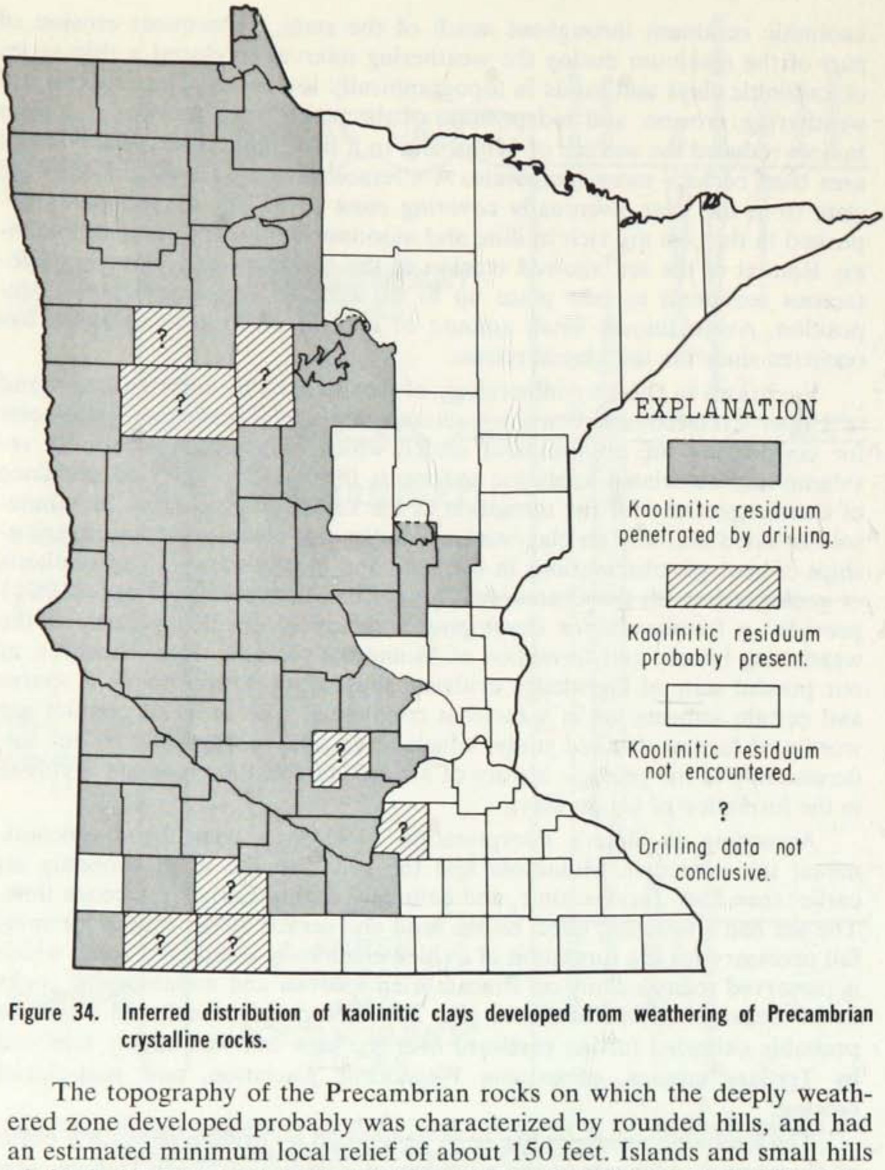

Figure 34. Inferred distribution of kaolinitic clays developed from weathering of Precambrian crystalline rocks.

The topography of the Precambrian rocks on which the deeply weathered zone developed probably was characterized by rounded hills, and had an estimated minimum local relief of about 150 feet. Islands and small hills of fresh igneous and metamorphic rocks, presently exposed along the Minnesota River Valley in the area of Redwood Falls and Morton, show surface relief of this type and magnitude (fig. 35). Some trace of the residuum generally is preserved on this surface, suggesting that pre-Pleistocene and Pleistocene erosion did not modify the unweathered bedrock surface significantly. This estimate is also based on the assumption that the fresh bedrock surface reflects, at least in a general way, the original topography of the land surface prior to weathering.

Figure 35. View looking southeastward of floor of Minnesota River Valley at NW¼ sec. 24 T. 113 N., R. 34 W., Redwood County. Pre-weathering relief on Precambrian surface may have been about 150 feet and may be represented by exhumed topography seen here.

As the epicontinental sea encroached on Minnesota from the west, the decrease in altitude of land surfaces caused a warming climatic trend and accelerated the rate of rock weathering. Sloan (1964) suggested that the climate in Minnesota during the weathering interval was most probably humid warm-temperate to humid subtropical. Weathering under humid subtropical or tropical conditions rather than under humid temperate conditions seems more likely to have been responsible for development of a residuum that commonly is about 100 feet thick. It is common under present-day humid subtropical or tropical weathering conditions to develop a residuum of several hundred feet in thickness whereas such thicknesses are not commonly developed under humid temperate conditions. The higher temperatures associated with higher rainfall also aid in accelerating the chemical weathering process:

"Precipitation in the humid tropics is not only very high quantitatively, but also very destructive in character. It occurs mostly as cloudbursts and downpours of terrifying violence. Great electrical storms introduce into the rainwater a very large amount of carbon dioxide, nitric acid and ammonia and thus greatly increase its chemical potency" (Krynine, 1936).

Water-well drillers have reported penetrating "decomposed granite" at depths in excess of 200 feet in southwestern Minnesota, but commonly report encountering "fresh granite ledges" at various intervals in deeper parts of the well. The reports suggest that weathering progressed downward along joints or fracture surfaces in the bedrock, causing decomposition of rocks in limited zones to considerable depths. Weathering along joint planes and other planes of weakness in parent rocks leads to the development of core stones of fresh rock, which under further weathering become smaller spheroidal boulders surrounded by highly weathered decomposed material. The core stones normally should decrease in size upward from the parent rock into the weathered zone, and should continue to decrease as weathering proceeds. Commonly during drilling through the weathered rock, fresh parent rock is encountered suddenly, and with continued drilling there is again an abrupt change from fresh rock to soft decomposed rock; the fresh parent rock of core stones accounts for drillers' reports of "fresh granite ledges" found within the highly weathered residuum.

It is along joint planes and other partings and fracture surfaces within the parent rock where weathering effects are first noticed, and where weathering progresses most rapidly. During the first stages of weathering under humid subtropical or tropical conditions, rainfall of slightly acid or nearly neutral pH reacts with feldspars and micas of granites and gneisses. Carbon dioxide in the atmosphere mixes with rainwater and forms carbonic acid which aids in the attack on feldspar and mica surfaces. Progressive weathering of near-surface material eventually leads to total destruction of feldspars and micas and to development of an amorphous hydrated alumina-silicate material similar in composition to kaolin minerals (Wollast, 1967), or to development of kaolin minerals themselves. Under humid subtropical or tropical conditions SiO_2 is continuously removed, resulting in near-surface concentration of Al_2O_3, leading eventually to development of gibbsite or similar aluminum-rich minerals. Laboratory studies on surface alteration of K-feldspar at low temperatures (Wollast, 1967) indicate that, in a leaching environment, if the concentration of silica in downward-moving waters is less than 5 mg/1, kaolinite will not form and bauxitization of the feldspar would occur. Wollast believes that the conditions necessary for bauxitization of K-feldspar are "good drainage and rains of high intensity and frequency, but of short duration, to avoid waterlogging."

Weathering of mafic rock types takes place in a similar fashion; however, in the first stages of weathering, montmorillonite develops instead of material of kaolinitic composition. Under more advanced stages of weathering montmorillonite gives way to a material of kaolin composition, and finally to the hydrous aluminum oxide minerals. Two samples of a weathered basalt dike (locality 53, samples 282-283) taken at distances of six and of one-half inches respectively from core stones of fresh basalt, have montmorillonite as their sole clay mineral constituent. Field relationships between fresh and weathered amphibolite at locality 55, and the set of weathered schist samples (samples 329-332) from Stearns County, suggest that the montmorillonite zone of weathering is probably limited to a thickness of about twenty feet in the basal part of the weathering profile. The formation of montmorillonite and its subsequent alteration to minerals of the kaolin group during chemical weathering has also been shown by Ferguson (1954), Kashtanov (1966), Fairbairn and Robertson (1966), and others.

The Precambrian Sioux Quartzite in Minnesota was chemically weathered in the same way as the remainder of the Precambrian igneous and metamorphic rocks. A thick weathered residuum probably did not develop on the quartzite as it did on granites, gneisses, and basic rock types because of the low permeability of the quartzite and because of its high quartz content and low content of other minerals. However, a part of the weathered residuum is preserved, and is exposed in the New Ulm Quartzite Quarries, Inc. at SW¼ sec. 35, T. 110 N., R. 30 W., Nicollet County. At this locality the quartzite has been weathered to a light pinkish white, friable sandstone. The clay fraction (sample 288) of the weathered quartzite is composed entirely of kaolinite. A detailed clay-mineral study of weathering products from this quarry has been made by G. S. Austin (in press). The fresh rock in the quarry has been shown by Miller (1961)[7] to consist of (other than quartz) sericite, illite, and diaspore.

Pleistocene glacial striae are common on quartzite surfaces exposed in southern and southwestern Minnesota, and evidence of chemical weathering on these rock surfaces generally is rare. The fresh rock surface exposed by glacial action gives one the impression that the quartzite was highly resistant to the intense chemical weathering that caused decomposition of the other rock types in Minnesota. Bleaching of the red color from quartzite for distances of a centimeter or two away from joint planes, however, is noticeable in exposures east of Jeffers in Cottonwood County, suggesting that any weathering products that had formed here have long since been removed by erosion.

The rate at which water moves downward through parent rock during weathering is of considerable importance in determining the nature of the alteration products developed during the breakdown of various rock-forming materials. Recent literature on rock weathering in warm, humid climates has placed more emphasis on the intensity of leaching and on the drainage conditions than it has on the composition of the parent rock itself. Weathering studies in Hawaii by Moberly (1963) and Nakamura and Sherman (1965), and in the British West Indies by Beaven and Dumbleton (1966), indicate that gibbsite rather than kaolin minerals forms if chemical weathering is intense, solution is rapid, and solution products are removed rapidly. Uehara and others (1966) have noted in Hawaii that zones rich in gibbsite and in direct association with channels of good internal drainage occur at considerable depths in the weathering profile. Moberly (1963), however, places more importance on parent-rock makeup, and has suggested that lack of sheet-lattice minerals in the parent rock may hinder clay mineral formation during weathering while aiding gibbsite development; Sand (1956) considered the presence of muscovite or secondary mica necessary

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[7] Miller, T.P., 1961, A study of the Sioux Formation of the New Ulm area: Unpublished Master's Thesis, Univ. of Minnesota, 75 p.

in the parent rock for kaolinite to develop during weathering. In addition, he believed that if weathering were intense and drainage good, hydrated halloysite rather than kaolinite would form.

Nakamura and Sherman (1965) in a weathering study in Hawaii envisioned the development of diverse micro-environments during the early stages of rock weathering in which "plagioclase feldspars weather to gibbsite or halloysite depending on the concentration gradient of alumina or silica within these micro-environments." As weathering progresses, such micro-environments blend into one another and may result in either resilication of gibbsite to form a kaolin mineral or desilication of a kaolin mineral to form gibbsite (Bonifas, 1959; Nossin and Levelt, 1967). The entire weathered zone undergoes desilication with continuing weathering, resulting finally in the formation of bauxite. Simonett and Bauleke (1963), in addition, noted in a weathering study in Australia that the abundance of gibbsite as well as halloysite tends to increase with increasing rainfall, while at the same time kaolinite shows the opposite relationship. Similarly, it has been shown that gibbsite is more abundant in the British West Indies where rainfall is high and leaching is intense (Beaven and Dumbleton, 1966).

Gibbsite has been noted to form during weathering at several localities in temperate climates also, suggesting that laterite formation is not exclusively limited to specific climatic zones (Pickering, 1962). Pickering suggests that the small number of gibbsite occurrences reported from temperate areas may be the result of inadequate techniques of mineralogical identification when gibbsite is associated with clay minerals. It is probable, then, that the gibbsite referred to by Pickering was associated with small channels that were the locus for the main downward movement of water.

The residuum in Minnesota, which grades downward into fresh parent rock, does not contain gibbsite, and thus two possibilities are suggested regarding the conditions of leaching during its formation: first, leaching of the parent rock might not have been sufficiently intense to remove enough SiO_2 to produce gibbsite, or secondly, if gibbsite had been produced during the weathering process it may have been resilicated later to form kaolinite. The first possibility seems more likely, because even bauxites do not develop to thicknesses of hundreds of feet; and it is also unlikely—with the relatively high percentage of primary quartz still present in the residuum—that the concentration of dissolved SiO_2 in leaching waters was sufficiently low during the weathering period to allow for formation of massive quantities of gibbsite. Very likely there was resilication of small amounts of gibbsite that may have formed along principal drainage channels.

The presence of halloysite in trace or very small amounts throughout almost the entire section of residuum is not easy to explain. Electron-micrographs show that tubular halloysite developed directly on certain cleavage surfaces of altering K-feldspars, whereas kaolinite seems to have formed directly on others. If this were generally true throughout the entire residuum at the time of weathering, we should expect to see larger quantities of halloysite as a residual weathering product. To add further to the problem, an increasing volume of recent literature indicates that during present-day weathering under conditions of good drainage, halloysite rather than kaolinite may be the first clay mineral to form or may be the only clay mineral to form (Alexander and others, 1943; Bates, 1962; Beaven and Dumbleton, 1966; Besoain, 1964; Beutelspacher and van der Marel, 1961; Birrell and others, 1955; Coleman and Farrar, 1964; Fairbairn and Robertson, 1966; Hardon and Favejee, 1939; Hay, 1960; Hendricks and Whittig, 1967; Kato, 1964-65; Kim and Kim, 1964; Linchenat and Shirokova, 1964; Lisitsyna, 1966, 1967; Makismović and Crnković, 1968; Moberly, 1963; Nakamura and Sherman, 1965; Neužil and Kužvart, 1968; Parham, 1969a,b; Patterson, 1964; Robertson, 1963; Sudo, 1959; Uehara and others, 1966; and Wolff, 1967). Some of the weathered rock types studied by these authors were volcanic ash, glassy tuffs, rhyolite, granite, quartz monzonite, granodiorite, syenite, andesite, basalt, kimberlite, anorthosite, gabbro, amphibolite, sedimentary rocks, and metamorphosed sediments. It is likely that many older studies as well as certain more recent ones, in which kaolinite is reported to form as the principal weathering product under conditions of good drainage, may be only partly correct. Depending on the technique of identification used, one could mistake halloysite for kaolinite. This does not imply that kaolinite is not forming as a weathering product in certain places, but perhaps does suggest that alteration of feldspar and micas directly to kaolinite during weathering may be less common than generally accepted (Parham, 1969a).

Kaolinite-rich residual weathered products are not uncommon in the geologic column. Halloysite, on the other hand, seems to be more common in younger weathered zones and less common in older weathered residual materials. Although some writers have postulated that there is a complete gradation between the kaolinite and halloysite structures, no examples of this have been clearly shown. In addition, attempts thus far to synthesize halloysite artificially have been generally unsuccessful, although Parham (1969a) has produced a material in low temperature artificial weathering of K-feldspar that has a morphology very similar to tubular halloysite. Nevertheless, it seems that halloysite may in fact alter to kaolinite under natural conditions given sufficient geologic time. The mechanisms involved in transition of crystals of halloysite of a tubular or spherical morphology to that of larger pseudohexagonal kaolinite crystals is not known at present.

The question arises also as to whether or not the igneous and metamorphic bedrock terrane was covered by vegetation during the episode of weathering. If, as Sloan (1964) has suggested, the period of weathering that produced the thick kaolinitic residuum started in Late Jurassic time, it would seem likely that the land surface in Minnesota would have been covered with vegetation because, according to Arkell (1956), the later part of the Jurassic Period was generally marked by a very mild climate even in high latitudes and by the presence of abundant and varied vegetation. Ruxton and Berry (1957) have shown that when deforestation takes place in the humid tropics over hilly deeply weathered terrane, erosion will quickly remove much of the upper decomposed material and will expose unweathered core stones. Continued erosion will lead to the down-slope movement of core stones, and eventually to some of them being carried to valley bottoms. In Minnesota, core stones have not been observed at the contact of the residuum and the overlying sedimentary rocks. In fact, they are rare in outcrops of the residuum of weathered granites and gneisses in Minnesota, although drilling indicates that they must occur deep in the weathered profile. Thus, the lack of core stones at the upper surface of the residuum suggests the presence of a vegetation cover over the land during the time of weathering. Ruxton and Berry (1959) also point out that if weathering conditions persist for long periods of time after weathering has reached its deepest level, core stones in the residuum would continue to decrease in size, and if the weathering process continues even longer, all core stones would be destroyed and there would be an abrupt transition from weathered residuum into fresh parent rock. This might explain the observed sharp contact between fresh and highly weathered granite in Stearns County (locality 89) at the Cold Spring "crystal" quarry.

The presence of abundant vegetation would have had additional effects on weathering of the bedrock. First, plants themselves probably extracted silica from ground water or directly from various silicate minerals. The interesting analysis and comprehensive collection of data by Lovering (1959) regarding silica accumulator plants, points to the effectiveness of many plants in extracting silica from the ground for use in plant structures above the ground. Leaves from those plants that accumulated silica would eventually drop and become part of the ground litter. Decay of the leaves would either allow the silica to be recycled downward through the residuum again and perhaps back into new plants or, due to heavy rainfall and surface runoff, the silica might be removed by streams. Resilication of some of the near-surface high-aluminum minerals by silica derived from decaying plants also is a possibility, but has not been recognized thus far in the weathered materials in Minnesota. Calculations by Lovering (1959) suggest that under warm climatic conditions, high rainfall, and adequate drainage, plants might be able to remove all the silica from one acre-foot of basalt in 5,000 years and under extremely intense weathering conditions might accomplish the same in 800 years. These figures do not allow for the silica removed by the normal downward percolation of rain water through the rock, which would increase the weathering rate still further. Mikhaylov's (1964) calculations on weathering rates of the Liberian Shield, under conditions similar to those outlined by Lovering (1959), indicate that plants alone could be responsible for the formation of a one-foot-thick aluminum laterite crust on dolerite in 20,000 years. Removal of a part of other chemical elements, such as calcium, sodium, potassium, etc., from the residuum by plants would occur in a similar fashion. Thus, it seems that upward migration of silica through the action of plants might have been important in determining the rate of decomposition in the bedrock.

Secondly, iron and other metal ions may have been removed from the near-surface weathering zone by chelation (Schalscha and others, 1967). Organic molecules, produced by decomposition of the vegetation cover, may have assisted in accelerating weathering during the early stages. Variations in the pH of descending waters would have influenced the extent to which organic complexes could form because both hydrogen ions and metal ions compete for complexing molecules, and hydroxyl ions and complexing molecules both compete for metals (Schatz and others, 1964). Even though detail is lacking, it seems probable that vegetation and its decomposition products played a significant part in developing the residuum in Minnesota.

The variables involved in the weathering environment that produced the kaolinitic residuum, such as relief, pH, rainfall, temperature, rate of leaching, and vegetation cover, have had their effect on the nature of the newly formed clay minerals. As noted earlier, the morphology of kaolinite produced ranges from well-formed pseudohexagonal plates to poorly formed plates having an "alligator skin" surface texture. Laths of kaolinite are more common in deeper parts of the weathered section, and pseudohexagonal plates are more common in the upper part. At some localities there is no indication of the presence of halloysite with kaolinite, and at others the two minerals appear to have formed in close proximity. The relationship of kaolin clay mineral morphology to the composition and type of parent rock is an obvious problem for study. Again, we are faced with obtaining continuous samples starting from known parent rocks and progressing upward through the various stages of decomposition into the completely altered residuum. Cores of this type have not been available in Minnesota for study.

Studies (Table 1) show that there is a reduction of about 40 to 60 percent in rock density during chemical weathering before the original rock texture and structure are destroyed. Residual weathering products collapse to occupy a smaller volume during rock weathering after a large part of the rock-forming minerals are leached away. It is common for clay-sized material from near-surface highly weathered rocks to be carried downward by

Table 1 — Change of density of various rock types during weathering prior to decrease of volume of weathered rock.

Rock type	Original Density	Weathered Density (No Volume Change)	Reference
dunite	2.80	1.58	Millott and Bonifas (1955)
nepheline syenite	2.58	1.54	Millott and Bonifas (1955)
biotite-plagioclase gneiss	2.8	1.35	Grant (1964)
basalt	2.7	1.12	Patterson (1964)
granite (Hong Kong)	2.6-2.7	1.4	C. M. Guilford, personal comm. 1967
quartz-monzonite gneiss	2.7-2.8	1.5	This study

percolating water into void spaces in the less weathered rocks. Rearrangement of the minerals during the reduction in volume destroys the texture and structure of the original rock and eventually leads to an increase in density of the final product over that of the partly weathered rocks. Table 1 contains density determinations for fresh Morton Gneiss samples from the Cold Spring quarry at Morton, Renville County, and the equivalent weathered rock from locality 74 (fig. 3).

Erosion by slope-wash and gullying action transported some of the fine-sized clay minerals and quartz of the residuum to lower elevations. A period of valley filling and sediment accumulation began. Reworking of the clays and sands by running water within the valleys generally concentrated these two size fractions into separate deposits. The quartz sands were not transported for long distances, as indicated by the angular shape of the quartz grains. The pseudohexagonal outlines of transported kaolinite flakes show some slight degree of wear, though, and it is also common to find short fragments of halloysite tubes in these sediments rather than the longer variety that occurs in non-transported materials of the residuum. Only two localities were found where cross-bedding was sufficiently well developed in clayey sands to measure (locality 4, strike N. 70° W., dip 10° NE, and locality 8, strike N. 21° E, dip 21° SE). Any main drainage channels that had developed in Minnesota flowed generally to the west toward the sea. Determination of the past drainage pattern through detailed drilling or through geophysical techniques would be of value in finding and delineating the thickest deposits of sedimentary kaolin clays.

Further weathering and erosion of Precambrian rocks eventually provided sufficient sediment to fill the meandering stream valleys, and concurrently the hills were reduced to a rolling plain. Further lowering of the land surface resulted primarily from chemical weathering. Kaolinite, halloysite, and residual unweathered feldspars decomposed further as rainwater leached additional silica from their structures, forming gibbsite from the aluminous-rich residue.

During this late stage in the weathering history the pisolitic kaolinite layer formed. A bauxitic texture was formed in the clay, but decomposition of silicate minerals did not progress sufficiently to produce a weathering product rich enough in aluminum minerals to be considered bauxite.

Altitudes of the upper surface of the pisolitic kaolinite layer vary as much as 50 to 60 feet locally as in Redwood County, but regionally are quite flat (fig. 36), suggesting that the layer formed on a widespread, flat, low-lying plain that covered a large part of western Minnesota. The change in altitude of the layer regionally is generally about one to two feet per mile. Laterite has formed on slopes in northern Australia commonly having gradients of 25 to 30 ft./mi. and on some up to 50 ft./mi. (Hays, 1964). A part of the local variation in altitude of the pisolitic bed in Minnesota probably is the result of differential compaction over weathered bedrock hills.

Meinzer, as early as 1911 (*in* Hall and others, 1911) suggested that perhaps a peneplain had formed over a part of southern Minnesota as a result of the intense weathering episode that took place prior to Late Cretaceous sedimentation. He visualized the Sioux Quartzite, of southwestern Minnesota, as having formed prominent ridges or mesas surrounded by widespread flatter areas of deeply weathered granite. His suggestion seems reasonable with respect to observations and data assembled in this report. The basic requirements necessary for designating a geologic surface as a peneplain as outlined by Thornbury (1956) seem to be fulfilled in this case. The stratigraphic and geomorphic evidence which Thornbury cites as

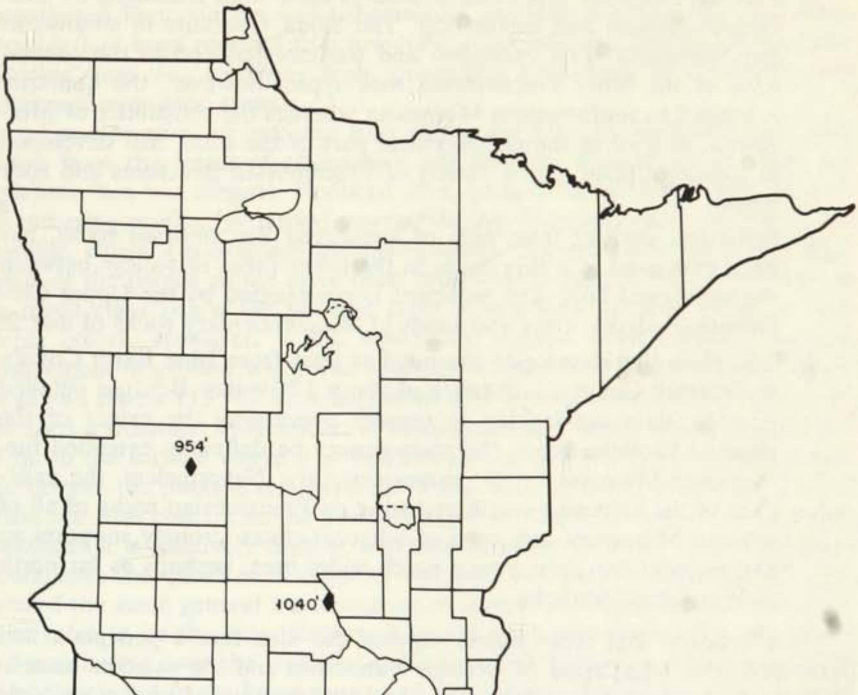

Figure 36. Map of Minnesota showing the altitude of the top of the Upper Cretaceous pisolitic kaolinite layer of unit 2. The Ottertail County altitude of 954 feet is an average of measurements taken at three localities, and the Redwood-Renville Counties altitude of 905 feet is an average of measurements taken at about twenty localities.

support for existence of a peneplain is listed below as it relates to Minnesota.

1. The altitude of the upper surface of the pisolitic layer suggests the development of a near-plain surface.
2. A thick, deeply weathered residuum is present beneath this surface.
3. There seems to be a general accordance of hill tops on the weathered Precambrian rocks. The pisolitic kaolinite layer in fact, has developed directly on Precambrian rock at two localities (51 and 91).
4. Precambrian rock types and structures have been truncated by Cretaceous erosion and weathering. The Sioux Quartzite in southwestern Minnesota is an exception and was not reduced to the general level of the other Precambrian rock types; however, the quartzite is limited to southwestern Minnesota whereas the remainder of Minnesota, at least in the north-central part of the state, had developed to a general plain over a variety of Precambrian structures and rock types.
5. Sediment, derived from hills of weathered Precambrian rocks, has been preserved as a thin cover in the lower areas or valleys between the weathered hills. The sediment is represented by the Upper Cretaceous kaolinitic clays and sands of the sedimentary rocks of unit 2.
6. The plain that developed extended at least from Blue Earth County to Ottertail County, a distance of about 170 miles. Because detailed geologic data are lacking at present concerning the extent of the pisolitic kaolinite layer, the plain cannot be definitely extended further over Minnesota with greater certainty. Nevertheless, the existence of the kaolinitic weathered zone on Precambrian rocks of all of western Minnesota and parts of adjacent states strongly supports an extension of the plain over a much wider area, perhaps as far north as Winnipeg, Manitoba.

It is believed that these points support the idea that a peneplain had developed over large areas of western Minnesota and the extreme eastern Dakotas during Late Cretaceous time, but confirmation of such a geologic feature awaits further detailed drill-hole data, particularly in the northwestern part of the state.

Local variations in the altitude of the surface on which the pisolitic kaolinite formed can account in part for the differences in thickness of the iron-rich pisolitic layer. This layer, as mentioned earlier, generally ranges in thickness from three to five feet, but is as much as 15 feet thick at locality 8, and only at this locality was it noted to rest on a thin, dark gray, clay-shale. The altitude of the top of the iron-rich pisolitic surface here is 880 feet, which is as low or lower than any measurements taken from other exposures in the area. In a literature review of laterites, Maignien (1966) has shown that in environments where weathered crusts develop over a relatively flat plain, those that form in topographically low areas always have a higher iron content than those formed on the slightly higher surrounding ground. The suggestion that the increased thickness of the pisolitic layer is related to its formation in a topographic low is also supported by the work of Simonett and Bauleke (1963). Their work on development of pisolites in modern tropical soils formed from basalt has shown that development of abundant pisolites is most closely related to conditions of poor drainage. Likewise, Mohr and van Baren (1954) have noted that in rainforests under the most advanced stages of lateritic weathering, lateritic concretions form below the surface of the soil in the zone that is constantly moist. Therefore, development of the pisolitic texture at the top of the Upper Cretaceous sedimentary rocks of unit 2, and in a few instances on weathered Precambrian rocks themselves, suggests not only that the countryside had been reduced to a low-lying plain but also that the water table at that time was relatively high, producing conditions of relatively poor drainage over wide areas.

Concentration of oxidized iron within the pisolitic kaolinite layer may have been the result of alternating wet and dry seasons or of short dry periods in a wet climate. Reduced iron, present in the lower part of such weathering profiles, is carried upward during drier periods to the top of the profile, where it is oxidized and precipitated. The reduced iron in the lower part of the profile would have been removed by ground-water flow and as a result clays below the pisolitic layer would tend to have white or very light colors. However, if the weathered surface were forested, upward movement of ground water due to evaporation would be minimized. Mohr and van Baren (1954) have suggested that when deforestation takes place in such a situation, evaporation of moisture from the soil will bring reduced iron to the surface where it is oxidized and precipitated, and where it acts to cement the pisolitic clay layer. It is not uncommon in Minnesota to find that the iron content in the pisolitic layer is relatively low at one locality whereas it is relatively high at a nearby locality. If forest cover had been complete, the effect of alternating wet and dry periods should have produced the same general concentration of iron over a wide region. This does not seem to be the case. Rather, it would seem that during the last stages of weathering over the wide flat plain that had formed in Minnesota, gaps had developed in the forest cover and evaporation during the dry season or during drier periods allowed oxidation of upward-moving iron to take place in tree-barren parts of the plain, thus cementing those portions of the pisolitic layer with iron oxide. Tree-covered areas would have inhibited upward movement of ground water and subsequent oxidation of iron, thus leaving the pisolitic layer iron-poor and light in color. The variation in iron content for five samples of the pisolitic layer is shown in Appendix A. No chemical analyses are available for samples from the most iron-poor areas; however, the chemical analyses of Appendix A show iron contents ranging from about 6 to 22 percent, which indicate in a general way the variability of iron content within the pisolitic clay layer.

The presence of incipient pisolitic textures in sediments below the pisolitic kaolinite layer at scattered localities suggests that temporary base level had been reached within various sites of sedimentation prior to leveling of the entire countryside. It is probable that in most instances such features would have been destroyed by subsequent erosion as temporary base levels were eliminated.

This, then, was the situation at the end of the formation of the pisolitic kaolinite clay of unit 2. A low-lying weathered plain, extending over much of the western half of Minnesota, had been formed under a humid subtropical or tropical climate, perhaps with alternating wet and dry seasons or a generally wet climate with short periods of low rainfall. A large epicontinental sea, lying to the west in the Dakotas, would eventually transgress across the flat tree-covered plain. The surficial materials of the plain had undergone severe chemical weathering and small amounts of gibbsite had been formed during the process.

During a part of Late Cretaceous time the low-lying plain of western Minnesota was subjected to minor erosion. Small streams cut down through the pisolitic layer into the underlying clays and sands of unit 2 (fig. 10), and subsequently these stream channels were filled by sediments of unit 3.

The epicontinental sea, lying to the west of Minnesota, began to transgress over the sedimentary rocks of unit 2 in western Minnesota in Late Cretaceous time. Large swamps were formed as the water moved in over the nearly flat surface. Vegetation, which covered a large part of the landscape, was slowly destroyed by the rising water table and by the development of swamps. Reducing conditions in the muds which were deposited in the swamps were responsible for preserving large quantities of organic material, and as a result most basal sedimentary rocks of unit 3 in Minnesota are dark gray or black and contain abundant organic remains and thin beds of lignite. The small amounts of siderite present in the uppermost part of the sedimentary rocks of unit 2 and in the lower part of unit 3 also are related to the reducing conditions. Lignites and coal beds commonly occur in sediments directly overlying bauxites and laterites in other parts of the world (Eyles, 1952; Fox, 1927; Harder, 1949).

The clay mineral assemblage present in the lowermost organic-rich clays of unit 3 is composed predominantly of kaolinite with minor amounts of montmorillonite; trace amounts of gibbsite are present locally. The kaolinite and gibbsite were derived locally from erosion of underlying sedimentary rocks of unit 2, but montmorillonite probably was derived from volcanic sources in the western United States. Culmination of the Laramide Orogeny took place in the west during the Cretaccous Period providing westerly winds with volcanic ash, the most probable parent material of montmorillonite. At least one bentonite bed occurs within the lower part of the Upper Cretaceous sedimentary rocks of unit 3 of Minnesota, representing the featheredge of one of the thicker bentonites of the Dakota or Wyoming region. Although bentonite seems to be uncommon in Upper Cretaceous sedimentary rocks of Minnesota, montmorillonite is common in these rocks and tends to increase in abundance from the base to the top of the Upper Cretaceous section. The progressive increase in montmorillonite upward in the section is accompanied by a progressive decrease in kaolinite.

By comparing the clay mineral assemblage of the sedimentary rocks of unit 2 with that of unit 3 it is apparent that a pronounced change in certain environmental conditions had taken place in the interval between deposition of the sediments of units 2 and 3. The climatic conditions had become cooler and rainfall had probably decreased, resulting in a climate more typical of temperate areas today. Kaolinite and gibbsite were no longer forming, at least not in any abundance in Minnesota, during Late Cretaceous time. Kaolinite and gibbsite in the basal part of rocks of unit 3 were derived from reworking of the old rock surface of unit 2, illustrating a general carry-over of one stable clay mineral assemblage into a time of new environmental conditions. Similar examples of clay mineral carry-over have been pointed out by Bentor and others (1963), and they visualize "a halo in space and time, within which the stable clay mineral composition can be easily recognized, regardless of transport and redeposition in a different environment." With the exception of spherical halloysite, kaolin and high-alumina minerals were no longer forming. Under temperate climatic weathering conditions and with lower rainfall, the three-layer clay minerals, i.e., illite, montmorillonite, and chlorite, would be the common clay minerals formed. These three-layer clay minerals do, in fact, comprise the great bulk of the clay minerals in stratigraphically higher parts of the Upper Cretaceous section.

Paleobotanical studies of sediments in the lower part of the Upper Cretaceous section by Chaney (1954) and by Pierce (1961) in part support the inference of climatic change. Sloan (1964) summarized their paleobotanical findings and pointed out their somewhat conflicting conclusions. Chaney felt that the climate during Late Cretaceous time in Minnesota was probably frost-free and more subtropical than temperate, based on his study of the venation of fossil leaf impressions, whereas Pierce concluded from pollen studies that the Upper Cretaceous flora had grown in a humid temperate climate. In addition, though, Sloan noted that "Chaney (1954) and Pierce (1957) both found evidences of a Cretaceous pine indistinguishable morphologically from the modern Red Pine, *Pinus resinosa*, in association with the leaf impression flora. This occurrence cannot be explained at present because Red Pine today exists only in cool temperate to cold climates." Whether Red Pine might have grown in the humid tropics during Cretaceous time is not known. Chaney suggested that pine cones were carried into the area of deposition by streams, and therefore do not aid in characterizing the climate at their depositional site. Their presence, nevertheless, at least suggests the nearness of a grossly different climatic zone than had existed a short time earlier while Upper Cretaceous rocks of unit 2 were being deposited. Pierce's conclusions are more in accord with the inferred climatic change of unit 2 based on clay mineralogy. Sloan was concerned with the differing conclusions reached by Chaney and Pierce, particularly by the fact that Pierce had suggested a humid temperature climate and not a moist subtropical climate for Minnesota during Late Cretaceous time. Sloan said, "This implication is very important for determining the nature of the weathering involved in the production of the . . .

deeply weathered pre-Cretaceous bedrock topography throughout the State." This would be true if the Upper Cretaceous sedimentary rocks of unit 3 were interbedded with the Upper Cretaceous sedimentary rocks of unit 2 at nearly all localities as he had stated; however, the fact that rocks of unit 3 lie disconformably on unit 2 eliminates the problem of having to produce a thick, kaolin-rich residuum over much of Minnesota under humid temperate climatic conditions. Further regional detailed paleobotanical studies in Minnesota are required to properly evaluate the relationship of climate to fossil plant material during Late Cretaceous time.

The Late Cretaceous sea in time receded to the west from Minnesota, exposing the State to erosive processes; no further marine invasions took place in Minnesota. Well developed drainage systems were established on the land surface and erosion along some of the major streams cut downward through the entire Upper Cretaceous rock section and residuum into fresh Precambrian rocks. These valleys were filled subsequently during Pleistocene time with glacial drift. The locations of most of these pre-Pleistocene valleys still remain unknown today. The flat glacially-produced topography was again eroded after retreat of the glaciers from Minnesota in post-Pleistocene time, and erosion is continuing today.

RECOMMENDATIONS

Some of Minnesota's kaolin clays seem to have potential for use as coating and filler clay for the paper industry, and as raw material for the ceramics and refractories industries. Presently, substantial quantities of kaolinite are used for paper coating and paper filler by paper manufacturers in the north-central states. Most of this clay comes from southern states and is transported into this area by rail. The high cost of transportation of the currently used kaolin clay makes Minnesota's deposits potentially attractive to clay producers and consumers. Thicknesses and areal extent of the Minnesota clays appear adequate for mining. Some of them contain kaolinite as the only clay mineral, and should be suitable for use as a paper coating or filler clay. One-quarter to one-third of the residual clay of unit 1, and a still larger proportion of the raw sedimentary clay of unit 2 is composed of kaolinite having well-formed pseudohexagonal plates.

Potential uses for kaolin clays in the ceramics and refractories industries are less restrictive than in the paper industry. In addition to the kaolinitic residual clays of unit 1 and the kaolinitic sedimentary clays of unit 2, which are both suitable for certain of these uses, the organic-rich, dark-gray to black ball clays of unit 3 are potentially of commercial importance in ceramic products. The fired color of the ball clays varies from white to pale pink, and the clays have a high degree of plasticity. Use of ball clays with less-plastic kaolins of unit 1 should produce a plastic clay of properties acceptable for a variety of refractory products. The fusion temperature for such a clay would be in the range of 1650° C. to 1775° C. Quartz, another common ingredient in various ceramic and refractory products, is available within Minnesota from the Ordovician St. Peter Sandstone and the Cambrian Jordan Sandstone (Hogberg, 1966).

If Minnesota kaolin clays are mined and used in the paper, ceramics, or refractories industries, the processed clay could find additional uses as an industrial mineral in other products, as for example as filler in rubber and plastics or as an extender in paint. In the event that kaolin clays become commercially feasible as a source of aluminum in the future, certain clays of unit 2 that contain small amounts of quartz would serve as good raw materials (see chemical analyses in Appendix A).

In considering commercial exploitation, the following points should be taken into consideration:

(1) many kaolin clay deposits have a moderately thick overburden, which could adversely affect mining costs,

(2) beneficiation to remove unwanted coarser fractions and non-clay minerals would be necessary before using the clays in the paper industry and would necessitate the allocation of sites for disposal of large amounts of tailings,

(3) an adequate supply of clean water must be available for processing the clays for use in the paper industry,

(4) the clay-size fraction would require bleaching to whiten and brighten the finished paper clay,

(5) some sedimentary clays in unit 2 are hard and of doubtful use for paper clays, whereas others are soft, break down readily in water and may be acceptable. Improved methods of wet-grinding the harder or larger particle sizes of kaolinite to increase recovery of the less-than-two-micron fraction might be required. The feasibility of various grinding techniques is now being considered by the U. S. Bureau of Mines (Stanczyk and Feld, 1963, 1965), and

(6) halloysite, and kaolinite having irregularly shaped "alligator-skin" plates occur in some samples from both units, and possibly would adversely increase the viscosity of the clay-water suspension during high speed application to paper.

Overburden along the Minnesota River Valley in the vicinity of Redwood Falls is generally in excess of 45 feet. Recently, however, highly weathered residuum was uncovered at a depth of one or two feet during construction of a cattle-watering pond in a farm pasture in the area of NE¼ sec. 33, and SW¼ sec. 34, T. 112 N., R. 33 W., Brown County. The occurrence is situated on a gently sloping surface that dips toward the Minnesota River and occupies an area about ¼ mile wide and two miles long (shaded area of map D). Other similar topographic features on the valley floor are present in the S½ sec. 2, T. 113 N., R. 36 W., Renville County and at N½ NE¼ sec. 8, T. 111 N., R. 32 W., Nicollet County, and are indicated as shaded areas on maps B and E respectively. These areas are possible expressions of other shallow, highly weathered parts of the residuum, and are worthy of investigation by drilling. Overburden in the vicinity of St. Cloud and Little Falls in many areas is about 10 or 20 feet thick. However, in this region exposures of kaolin clay are scarce and little is known of distribution and quality of the clays.

About one-third of the residuum (unit 1) by weight would constitute kaolin clay suitable for paper coating and filling. The tailings remaining in addition to the stripped-off overburden would therefore constitute considerable bulk in waste piles. The planning of future mining operations along the Minnesota or Mississippi Rivers should take into consideration proper location of waste disposal sites where the tailings will not add additional pollution to the rivers. Consideration too should be given to the flood possibilities along the valleys of these rivers when selecting waste disposal sites.

An adequate water supply for paper-clay processing may have to be obtained from the rivers, because available ground-water supply in the kaolin-bearing rocks is generally small, and that in the glacial-drift overburden may not be reliable. If river water were used, it would have to be cleaned prior to use so as not to contaminate the clays. Detailed water-supply data are being collected by the United States Geological Survey.

The response of kaolin clays to chemical bleaching is quite variable; some samples having coatings of oxidized iron show considerable increase in whiteness and brightness after treatment whereas others having a silver-green color do not. Because each paper-clay company designs bleaching processes to fit its own raw material, it is likely that one or more bleaching techniques may improve the color characteristics of the silver-green kaolin clays.

Because both the sedimentary section and the residuum vary in thickness and lithology from one drill hole to another over short lateral distances as a result of the several erosional surfaces within the rock column, quantitative estimation of reserves is complicated. Details of the regional topography of each unconformity are sparse, and patterns of past drainage systems established on these surfaces for the most part are lacking. The sedimentary kaolin clays of unit 2, which are known to be at least 45 feet thick in some channels or valleys, thin rapidly away from the valleys but probably remain relatively uniform in thickness along the strike of the channels. Closely spaced drilling or detailed geophysical studies would be required to determine the ancient drainage pattern in an area selected for exploration. Also, the depth of weathering on the Precambrian rock surface varies from place to place. Halloysite and illite may be present in trace amounts in unit 1, and illite occurs in excess of trace amounts at the base of the unit.

Clay mineral analyses do not show clearly whether the kaolinite zone developed to a greater thickness on top of Precambrian rock hills, on the flanks of hills, or in the valley bottoms. As Grant (1960), however, pointed out in his study of the humid tropics of Hong Kong, the depth of weathering is greater on the south- and west-facing slopes of granitic hills and least on the north slopes. Insolation is largely responsible for differences in the rate and depth of weathering on opposite sides of the hills. During the drier months of the year the south flanks of the hills receive a large amount of solar radiation which dries and cracks the soil, thus inhibiting abundant plant growth. Rainfall can penetrate the desiccated soil and the underlying residuum during the wet seasons and leach the bedrock. On the north-facing slopes, on the other hand, where the soils have a heavier cover of vegetation and the slope receives less solar radiation, the depth of weathering is less. A parallel situation could have existed in Minnesota during the formation of the residuum.

Topographic depressions that existed in Late Cretaceous time on Precambrian bedrock hills are the most likely areas for the occurrence of thickest kaolinite-rich zones. The distance above the water table would have been greater in these depressions than in the valleys, and thus would have allowed for a greater depth of leaching. Rainfall trapped in such topographic depressions would have time to percolate downward through the bedrock, and thus contribute to developing thick kaolinite-rich weathered zones. On hill tops, distances to the water table would have been at a maximum, but rainfall runoff would have been high and less effective in leaching the bedrock. Even though the topographic situation at the time of weathering is not known for the following three localities, the kaolinite-rich weathered zone is relatively thick at each:

Locality 8	at least 13 feet (illite present in trace amounts).
Locality 18	at least 27 feet (illite present in trace amounts).
Locality 46	at least 19½ feet (no trace of illite).

Determining the approximate altitude at which core stones of fresh parent rock occur in the residuum is another problem that may be encountered in exploratory drilling. The altitude of the transition from soft weathered rock to the zone of abundant core stones can be determined, as Ruxton and Berry (1957) have suggested, by oblique drilling. Oblique drilling minimizes the likelihood of drilling downward along weathered joints and has been used successfully in foundation engineering studies over deeply weathered bedrock terrains.

Preliminary field tests with portable electrical resistivity equipment carried out by the Minnesota Geological Survey suggest that this technique may be suitable for determining the thickness and continuity of the three kaolin-bearing units. Expanded profiles, using the Wenner electrode configuration, were used. The electrical resistivity of the sedimentary rocks of unit 3 was found to be lowest, that of the sedimentary rocks of unit 2 was intermediate, and that of the residuum (unit 1) was highest. These results are only qualitative; however, this technique is inexpensive and worthy of more field testing for exploration for Minnesota kaolin clays.

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APPENDIX A

Chemical Analyses of Selected Samples.

Table A-1 — Chemical analyses (in weight percent) of uppermost pisolitic kaolinite clay of unit 2. (Source: Bergquist, 1943)

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. NW¼ SE¼ sec. 3, T. 112 N., R. 34 W.; Renville Co. (Sample 42 shown in fig. 6.)
II. NW¼ sec. 11, T. 112 N., R. 34 W.; Renville Co.
III. SE¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W.; Redwood Co., along Crow Creek.
IV. SW¼ sec. 2, T. 112 N., R. 35 W., Redwood Co.; along Crow Creek.
V. E½ SW¼ sec. 2, T. 112 N., R. 35 W., Redwood Co.; 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.

Table A-2 — Chemical analyses (in weight percent) of sedimentary rocks of units 2 and 3.
(Analyses from Minnesota Geological Survey open files.)

Sample No. and Locality	Location	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Ignition loss	Total
					Unit 2					
Sample 39 Locality 5	SE¼ NW¼ NW¼ sec. 2 T112N R35W, Redwood Co.	38.02	41.32	1.52	0.16	0.26	0.00	0.00	14.22	96.50
Sample 50 Locality 9	SW¼ SE¼ NW¼ sec. 11 T112N R34W, Redwood Co.	35.58	44.80	3.44	0.08	0.07	0.07	0.04	14.12	98.20
Sample 104 Locality 52	SE¼ SE¼ SE¼ sec. 34 T113N R35W, Redwood Co.	42.00	36.70	4.56	0.16	0.18	0.00	0.13	13.64	97.37
					Unit 3					
Sample 58 Locality 5	SW¼ NW¼ NW¼ sec. 2 T112N R35W, Redwood Co.	35.92	39.14	1.28	0.25	0.46	0.02	0.16	18.78	96.01
Sample 107 Locality 38	NW¼ NW¼ SW¼ sec. 21 T112N R33W, Renville Co.	52.54	24.36	8.00	0.25	1.61	0.00	1.76	9.18	97.70

APPENDIX B

Described Sections and Sample Localities.

Localities 15 through 42 correspond to localities A through BB in Minnesota Geological Survey Report of Investigations 3 (Parham and Hogberg, 1964). Data include references to some samples and sample localities described in unpublished manuscript by Bickford and Price (1947), on open file with Minnesota Geological Survey. The original notation of sample localities of Bickford and Price are indicated. X-ray diffraction analyses of the less-than-two-micron fraction of samples collected by Bickford and Price are given in Appendix D.

Locality 1

Redwood Co., SE¼ NW¼ NE¼ 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
Upper Cretaceous:		
Unit 3		
Lignite streak		1-2
Unit 2		
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
Unit 1		
Precambrian metamorphic rock, highly weathered, clayey, yellow-brown (Sample 54)	6	0

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

Locality 2

Redwood Co., SW¼ SW¼ NW¼ 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., SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W., section exposed on south side of U.S. Highway 19. (Bickford and Price locality *Hendersen.*)

	ft.	in.
Pleistocene:		
Glacial drift	60	0
Upper Cretaceous:		
Unit 3		
Shale, light-gray	1	0
Lignite		2
Clay, gray (Sample 57)	1	0
Covered interval	1	6
Clay, black, organic-rich		3

Clay, gray	1	0
Lignite		2
Clay, gray, shaly toward base	1	6
Clay, black, organic-rich		2
Clay, gray	1	4
Lignite		4
Clay, shaly, dark-gray, grades downward to medium-gray clay with numerous lignite fragments. (Sample 56 from top 1.5 feet)	3	0
Bentonite, yellowish-green, white streak at base; altitude 904 feet (Sample 33)		8
Shale, tannish-gray (Sample 132)	1	3
Shale, dark-gray to black (Sample 131)	1	0
Lignite		8
Clay, light-gray, root traces present (Sample 55)		6
Clay, gray, lignite streaks throughout (Sample 129)	1	6
Clay, grayish-green, lignite fragments at base (Sample 128) (Sample 133 is a composite of Samples 128 through 132).	1	0
Unit 2		
Clay, sandy, iron-stained, hard, somewhat pisolitic toward top	1	4
Clay, light-gray to tan, poorly exposed	5	6

Locality 4

Redwood Co., SE¼ SW¼ sec. 35, T. 113 N., R. 35 W., Morton clay pit of Ochs Brick and Tile Company.

Pleistocene:	ft.	in.
Glacial drift (Description of these sediments is discussed in section on glacial deposits)	46	0
Upper Cretaceous:		
Unit 3		
Clay, black and gray, highly contorted from glacial overriding (Sample 12)	4-5	0
Bentonite, dark-green clay, altitude 941 feet (Sample 15)		1-8
Clay, white, conchoidal fracture (Sample 69)		1
Sand, lignite, lignitic clay, and light-gray clay in alternating thin layers (Sample 11)	8-10	0
Clay, white to buff and gray, sandy, base below pit floor (Sample 10)	6	0

Note: This section was taken from the southwest corner of the pit and represents a Cretaceous channel deposit in the underlying sediments of Unit 2. Further along the pit face to the north, the channel sediments are missing and the sediments of Unit 3 rest directly on the hard, iron-stained, pisolitic clay of Unit 2. Below the bentonite layer at the north end of the pit, the sediments overlying the pisolitic clay consist of approximately 13 feet of alternating thin layers of sand, lignite, lignitic clay and light-gray clay. The description below is of the Cretaceous sediments exposed along the north end of the east pit face.

Unit 2		
Clay, hard, iron-stained, pisolitic, buff	3	0

Clay, light-buff, some quartz present, scattered pisolites; exposed in northeast corner of pit along small drainage (Sample 14)	5	6
Sand, sandy clay, and pisolitic clay in alternating layers; base is rust-colored zone and very pisolitic (Sample 13); contains 2-3-inch angular quartz pebbles; base cuts into sediments below	5	6
Sandstone, white, medium to coarse-grained, angular grains, cross-bedded, 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., SW¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W., outcrop high along west bank of Crow Creek. (Bickford and Price locality *M.*)

	ft.	in.
Pleistocene:		
Glacial drift	60	0
Upper Cretaceous:		
Unit 3		
Clay, purplish-gray (Sample 60)	1	4
Lignite or lignitic clay		1
Clay, gray (Sample 59)	1	0
Lignite		2
Clay, gray, light-gray at top	1	0
Lignite streak		½
Clay, gray	2	0
Lignite or lignitic clay		1
Clay, gray		2
Lignite (Sample 58 includes section up to glacial drift. Chemical analysis in Appendix A)		1
Unit 2		
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 chemical analysis in Appendix A)	4	6
Clay, tan, contains some sand (Sample 38)	3	0
(This lower part of described 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, lenses somewhat pisolitic; large quartz fragments scattered in sandy parts and in some of the smoother clay	14	6
Clay, sandy, medium- to fine-grained, white and ferruginous	3	0
Clay, contains coarse angular white quartz sand	1	0
Unit 1		
Decomposed gneiss, texture preserved, greenish-gray to brown; kaolinized feldspar, contains coarse quartz fragments up to 6 inches in length	28	0

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[3] Bergquist, op. cit.

Covered interval 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 locality for about ¾ mile at approximately the same altitude. 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 localities, but at junction of northwest-flowing tributary in SW¼ of sec. 2, approximately 20 feet of light bluish-green, highly weathered metamorphic rock is exposed in the east bank just above creek level.

Locality 6

Redwood Co., NE¼ NW¼ NE¼ sec. 8, T. 112 N., R. 34 W., outcrop in east wall of valley at intersection of two small streams. (Bickford and Price locality *P.*)

Pleistocene:	ft.	in.
Glacial drift	70	0
Upper Cretaceous		
Unit 2		
Clay, light-gray, pisolitic, contains root traces (Sample 43)	3	6
Covered interval	15	0
Clay, sandy, buff	2-3	0
Clay, sandy, conglomeratic, ¼-inch quartz grains		6
Clay, buff		6
Sandstone, grayish-tan		6
Clay, iron-stained, sandy	1	6
Clay, light-gray to rust, high sand content; contains angular quartz fragments up to 2-inch diameter	3	6
Clay, brown, pisolitic		6
Clay, gray, sandy		3
Sand, clayey, iron-stained		6
Clay, light-gray, contains 1-2-inch quartz pebbles	1	0
Covered interval to creek level	6	0

Locality 7

Renville Co., SE¼ SE¼ SW¼ sec. 3, T. 112 N., R. 34 W., outcrop along north side of gravel road and below bridge at stream. (Bickford and Price locality *C.*)

Pleistocene:	ft.	in.
Glacial drift to top of bluff	137	0
Upper Cretaceous:		
Unit 3		
Sand, clayey, white	6	0
Clay, light-gray (Sample 35)	6	0
Sand, clayey, white, lignite fragments near top; contains 1-inch quartz pebbles	6	0
Covered interval	3	0
Unit 2		
Sand, rust-colored, slightly pisolitic at top	5	0
Unit 1		
Highly weathered gneiss, whitish-blue	4	0
Covered interval to creek level; elevation 840 feet at base of section	3	0

Locality 8

Renville Co., SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W., south bank of creek below railroad grade. (Bickford and Price locality *E.*)

Pleistocene:	ft.	in.
Glacial drift	120	0
Upper Cretaceous:		
Unit 2		
Clay, hard, pisolitic, iron-stained, forms cliff; pisolites iron-coated, buff cores, up to 1-inch diameter (Sample 42)	15	0
Clay-shale, dark-gray, organic-rich (Sample 338)		8
Clay, tan	1	0
Clay, tannish-gray, some pisolites present (Sample 134)	5	3
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		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

Note: Sample 52 also includes the lower 2.5 feet of Sample 134.

Unit 1		
Clay, bluish-green weathered metamorphic rock	1	0
Base covered at creek level.		

Locality 9

Renville Co., SW¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W., outcrop along north side of gravel road. (Bickford and Price locality *A.*) (This same section is exposed along road about 300 feet to the east.)

Pleistocene:	ft.	in.
Glacial drift	110	0
Upper Cretaceous:		
Unit 2		
Clay, hard, light-buff, some scattered pisolites toward top (Sample 50, chemical analysis in Appendix A)	2	0
Clay, sandy, red and buff, very red toward base (Sample 50). Altitude of road at base is 865 feet	8	6

Locality 10

Renville Co., SW¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W., outcrop along north side of gravel road.

Pleistocene:	ft.	in.
Glacial drift	115	0
Upper Cretaceous:		
Unit 2		
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 36)	1	0
Clay, buff, sandy at base (road) (Sample 51)	9	0
Base of section at road, altitude 870 feet.		

Note: Sample 51 includes entire lower 15.5 feet of exposed section.

Locality 11

Renville Co., W½ SW¼ NW¼ sec. 27, T. 112 N., R. 33 W.; outcrop along north side of gravel road. Same section is repeated east along road at SE¼ SW¼ NW¼ sec. 27, T. 112 N., R. 33 W.

	ft.	in.
Pleistocene:		
Glacial drift	150	0
Upper Cretaceous:		
Unit 3		
Clay or shale (?), dark-gray, weathered	1	3
Lignite, elevation 840 feet		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., NW¼ SE¼ SE¼ sec. 33, T. 112 N., R. 33 W.; outcrop in creek through farm yard south of gravel road.

	ft.	in.
Pleistocene:		
Glacial drift	15	0
Upper Cretaceous:		
Unit 3		
Shale, buff to gray	2	0
Lignite		2
Clay, light-gray (Sample 48)	1	0
Sand and clay laminated; 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
Sand and clay, laminated; light-colored laminae composed of quartz-rich sand, dark-colored laminae composed of clay	3	0
Sandstone		2
Lignite		7
Clay, black, organic-rich (Sample 46)	1	0

Base covered at 887 feet, altitude at creek level.

Locality 13

Brown Co., NE¼ NW¼ NW¼ sec. 3, T. 111 N., R. 33 W., section exposed in creek bank north and south of road. (Bickford and Price locality *N*.)

	ft.	in.
Pleistocene:		
Glacial drift	10	0
Upper Cretaceous:		
Unit 2		
Clay, highly weathered material derived from alteration of metamorphic rock; light-yellow to white, much quartz present (Sample 49)	25	0

Locality 14

Renville Co., SE¼ SE¼ NE¼ sec. 31, T. 112 N., R. 32 W., outcrop on east side of Fort Ridgley Creek.

Pleistocene:	ft.	in.
Glacial drift	60	0
Upper Cretaceous:		
Unit 2		
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 ⅓ to ½ quartz	10	6
Unit 1		
Massive quartz, highly weathered; contains numerous thin joint fillings of white clay, exposed to creek level; dominant joints strike N. 45° W., dip vertical	26	6

Locality (A) 15

Redwood Co., in Alexander Ramsey State Park, SW¼ SW¼ NE¼ sec. 36, T. 113 N., R. 36 W., exposure SW of bituminous road, between 927 and 937 feet altitude. (Bickford and Price locality *Park.*)

Pleistocene:	ft.	in.
Covered interval	75	0
Upper Cretaceous:		
Unit 2		
Altered material, buff, very clayey, derived from metamorphic rock; somewhat iron-stained; section covered to road level	10	0

Locality (B) 16

Redwood Co., in Alexander Ramsey State Park, SE¼ SW¼ NE¼ sec. 36, T. 113 N., R. 36 W., bluff on north side of Redwood River, base of outcrop at river level, 862 ft. altitude. (Bickford and Price locality *Ramsey.*)

Pleistocene:	ft.	in.
Glacial drift	2	0
Upper Cretaceous:		
Unit 1		
Highly altered Precambrian metamorphic rock, tan to pale green; quartz present mostly in 2 mm size range	74	0

Locality (C) 17

Redwood Co., SW¼ NE¼ SW¼ sec. 30, T. 113 N., R. 35W., high bluff along Redwood River; base of outcrop at river level, altitude 845 feet. (Bickford and Price locality *Mann.*)

Pleistocene:	ft.	in.
Glacial drift	53	0
Upper Cretaceous:		
Unit 1		
Weathered Precambrian metamorphic rock, yellow to buff in middle and upper part, greenish-brown near base; abundant muscovite and iron minerals in lower part, some apparent foliation preserved in soft, altered rock near river level	98	0

Locality (D) 18

Redwood Co., NW cor. SW¼ NW¼ SW¼ sec. 29, and SE cor. of SE¼ NE¼ SE¼ sec. 30, T. 113 N., R. 35 W., exposures along bituminous road south of North Redwood; base of described section in ditch at fork in road. (Bickford and Price locality *North Redwood.*)

Pleistocene:	ft.	in.
Glacial till	3	0
Upper Cretaceous:		
Unit 3		
Clay, lignitic, partially slumped section	1	6
Unit 2		
Clay, hard, pisolitic (Sample 80)	1	0
Clay, sandy, some pisolites present, iron-stained, some rudimentary bedding (Sample 79)	7	0

Note: 25 yards south of main exposures a white to gray 3-foot clay is found directly below the 1-foot pisolitic clay (Sample 81).

	ft.	in.
Clay, contains small amount of sand (Sample 80)	2	0
Clay, sandy, pisolitic toward base (Sample 80)	4	0
Unit 1		
Highly weathered Precambrian granite-gneiss, pale green, gneissic texture preserved, some fresh K-feldspar present, biotite common toward base of section (Sample 320)	47	0

Altitude of contact of weathered Precambrian with overlying sediments of unit 2 is 940 ft.

Locality (E) 19

Redwood Co., NW¼ NW¼ NE¼ sec. 32, T. 113 N., R. 35 W., outcrop along unimproved road. (Bickford and Price locality *Gulley.*)

Pleistocene:	ft.	in.
Glacial drift; altitude 1000 feet at top	75	0
Upper Cretaceous:		
Unit 2		
Clay, mostly float, white, pisolitic, some sand present; gray toward base; section covered to base of hill	10	0

Locality (F) 20

Redwood Co., SW¼ SW¼ NW¼ sec. 33, T. 113 N., R. 35 W., outcrop along unimproved road.

Pleistocene:	ft.	in.
Glacial drift	57	0
Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, highly weathered; much clay and sand present; tan, limonite-stained; base of outcrop in farm yard	28	0

Locality (G) 21

Renville Co., NW¼ NW¼ NW¼ sec. 4, T. 112 N., R. 34 W., outcrop along State Highway 19.

Pleistocene:	ft.	in.
Glacial drift; altitude of base 892 feet	118	0
Upper Cretaceous:		
Unit 2		
Clay, pisolitic, hard, limonite-stained; forms ledge; base covered	2	0

Locality (H) 22

Renville Co., NE¼ NE¼ SE¼ sec. 4, T. 112 N., R. 34 W., outcrop along gravel road; section measured down from railroad right-of-way. (Bickford and Price locality *B.*)

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

Locality (I) 23

Redwood Co., SW¼ NW¼ SE¼ sec. 9, T. 112 N., R. 34 W., along creek below cemetery. (Bickford and Price locality *S.*)

	ft.	in.
Pleistocene:		
Glacial drift	50	0
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss; better preservation of gneissic texture in lower 3.5 feet of section; sandy toward Pleistocene contact	19	0

Locality (J) 24

Redwood Co., NW¼ NW¼ NW¼ sec. 15, T. 112 N., R. 34 W., outcrop along gravel road.

	ft.	in.
Pleistocene:		
Glacial drift; altitude of top 969 feet	44	0
Upper Cretaceous:		
Unit 3		
Shale, black, organic-rich		6
Sandstone and lignite, tan, in alternating thin layers	3	0
Clay, very light-gray, sandy in lower part	2	0
Sandstone, white to pale buff; clayey throughout; altitude of base 914 feet	5	6

Locality (K) 25

Redwood Co., SW¼ SE¼ NW¼ sec. 15, T. 112 N., R. 34 W., outcrop in creek bank below farm yard.

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

Locality (L) 26

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

	ft.	in.
Upper Cretaceous:		
Unit 3		
Sandstone, white, grades downward to orange at road level	6	0

Locality (M) 27

Renville Co., SW¼ SW¼ NW¼ sec. 11, T. 112 N., R. 34 W., outcrop along gravel road.

Pleistocene:	ft.	in.
Glacial drift	4	0
Upper Cretaceous:		
Unit 2		
Red and yellow sandstone and clayey sandstone in alternating layers; base covered at road level	8	0

Locality (N) 28

Renvile Co., SE¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W., outcrop along gravel road.

Pleistocene:	ft.	in.
Glacial drift; altitude of base 884 feet	5	0
Upper Cretaceous:		
Unit 2		
Clay, top 1 foot hard, pisolitic, limonite-stained, grades downward to buff clay with few pisolites; road level at base of section	5	0

Locality (O) 29

Renville Co., SW¼ NW¼ SE¼ sec. 18, T. 112 N., R. 33 W., outcrop along gravel road. (Bickford and Price locality *H*.)

Pleistocene:	ft.	in.
Glacial drift; altitude of base 853 feet	147	0
Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, weathered, buff; some fresh, pink K-feldspar phenocrysts present; base of section at road	7	0

Locality (P) 30

Renville Co., NE¼ SE¼ sec. 18, T. 112 N., R. 33 W., outcrop along gravel road.

Pleistocene:	ft.	in.
Glacial drift	144	0
Upper Cretaceous:		
Unit 1		
Mafic Precambrian metamorphic rock, deeply weathered, dark; many calcite-filled fractures; greenish-yellow, platy serpentine in veins; base at road level, altitude 844 feet	10-12	0

Locality (Q) 31

Renville Co., NW¼ NW¼ NW¼ sec. 20, T. 112 N., R. 33 W., outcrop on east side of creek.

Pleistocene:	ft.	in.
Glacial drift	30	0

Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, highly weathered; clayey with large amounts of quartz, yellow-buff color, red staining toward top; base at creek level, altitude 875 feet	14	0

Locality (R) 32

Brown Co., SE¼ NW¼ NW¼ sec. 30, T. 112 N., R. 33 W., outcrop behind barn south of road.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Weathered Precambrian gneiss, yellowish-brown; base of outcrop altitude 855 feet	5	0

Locality (S) 33

Brown Co., Cen. NW¼ NW¼ sec. 30, T. 112 N., R. 33 W., outcrop in farm yard at junction of road and creek.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered, soft, rust-colored Precambrian gneiss	9	0

Locality (T) 34

Brown Co., SE¼ NW¼ SW¼ sec. 29, T. 112 N., R. 33 W., exposure in small pit.

	ft.	in.
Pleistocene:		
Glacial drift	15	0
Upper Cretaceous:		
Unit 1		
Precambrian weathered gneiss, clayey, yellow	2	0

Locality (U) 35

Brown Co., SW¼ NE¼ SW¼ sec. 29, T. 112 N., R. 33 W., outcrop in back of farm house.

Upper Cretaceous:
Unit 1
Weathered Precambrian gneiss, small exposure, yellow, clayey.

Locality (V) 36

Brown Co., SE¼ NW¼ SW¼ sec. 29, T. 112 N., R. 33 W., outcrop along creek bank.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, weathered, yellow, clayey; elevation of base at creek level 870 feet	14	0

Locality (W) 37

Brown Co., NW¼ SW¼ SE¼ sec. 29, T. 112 N., R. 33 W., outcrop along road up hill opposite farm house.

	ft.	in.
Pleistocene:		
Sand; altitude of base 880 feet	6	0
Upper Cretaceous:		
Unit 2		
Clay, hard, pisolitic, iron-stained; base covered	2	0

Locality (X) 38

Renville Co., NW¼ NW¼ SW¼ sec. 21, T. 112 N., R. 33 W., outcrop along gravel road. (Bickford and Price locality *G.*)

	ft.	in.
Pleistocene:		
Sand and gravel	15-20	0
Clay, brownish-green (Sample 105)	1	0
Pleistocene deposits fill channel in underlying sediments.		
Upper Cretaceous:		
Unit 3		
Shale, tan, silty (Sample 108)	3	0
Shale, gray and brown, contains some 2-inch diameter ironstone concretions; chemical analysis in Appendix A	8	0
(Sample 107) top 5 feet. (Sample 106) bottom 3 feet.		
Unit 2		
Clay, pisolitic in top 4 feet; hard, white, iron-staining on joint and bedding surfaces; tan toward base	6	6

Locality (Y) 39

Renville Co., SE¼ SW¼ SE¼ sec. 27, T. 112 N., R. 33 W., outcrop at driveway of farm house.

	ft.	in.
Pleistocene:		
Glacial drift	15	0
Upper Cretaceous:		
Unit 2		
Clay, hard, pisolitic, buff, limonite-stained toward top; altitude of base at gravel road 860 feet	5	0

Locality (Z) 40

Renville Co., SW¼ SE¼ SE¼ sec. 35, T. 112 N., R. 33 W., outcrop along gravel road. (Bickford and Price locality *Berg.*)

	ft.	in.
Pleistocene:		
Glacial drift	15	0
Upper Cretaceous:		
Unit 2		
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) 41

Nicollet Co., NW¼ NE¼ NW¼ sec. 1, T. 111 N., R. 33 W., outcrop along gravel road. (Bickford and Price locality *K*.)

	ft.	in.
Pleistocene:		
Glacial drift; altitude of base 850 feet	10	0
Upper Cretaceous:		
Unit 2		
Clay, limonite-stained at top; gray and sandy in middle part; red staining toward base; lower part clay, sandy and gray; base of outcrop at road level	5	0

Locality (BB) 42

Brown Co., SW¼ NW¼ SW¼ sec. 8, T. 111 N., R. 32 W., outcrop along creek bank.

	ft.	in.
Pleistocene:		
Glacial drift	30	0
Upper Cretaceous:		
Unit 2		
Quartz sandstone, very coarse-grained	5	0
Covered interval to creek level	10	0

Locality 43

Redwood Co., Cen. NE¼ NW¼ sec. 31, T. 113 N., R. 35 W., southwest of abandoned racetrack.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss, tan to brownish-red, red toward top, top 6 feet sampled (Sample 277)	6	0

Locality 44

Renville Co., SE¼ NW¼ SW¼ sec. 3, T. 112 N., R. 34 W., exposure along north side of gravel road.

	ft.	in.
Pleistocene:		
Mostly glacial till to top of valley bluff	110	0
Upper Cretaceous:		
Unit 3		
Shale, blue-gray (Sample 281)		6
Unit 2		
Clay, pisolitic, top 4-6 inches iron-stained, pisolites numerous, clay grades downward to white or gray and to tan at base. Pisolites decrease in abundance toward base. Lower 1 foot has blocky fracture, root traces present. Altitude of contact with shale above is 880 feet	5	0
(Sample 280) top 4-6 inches.		
(Sample 279) lower 4.5 feet.		
Clay, blocky, tan to buff, gradational contact with clay unit above (Sample 278)	5	0
Covered interval	15	0
Road level, altitude at road center 885 feet.		

Locality 45

Redwood Co., SW¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W., along west bank of Crow Creek.

	ft.	in.
Pleistocene:		
Glacial drift	62	0
Upper Cretaceous:		
Unit 3		
Clay or shale, lignitic, soft	2	0
Unit 2		
Clay, pisolitic, hard, iron-stained	6	0
Clay, buff to tan, contains minor amount of quartz sand (Sample 72)	14	0
Unit 1		
Highly weathered Precambrian gneiss, gneissic texture preserved, much cover in lower part of section. Total thickness of weathered gneiss and covered interval to creek level	51	0

Locality 46

Redwood Co., NE¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W., outcrop along Crow Creek. (Bickford and Price locality *Crow Creek.*)

	ft.	in.
Pleistocene:		
Glacial drift	30	0
Upper Cretaceous:		
Unit 3		
Clay-shale, light-gray		4
Clay, lignitic		4
Unit 2		
Clay, pisolitic, hard, red	1	4
Clay, buff to tan, much iron-staining toward top, some sand-size quartz present (Sample 74)	9	9
Unit 1		
Highly weathered Precambrian gneiss, buff, exposed to creek level where approximate altitude is 900 feet (Sample 73)	21	0

Locality 47

Redwood Co., SW¼ NE¼ SW¼ sec. 2, T. 112 N., R. 35 W., outcrop along Crow Creek.

	ft.	in.
Pleistocene:		
Sand and gravel	55	0
Abandoned gravel pit at top of bluff.		
Upper Cretaceous:		
Unit 2		
Clay, pisolitic, hard, red, maximum thickness		6
Unit 1		
Highly weathered Precambrian gneiss, top 5 feet clay-rich, top half tan, lower half blue (Sample 75)	35	0
Covered interval to creek level	5	0

Locality 48

Redwood Co., SE¼ SW¼ NW¼ sec. 2, T. 112 N., R. 35 W., outcrop along Crow Creek.

	ft.	in.
Pleistocene:		
Glacial drift	82	0
Upper Cretaceous:		
Unit 3		
Clay, light-gray (Sample 78)	1	6
Clay, lignitic (Sample 78)		2
Clay, light-tan (Sample 78)		8
Clay, gray (Sample 78)	3	0
Lignite		2
Clay, purple, root traces present		1
Unit 2		
Clay, pisolitic, hard, red	2	0
Covered interval to creek level.		

Locality 49

Redwood Co., NW¼ SW¼ NW¼ sec. 2, T. 112 N., R. 35 W., outcrop along Crow Creek.

	ft.	in.
Pleistocene:		
Glacial drift	49	0
Upper Cretaceous:		
Unit 3		
Gray and black lignitic clay in alternating bands		6
Unit 2		
Clay, pisolitic, hard, red. Altitude of top is 860 feet	1	3
Clay, buff to tan (Sample 77)	11	0
Covered interval	4	0
Unit 1		
Highly weathered Precambrian gneiss	1	0
Covered interval to creek level	43	0
Altitude of base of covered interval 860 feet.		

Locality 50

Renville Co., SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W., outcrop on south bank of creek.

	ft.	in.
Pleistocene:		
Glacial drift	135	0
Upper Cretaceous:		
Unit 3		
Shale, micaceous, gray, non-calcareous, some ½-inch fossil leaves, scattered ½-inch pyrite concretions present, scattered coal streaks present (Sample 76)	5	3
Clay, light-gray, contains many lignite fragments		1
Altitude of contact with unit below is 860 feet.		
Unit 2		
Clay, pisolitic, hard, iron-stained	1	0
Base covered.		

Locality 51

Redwood Co., NW¼ SW¼ SW¼ sec. 2, T. 112 N., R 35 W., outcrop along Crow Creek where creek changes direction from east to north.

	ft.	in.
Pleistocene:		
Glacial drift. Mostly till in lower part	50	0
Upper Cretaceous:		
Unit 3		
Bentonite, waxy (Sample 126)		1-2
Unit 2		
Clay, pisolitic, hard, red	1	0
Clay, upper 2/3 buff to white, less pisolitic than unit above, lower 1/3 buff to gray, not pisolitic	6	3
Unit 1		
Highly weathered Precambrian metamorphic rock, clay-rich, light blue-gray (Sample 146)	11	0
Altitude of base of section at creek level 900 feet.		

Locality 52

Redwood Co., SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Lignite and clay streak		2
Section covered above.		
Unit 2		
Clay, top ½ pisolitic, hard, buff, lower ½ white (Sample 103)	4	0
Approximate altitude of top of pisolitic clay 900 feet.		
Clay, white. Sample taken with auger. (Sample 104 chemical analysis in Appendix A.)	3	0

Locality 53

Redwood Co., approximate center of NE¼ sec. 23, T. 112 N., R. 34 W., northwest corner of road intersection.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian basalt dike, spheroidal weathering well developed at top of exposure.		
(Sample 284) fresh basalt.		
(Sample 283) slightly weathered basalt surrounding fresh basalt taken from approximately 1 inch away from fresh rock.		
(Sample 282) highly weathered basalt taken from weathered material between two adjacent core stones. Weathered material taken from approximately 6 inches away from fresh rock.		

Locality 54

Redwood Co., NW¼ NE¼ SE¼ sec. 24, T. 113 N., R. 36 W., 100 yards upstream from railroad bridge.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, highly weathered, soft, micaceous, tan to greenish-tan (Sample 270)	20-25	

The same weathered rock exposed 25 yards upstream on east side of creek. Ten feet exposed.

125 yards further upstream is small exposure of highly weathered Precambrian rock.

Clay, soft, rust-colored (Sample 271)	1	6
Clay, soft, silver-blue (Sample 272)		6

Locality 55

Redwood Co., SW¼ SE¼ SW¼ sec. 4, T. 113 N., R. 36 W., outcrop along east bank of creek where creek turns to the north-northeast.

	ft.	in.
Pleistocene:		
Glacial drift	90	0
Upper Cretaceous:		
Unit 1		
Precambrian metamorphic rock, highly weathered, horizontally banded, tan and maroon, with some small spots of green (Sample 276)	15-20	0
Amphibolite, highly weathered blocks cut by quartz-feldspar veins. Weathered amphibolite is soft, red or maroon (Sample 275)	20	0

Feldspar in veins has altered to white or silver-green clay and in some instances is stained green with malachite, some traces of native copper in the weathered veins. White clay (Sample 274).

Base of exposure at creek level.

Locality 56

Redwood Co., SE¼ NW¼ sec. 1, T. 112 N., R. 35 W., cuttings from water well at first house east of mink farm on south side of road.

	ft.	in.
Pleistocene or alluvium:	10	0
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, clayey, buff (Sample 70)	7-10	0
Highly decomposed gneiss, clayey, blue (Sample 71)	40	0

Base of well in fresh gneiss.

Locality 57

Redwood Co., Cen. W½ SW¼ sec. 34, T. 113 N., R. 35 W.

	ft.	in.
Pleistocene:		
Glacial drift	87	0
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, upper part buff and lower part blue-green	33	0

Base at creek level, 880 feet altitude.

Locality 58

Redwood Co., SW¼ NE¼ SE¼ sec. 33, T. 113 N., R. 35 W.

	ft.	in.
Pleistocene:		
Glacial drift	110	0

Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss, buff, exposed at altitude of approximately 900 feet	3	0
Section covered to base of bluff.		

Locality 59

Redwood Co., NE¼ SW¼ NW¼ sec. 2, T. 112 N., R. 35 W., small exposure about half-way up west bluff of Crow Creek beneath Pleistocene cover.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Clay, lignitic		1
Clay, gray		11
Clay, lignitic		1
Unit 2		
Clay, pisolitic, hard, iron-stained	6	0
Section covered to base of hill.		

Locality 60

Redwood Co., SW¼ NW¼ SW¼ sec. 2, T. 112 N., R. 35 W., small exposure in base of Crow Creek.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, iron-rich	8	0

Locality 61

Redwood Co., SE¼ NE¼ SW¼ sec. 2, T. 112 N., R. 35 W., small outcrop beneath Pleistocene glacial drift just below terrace.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Lignite, clayey		3
Clay, purple-gray		5
Unit 2		
Clay, pisolitic, hard, red	3	0
Section covered to base of hill.		

Locality 62

Redwood Co., SE¼ SW¼ NE¼ sec. 2, T. 112 N., R. 35 W., small exposure along fence line below Pleistocene glacial drift.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Clay, gray, thin seams of lignite present	5	0
Unit 2		
Clay, pisolitic, hard, red	1	0
40 feet of cover to creek level.		

Locality 63

Redwood Co., SW¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W., exposure along Crow Creek.

	ft.	in.
Pleistocene:		
Glacial drift	78	0
Upper Cretaceous:		
Unit 3		
Clay, dark-gray	1	8
Clay, light-gray		3
Unit 2		
Clay, pisolitic, hard, iron-stained	1	6
Clay, pisolitic, light-gray	3	0
Clay, buff, slightly sandy	3	0
Clay, light-gray and light-brown	8	0
Covered interval to creek level (altitude 895 feet).		

Locality 64

Redwood Co., W½ sec. 31, T. 113 N., R. 35 W., scattered exposures along N-S road and near farm buildings. Pleistocene glacial drift covers section.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, rust-colored, gneissic texture well preserved.		

Locality 65

Renville Co., NE¼ NE¼ NE¼ sec. 35, T. 113 N., R. 35 W., small exposure near crusher in Morton Aggregates Co. pit.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	4	0

Locality 66

Renville Co., SW¼ SE¼ NE¼ sec. 26, T. 113 N., R. 35 W., exposure on north side of road; overlain by Pleistocene glacial drift.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	6	0
Altitude of base of exposure 890 feet.		

Locality 67

Renville Co., NW¼ SW¼ NE¼ sec. 27, T. 113 N., R. 35 W., small exposure along road to Rainbow Briquette Co. Exposure is overlain by Pleistocene glacial drift.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	5-10	0
Altitude of base of exposure 850 feet.		

Locality 68

Renville Co., NE¼ SW¼ NW¼ sec. 27, T. 113 N., R. 35 W., small exposure along north side of road.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	10	0
Overlain by alluvium.		

Locality 69

Renville Co., SW¼ SW¼ SE¼ sec. 21, T. 113 N., R. 35 W.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	8	0
Overlain by Pleistocene glacial drift.		

Locality 70

Renville Co., NW¼ SE¼ SW¼ sec. 21, T. 113 N., R. 35 W.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss, top 1-2 feet very clayey	10-12	0
Overlain by alluvium.		

Locality 71

Renville Co., NE¼ NE¼ NE¼ sec. 32, T. 113 N., R. 34 W., exposure along Birch Coulee. Pleistocene glacial drift cover above.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, blue-white, some fresh biotite and K-feldspar present	10-15	0

Locality 72

Renville Co., NW¼ SW¼ NW¼ sec. 33, T. 113 N., R. 34 W., small exposures along Birch Coulee. Pleistocene glacial drift cover.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, some parts rust-red, others blue-green. Highly weathered, fine-grained, metamorphic rock above gneiss	10-15	0

Locality 73

Renville Co., SE¼ NE¼ NE¼ sec. 32, T. 113 N., R. 34 W., exposure along Birch Coulee. Pleistocene glacial drift cover.

	ft.	in.
Pleistocene:		
Sand, scattered lignite fragments 4 feet from base	15	0
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss	11	6
Covered interval to creek level (890 foot altitude)	5	0

Locality 74

Renville Co., NW¼ SW¼ NW¼ sec. 33, T. 113 N., R. 34 W., exposure along west side of Birch Coulee. (See figure 3.)

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian gneiss, gneissic textures and structures well preserved. Buff to silver-green. Some K-feldspars have fresh appearance, others are decomposed. (Sample 324 is grab sample of thin, weathered amphibolite lens in outcrop.)	35	0
Base of exposure at creek level.		

Locality 75

Renville Co., NW cor., NE¼ SW¼ SW¼ sec. 33, T. 113 N., R. 34 W., 5 feet of cover overlying exposure.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Weathered Precambrian metamorphic rock, buff	10-12	0
Weathered gneiss, rust-colored	42	0
Altitude of base of exposure at creek level is 840 feet.		

Locality 76

Renville Co., NE cor., SE¼ SE¼ sec. 3, T. 112 N., R. 34 W., small exposure along creek overlain by Pleistocene glacial drift.

	ft.	in.
Upper Cretaceous:		
Unit 2		
Clay, pisolitic, hard, red	2-3	0
Clay	4-5	0
Altitude of base of exposure at creek level 850 feet.		

Locality 77

Renville Co., NE¼ NW¼ SW¼ sec. 22, T. 113 N., R. 35 W., small exposure along old road.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss, some gneissic texture preserved	10	0

Locality 78

Brown Co., SE¼ SE¼ SE¼ sec. 29, T. 112 N., R. 33 W., rocks poorly exposed along south side of road.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Shale, gray, contains ironstone concretions	1	0

Locality 79

Brown Co., NW¼ NW¼ sec. 30, T. 112 N., R. 33 W., large, cattle-feeding pen surrounded by bedrock.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	10	0

Locality 80

Brown Co., SW¼ SW¼ sec. 29, T. 112 N., R. 33 W., exposure along creek.

	ft.	in.
Pleistocene:		
Till	30-35	0
Sand, cross-bedded	10	0
Sand and gravel	15-20	0
Upper Cretaceous:		
Unit 1		
Decomposed Precambrian gneiss	10	0

Locality 81

Brown Co., NE¼ NE¼ sec. 26, T. 109 N., R. 35 W., Ochs Brick and Tile Company clay pit near Springfield.

	ft.	in.
Pleistocene:		
Glacial drift	10-18	0
Upper Cretaceous:		
Unit 3		
Shale, weathered	2	0
Shale, light-gray, fissile (Sample 8)	2	0
Shale, gray, fair bedding (Sample 7)	1	6
Lignite		8
Clay, dark-gray, sandy (Sample 5)	1	8
Sand and clay, laminated, mostly sand, black clay, white sand, contains limestone nodules of approx. 10-inch diameter (Sample 4 consists of sample of clayey sand.)	5	6
Conglomeratic zone; mixture of sandstone, ironstone concretions, and clay		10
Shale, gray, poorly bedded (Sample 3). Sandstone streak in lower part	4	4
Ironstone layer		1
Clay, laminated, sandy, black clay, white sand, two laminations per inch	1	6
Ironstone layer		1
Sand and clay, laminated, dark-gray clay, white sand (Sample 2)	6	3
Shale, gray, fairly well bedded (Sample 1)	5	10
Bentonite, dark-green (Sample 246)		2
Shale, gray	1	6
(Base of pit.)		

Locality 82

Yellow Medicine Co., NW¼ SW¼ sec. 14, T. 115 N., R. 39 W., roadcut along south side of highway.

	ft.	in.
Pleistocene:		
Patches of till exposed above road level	65	0
Upper Cretaceous:		
Unit 3		
Shale, gray, some slumping evident (Sample 249)	2	0
Sand, iron-cemented, rust-color, occurs as flat fragments in thin bed		3
Unit 2		
Clay, pisolitic, light-gray with rust-colored pisolites, grades downward into quartz sand (Sample 247)		6
Quartz sand, angular grains, fine to coarse-grained, some ¼-inch rounded quartz grains present	1	0
Base of sand not exposed.		

Locality 83

Yellow Medicine Co., NW¼ SE¼ SE¼ sec. 9, T. 115 N., R. 39 W., small outcrop west of railroad bridge, on north side of creek. Pleistocene glacial drift cover above.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian schist, weathered, rusty-yellow, soft (Sample 257)	3	0
Amphibolite, fresh, exposed to creek level	4-5	0

Locality 84

Yellow Medicine Co., NW¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W., outcrop along north side of creek downstream of railroad bridge. Pleistocene glacial drift cover above.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Weathered Precambrian rock, tan, soft (Sample 258)	10-20	0
Base of section at creek level.		

Locality 85

Yellow Medicine Co., SW¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W., outcrop on north side of creek. Section covered with Pleistocene glacial drift.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian rock, highly weathered, soft, red zone 20 feet wide extends to top of outcrop (Sample 261). Tan to olive-drab, highly weathered Precambrian rock on both sides of red zone (Sample 260). Base at creek level	25	0

Locality 86

Yellow Medicine Co., SW¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W., outcrop on south side of creek downstream from locality 85. Pleistocene conglomerate above exposure.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Precambrian rock, highly weathered, greenish-yellow to red, soft. Many white, thin clay veins in weathered rock (Sample 262)	10	0

Locality 87

Yellow Medicine Co., SE¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W., exposure on south side of creek. Pleistocene glacial drift cover.

	ft.	in.
Upper Cretaceous:		
Unit 1		
Highly weathered Precambrian granite or gneiss (?), soft, clay-rich, white to tan, top part white (Sample 263 taken from top 15 feet of exposure). Base of exposure at creek level	25	0

Locality 88

Blue Earth Co., NW¼ SW¼ SW¼ sec. 25, T. 108 N., R. 27 W., outcrop along gravel road.

	ft.	in.
Pleistocene:		
Glacial till with cemented sand and gravel at base	35	0
Upper Cretaceous:		
Unit 2		
Clay, pisolitic, hard, white to tan (Sample 110)	5	0
Conglomerate, rust-colored		2-3
Cambrian:		
Sandstone, greenish-brown	1	0
Jordan Sandstone, white, quartz grains rounded and frosted	2-3	0
Covered interval to road level	5	0

Locality 89

Stearns Co., T. 124 N., R. 29 W., southeast and east banks above working face of Cold Spring "crystal" quarry.

	ft.	in.
Upper Cretaceous:		
Unit 3		
Shale, overlain by spoil banks (composed mostly of Pleistocene glacial drift) of variable thickness	9	0
(Sample 303) top 3 feet of shale.		
(Sample 302) basal 2 feet of shale.		
Unit 2		
Clay, pisolitic, eroded to featheredge along south part of east working face (Sample 295)		0-6
Unit 1		
Highly weathered Precambrian granite, mostly clay, blue-white	6	8
(Sample 301) 68-80 inches above base.		
(Sample 300) 51 to 68 inches above base.		
(Sample 299) 34 to 51 inches above base.		
(Sample 298) 17 to 34 inches above base.		
(Sample 297) from 0 to 17 inches above fresh granite base.		

Locality 90

Stearns County, SE¼ SE¼ NW¼ sec. 23, T. 123 N., R. 31 W., outcrop in first west tributary to Sauk River north of bridge, west of Richmond. (Bickford and Price locality *Rich*, samples 1-7, and 9.)

	ft.	in.
Pleistocene:		
Glacial drift	25	0
Upper Cretaceous:		
Unit 3		
Clay-shale, light-gray (Sample 29)	7	0
Lignite		6
Clay, dark-gray (Sample 28)	2	0
Unit 2		
Clay, pisolitic, iron-stained, light-gray (Sample 27)	5-6	0
Base of outcrop at river level.		

Locality 91

Morrison County, 1680 feet west and 1440 feet south of the NW cor. sec. 8, T. 127 N., R. 29 W., about 230 yards north of west end of bridge over Mississippi River. (Bickford and Price locality *Bolus.*)

	ft.	in.
Pleistocene:		
Glacial drift and alluvium	10	0
Upper Cretaceous:		
Unit 3		
Clay, light-gray (Sample 25)	1	0
Unit 1		
Precambrian igneous rock, pisolitic, iron-rich, weathered (Sample 26)	3	0
Covered interval to river level	3	0

Locality 92

Morrison County, SW¼ SW¼ sec. 20, T. 39 N., R. 32 W., on east bank of the Mississippi River below Blanchard Dam.

	ft.	in.
Pleistocene:		
Glacial drift	10-15	0
Upper Cretaceous:		
Unit 1		
Precambrian staurolite schist, highly weathered, grab sample (Sample 291)	5-6	0
Base of outcrop at river level.		

APPENDIX C

X-ray diffraction analyses of the less-than-two-micron fraction of samples collected by the author.

X-ray diffraction analyses of the less-than-two micron fraction of samples collected by Parham and Hogberg (1964), and by the author for this study are included here.

The data are listed by county.

Asterisk (*) indicates that electron microscope data for this sample are listed in APPENDIX E.

Key:

K	kaolinite	Feld	feldspar
I	illite	Pot	potassium
M	muscovite	Q	quartz
Mont	montmorillonite	Cr	cristobalite
Mx	mixed layer material	Gyp	gypsum
V	vermiculite	Cal	calcite
C	chlorite	D	dolomite
G	gibbsite	t	trace
B	boehmite	O	other
Plag	plagioclase		

Numbers in APPENDIX C to the right of the kaolinite, muscovite-illite, and montmorillonite columns, e.g., K(8) M-I(1) Mont(1) refer to the ratios of the intensity of first order x-ray peaks for each mineral minus the background count. The ratio indicates, in a general way, the relative abundance of each clay mineral.

Benton County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
325	SW¼ SW¼ SW¼ sec. 11, T. 36 N., R. 31 W.	K	I(t)	—	—	—	Precambrian granite, highly weathered; clay-rich, light silver-gray, drill core sample from 43.0-43.8 feet. Overlain by Pleistocene glacial drift.
326	SW¼ SW¼ SW¼ sec. 11, T. 36 N., R. 31 W.	K	—	—	—	—	Precambrian granite, decomposed; drill core sample from 48-49 feet.

Blue Earth County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
110	NW¼ SW¼ SW¼ sec. 25, T. 108 N., R. 27 W.	K	—	—	—	—	Clay, pisolitic, hard, white to tan.

Brown County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
1	NE¼ NE¼ sec. 26, T. 109 N., R. 35 W.	K	I	Mont.	—	C	Shale, gray.
2	............do.............	K	I	Mont.	—	C	Sand and clay, laminated.
3	............do.............	K	I	Mont.	—	C	Shale, gray.
4	............do.............	K	I	Mont.	—	C	Sand and clay, laminated.
5	NE¼ NE¼ sec. 26, T. 109 N., R. 35 W.	K	I	—	—	C?, Q, Mx	Clay, dark-gray.
7	............do.............	K	I	Mont.	—	C, Q, Gyp.	Shale, gray.
8	............do.............	K	I	Mont.	—	Q	Shale, light-gray.
246	............do.............	K	I(t)	Mont.	—	—	Bentonite, dark-green, waxy appearance.
45	SE¼ NW¼ sec. 31, T. 110 N., R. 30 W.	K?	I(6)	Mont.(4)	—	C?	Clay, shale, green, sandy.
46	NW¼ SE¼ SE¼ sec. 33, T. 112 N., R. 33 W.	K(5.5)	I(1.5)	Mont.(3.0)	—	—	Clay, black, organic-rich.
47	............do.............	K(7.0)	I(2.0)	—	—	Mx-V(1)	Shale, dark-gray to black, contains scattered ironstone concretions.
48	............do.............	—?	I	—	—	Mx, C, Q	Clay, light-gray.
49	NE¼ NW¼ NW¼ sec. 3, T. 111 N., R. 33 W.	K	I(t)	—	—	—	Metamorphic rock, highly weathered, clay-rich, light-yellow to white, abundant quartz.
144	Cen. NE¼ NE¼ sec. 4, T. 109 N., R. 30 W.	K	I(t)	Mont.(t)	—	—	Clay seams in cross-bedded sandstone, light-gray.
145	............do.............	K(5.5)	I(3.5)	Mont.(1)	—	Mx, Q	Clay, lignitic, seams in cross-bedded sandstone.
323	NW¼ NE¼ sec. 4, T. 109 N., R. 30 W.	—	I(4.5)	Mont.(5.5)	—	C	Clay, gray.

Mower County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
111	NW¼ NW¼ SW¼ sec. 32, T. 103 N., R. 17 W.	K(7.5)	I(2.5)	—	—	Q, Goe, Mx	Clay, red, 4.7 feet, auger sample.
112	Cen. SE¼ SE¼ sec. 35, T. 103 N., R. 17 W.	K(4.5)	I(5.5)	—	—	Q, Mx, Goe	Clay, mottled red, green, brown, and white, 12-foot auger sample.
113	NW¼ NW¼ NE¼ sec. 33, T. 101 N., R. 18 W.	K(3)	I(7)	—	—	Mx	Clay, red, tan, brown and green, 7-foot auger sample.
114	SW¼ SW¼ SW¼ sec. 28, T. 101 N., R. 18 W.	K(6)	I(4)	—	—	Q, Mx, Goe	Clay, red, 3-foot auger sample.
166	NE¼ SE¼ SW¼ sec. 23, T. 103 N., R. 18 W.	K(5.5)	I(4.5)	—	—	Q, Mx, Goe	Clay, red and white, 13-foot auger sample.
266	NW¼ SW¼ NW¼ sec. 25, T. 102 N., R. 18 W.	K(7.5)	I(2.5)	—	—	Q, Mx	Clay, red, 6.2 feet, auger sample.
269	Cen. SW¼ sec. 23, T. 103 N., R. 18 W.	K(9)	I(1)	—	—	Q, Mx, Goe	Clay, red, top 6 inches of 5-foot bed, auger sample.

Nicollet County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
142	SW¼ NW¼ NW¼ sec. 35, T. 110 N., R. 30 W.	—	I(6)	Mont.(4)	—	—	Shale, green, soft.
143	............do.............	K?	I(5.5)	Mont.(4.5)	—	Cal, C?	Shale, red, soft.
	Samples 304-A through 304-U are sample cuttings of weathered Precambrian gneiss from water well.						
304-A	SW¼ NW¼ NE¼ sec. 6, T. 111 N., R. 32 W., Fort Ridgley State Park, headquarters area.	K(9)	I(1)	—	—	—	Altitude of sample interval 930-935 feet.
304-B	............do.............	K(10)	—	—	—	—	Altitude 925-930 feet.
304-C	............do.............	K(9)	I(1)	—	—	—	Altitude 920-925 feet.
304-D	............do.............	K(9)	I(1)	—	—	—	Altitude 915-920 feet.
304-E	............do.............	K(9)	I(1)	—	—	—	Altitude 910-915 feet.
304-F	............do.............	K(9)	I(1)	—	—	—	Altitude 905-910 feet.
304-G	............do.............	K(9)	I(1)	—	—	—	Altitude 900-905 feet.
304-H	............do.............	K(9)	I(1)	—	—	—	Altitude 895-900 feet.
304-I	............do.............	K(8)	I(2)	—	—	—	Altitude 890-895 feet.
304-J	............do.............	K(8)	I(2)	—	—	—	Altitude 885-890 feet.
304-K	............do.............	K(8)	I(2)	—	—	—	Altitude 880-885 feet.
304-L	............do.............	K(8)	I(2)	—	—	—	Altitude 875-880 feet.
304-M	............do.............	K(6.5)	I(2.5)	Mont.(1)	—	—	Altitude 870-875 feet.
304-N	............do.............	K(8)	I(1.5)	Mont.(0.5)	—	—	Altitude 865-870 feet.
304-O	............do.............	K(6.5)	I(2.5)	Mont.(1)	—	—	Altitude 860-865 feet.
304-P	............do.............	K(5.5)	I(3)	Mont.(1.5)	—	Pot. & plag. feld.	Altitude 855-860 feet.
304-Q	............do.............	K(6.5)	M(2.5)	Mont.(1)	—	Pot. & plag. feld.	Altitude 850-855 feet.

Nicollet County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
304-R	............do.............	K(5.5)	M(3)	Mont.(1.5)	—	Q, Pot. & plag. feld.	Altitude 845-850 feet.
304-S	............do.............	K(6)	M(2.5)	Mont.(1.5)	—	Pot. & plag. feld.	Altitude 840-845 feet.
304-T	............do.............	K(4.5)	I(3.5)	Mont.(2)	—	Q, Pot. & plag. feld.	Altitude 835-840 feet.
304-U	............do.............	K(4.5)	I(4.5)	Mont.(1)	—	....do....	Altitude 825-835 feet.

Goodhue County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
20	NE¼ NW¼ sec. 26, T. 111 N., R. 15 W.	K(6.5)	I(3.5)	—	—	Mx, Q	Clay, light-gray, sandy, 10 feet exposed in Thomforde clay pit.
21	S½ sec. 3 and N½ sec. 10, T. 111 N., R. 15 W.	K(6.5)	I(3.5)	—	—	Mx	Clay, white, contains some sand, exposed in clay bank clay pits.

Itasca County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
30	SE¼ SE¼ sec. 24, T. 57 N., R. 22 W.	—	I	Mont.	—	C	Shale, gray, mostly non-calcareous, some scattered pyrite concretions and gypsum present.

Lyon County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
259	SE¼ sec. 16, T. 110 N., R. 39 W.	K(3.5)	I(2.0)	Mont.(4.5)	—	—	Shale, dark-gray, fissile, contains marine fossils.

Morrison County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
291	SW¼ SW¼ sec. 20, T. 39 N., R. 32 W.	K	—	—	—	—	Staurolite schist, weathered.

Redwood County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
10*	SE¼ SW¼ sec. 35, T. 113 N., R. 35 W.	K	—	—	—	—	Clay, white to buff, sandy.
11	............do.............	K	—	—	G(t)	—	Clay, lignitic, with some sandy layers.
12	............do.............	K(9)	I(1)	Mont.(t)	—	—	Clay, black and gray.
13	............do.............	K	—	—	—	—	Clay, sandy, pisolitic, with sandy layers.
14	............do.............	K	—	—	G	—	Clay, light-buff, some quartz present, scattered pisolites.
15	............do.............	K(t)	—	Mont.	—	—	Bentonite, dark-green.

Redwood County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
33*	SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W.	K(t)	—	Mont.	—	—	Bentonite, yellowish-green.
34*	SW¼ SW¼ NW¼ sec. 33, T. 113 N., R. 35 W.	K	—	—	—	—	Decomposed gneiss, white.
38*	SW¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	—	—	Clay, tan, contains some sand.
39*	............do.............	K	—	—	—	—	Clay, white, limonite staining on joint surfaces.
40*	............do.............	K	—	—	—	—	Clay, white, hard, brecciated texture.
41	............do.............	K	—	—	G	—	Clay, pisolitic, iron-stained, hard.
43	NE¼ NW¼ NE¼ sec. 8, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, pisolitic, light-gray.
53*	SE¼ NW¼ NE¼ sec. 32, T. 113 N., R. 35 W.	K	—	—	—	—	Clay, white to tan and yellow, top part pisolitic and iron-stained.
54*	............do.............	K	I(t)	—	—	—	Decomposed gneiss, clayey, yellowish-brown.
55*	SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W.	K	I(t)	—	—	—	Clay, light-gray, root traces present.
56	............do.............	K	—	Mont.	—	—	Clay, shaly, dark-gray.
57	............do.............	K	I	Mont.	—	Q	Clay, gray.
58*	SW¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	G	—	Clay, gray to purplish-gray.
59	............do.............	K	—	Mont.(t)	G(t)	—	Clay, gray.

Redwood County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
60*	. . . . .do.	K	—	—	G	—	Clay, purplish-gray.
69*	SE¼ SW¼ sec. 35, T. 113 N., R. 35 W.	K	—	Mont.(?)	—	—	Clay, hard, conchoidal fracture.
70*	SE¼ NW¼ sec. 1, T. 112 N., R. 35 W.	K(9)	I(1)	—	—	—	Decomposed gneiss, buff.
71	. . . . .do.	K(9)	I(1)	—	—	—	Decomposed gneiss, light-blue.
72*	SE¼ NW¼ NW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	—	—	Clay, buff to tan, sparse sand present.
73*	NE¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	—	—	Decomposed gneiss, buff.
74	. . . . .do.	K	—	—	—	—	Clay, buff to tan, some sand present.
75*	SE¼ NE¼ SW¼ sec. 2, T. 112 N., R. 35 W.	K	I(t)	—	—	—	Decomposed gneiss, upper part tan, lower part silver-blue.
77	NW¼ SW¼ NW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	—	—	Clay, buff to tan.
78	SE¼ SW¼ NW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	G	—	Clay, tan to gray.
79	SE Cor., SE¼ NE¼ SE¼ sec. 30, T. 113 N., R. 35 W.	K	—	—	—	—	Clay, sandy, some iron-staining, pisolitic in parts.
103	SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W.	K	—	—	—	—	Decomposed gneiss, clayey, white.
104*	. . . . .do.	K	—	—	—	—	Decomposed gneiss, clayey, white.

Redwood County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
125	NW¼ NW¼ NW¼ sec. 8, T. 112 N., R. 35 W.	—	I(t)	Mont.	—	Cr.	Shale fragments, greenish-gray, hard, fissile, from Pleistocene gravel.
126	NW¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W.	K	—	Mont.	—	—	Bentonite, green.
128	SE¼ SE¼ SE¼ sec. 34, T. 113 N., R. 35 W.	K	—	—	—	—	Clay, grayish-green.
129	............do.............	K	—	—	G(t)	—	Clay, gray, lignite streaks throughout.
130	............do.............	K	—	Mont.(t)	—	Q	Shale, dark-gray to black.
131	............do.............	K	—	Mont.	G(t)	—	Shale, dark-gray to black.
132	............do.............	K	—	Mont.	G(t)	—	Shale, tannish-gray.
146	NW¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W.	K	—	—	—	—	Metamorphic rock, highly weathered, clay-rich, light blue-gray.
270	NW¼ NE¼ SE¼ sec. 24, T. 113 N., R. 36 W.	K(7)	M(3)	—	—	—	Metamorphic rock, highly weathered, micaceous, greenish tan.
271*	SE¼ NW¼ SE¼ sec. 24, T. 113 N., R. 36 W.	K	—	—	—	—	Clay, soft, rust-colored, highly weathered Precambrian rock.
272*	............do.............	K(9)	M(1)	—	—	—	Clay, soft, silver-blue, highly weathered Precambrian rock.
274*	SE¼ SW¼ sec. 4, T. 113 N., R. 36 W.	K	I(t)	Mont.	—	—	Clay, white, malachite-stained.

Redwood County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
275	............do.............	K	I(t)	Mont.	—	—	Amphibolite, highly weathered, soft, red or maroon.
276*	............do.............	K	I(t)	—	—	—	Metamorphic rock, highly weathered, tan and maroon, horizontally banded.
277	Cen. NE¼ NW¼ sec. 31, T. 113 N., R. 35 W.	K	—	—	—	—	Decomposed gneiss, tan to brownish-red.
282	Cen. NE¼ sec. 23, T. 112 N., R. 34 W.	—	—	Mont.	—	—	Basalt, highly weathered.
283	............do.............	—	—	Mont.	—	—	Basalt, slightly weathered.
320	NW Cor. SW¼ NW¼ SW¼ sec. 29, T. 113 N., R. 35 W.	K	—	—	—	—	Highly weathered gneiss, clay-rich.

Renville County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
35*	SE¼ SE¼ SW¼ sec. 3, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, light-gray.
36	SW¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, buff, soft.
37	W½ SW¼ NW¼ sec. 27, T. 112 N., R. 33 W.	K	—	—	—	—	Clay, very light-gray, contains root traces.

Renville County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
42*	SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, pisolitic, hard, iron-stained.
44*	SE¼ SE¼ NE¼ sec. 31, T. 112 N., R. 32 W.	K	—	—	—	—	Clay, white, quartz-rich.
50*	SW¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, scattered pisolites present, light-buff toward top, red and buff toward base.
51*	SW¼ SE¼ NW¼ sec. 11, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, hard, buff, some pisolites present toward top.
52	SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, gray to tan, top part pisolitic, lower part sandy.
76	SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 N.	K(5)	I(2.5)	Mont.(2.5)	—	Q	Shale, gray, micaceous, non-calcareous, contains some pyrite.
80	SE Cor. SE¼ NE¼ SE¼ sec. 30, T. 113 N., R. 35 W.	K	—	—	G	—	Clay, pisolitic, iron-stained.
81	............do.............	K	—	—	—	—	Clay, white to gray.
105	NW¼ NW¼ SW¼ sec. 21, T. 112 N., R. 33 W.	K(8)	I(2)	—	—	V, Mx	Clay, soft, brownish-green, weathered.
106	............do.............	K(5)	I(3)	Mont.(2)	—	—	Shale, gray to brown, scattered ironstone concretions present, fossil leaves present.
107	............do.............	K(6)	I(2)	Mont.(2)	—	Q	.............do................
108	............do.............	K(7.5)	I(1)	Mont.(1.5)	—	Q	Shale, silty, tan.

Renville County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
134	SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W.	K	—	—	—	—	Clay, tannish-gray, some pisolites present.
142	SW¼ NW¼ NW¼ sec. 35, T. 110 N., R. 30 W.	—	I	Mont.	—	—	Shale, green, poorly bedded.
143	............do.............	K(t?)	I	Mont.	—	Feld?	Shale, red, poorly bedded.
278	SE¼ NW¼ SW¼ sec. 3, T 112 N., R. 34 W.	K	—	—	—	—	Clay, blocky, tan to buff.
279	............do.............	K	—	—	G	—	Clay, pisolitic, iron-stained.
280	............do.............	K	—	—	G	—	Clay, pisolitic, iron-stained.
281	............do.............	K	I(t)	—	G	V	Shale, blue-gray.
324	NW¼ SW¼ NW¼ sec. 33, T. 113 N., R. 34 W.	K	—	—	—	—	Amphibolite, highly weathered, soft, gray.
338	SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W.	K	I(t)	—	—	V	Clay-shale, dark-gray, organic-rich.

Stearns County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
27	NW¼ NE¼ sec. 23, T. 123 N., R. 31 W.	K	—	—	G	B	Shale, light-gray.
28	............do.............	K	—	—	G	—	Clay, dark-gray.
29	............do.............	K	—	—	G	—	Clay, pisolitic, light-gray.
295	East face, Cold Spring "crystal" quarry, T. 124 N., R. 29 W.	K	—	—	—	—	Clay, pisolitic.

Stearns County (continued)

Sample number	Location	K	M-I	Mont.	G	O	Sample description
297	do	K	—	—	—	—	Highly weathered granite, mostly clay, blue-white.
298	do						do
299	do	K	—	—	—	—	do
300	do	K	—	—	—	—	do
301	do	K	—	—	—	—	do
302	do	K(6)	I(2)	Mont.(2)	—	V?, Q	Shale.
303	do	K(4)	I(2)	Mont.(4)	—	Q, V?	Shale.
327	Cen. SE¼ NW¼ sec. 6, T. 125 N., R. 32 W.	K(8)	I(2)	—	—	—	Highly weathered Precambrian granite or gneiss. Drill core sample from 78.5-79.2 feet. Overlain by Pleistocene glacial drift.
328	do	K(7)	M(3)	—	—	—	Highly weathered Precambrian granite or gneiss. Drill core sample from 85.5-85.6 feet.
329	SE¼ SW¼ NW¼ sec. 6, T. 125 N., R. 32 W.	K(4.5)	I(3)	Mont.(2.5)	—	—	Precambrian schist; highly weathered, dark-green, overlain by Pleistocene glacial drift, drill core sample from 40.5-41.5 feet.
330	do	K(3.5)	I(2)	Mont.(4.5)	—	—	Precambrian schist, highly weathered, light-green drill core sample from 45.5-46.8 feet.
331	do	K(3)	I(2)	Mont.(5)	—	—	Precambrian schist, highly weathered, olive-green, drill core sample from 50.5-52.5 feet.
332	do	K(1)	I(1.5)	Mont.(7.5)	—	—	Precambrian schist, highly weathered, light-green, drill core sample from 56.5-57.5 feet.

Wabasha County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
289	SE¼ sec. 26 and NE¼ sec. 35, T. 109 N., R. 14 W.	K(9)	I(1)	—	—	—	Clay, white, soft, exposed in pipeline trenches.

Yellow Medicine County

Sample number	Location	K	M-I	Mont.	G	O	Sample description
247*	NW¼ SW¼ sec. 14, T. 115 N., R. 39 W.	K	—	—	—	—	Clay, pisolitic, light-gray.
249	............do.............	K	I	Mont.	—	—	Shale, gray.
257	NW¼ SE¼ SE¼ sec. 9, T. 115 N., R. 39 W.	—	I	Mont	—	?	Schist, slightly weathered rust-yellow.
258	NW¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W.	K	I(t)	—	—	—	Decomposed gneiss, tan.
260*	SW¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W.	K	—	—	—	—	Schist, decomposed, olive-drab.
261*	............do.............	K	I	—	—	—	Schist, decomposed, red.
262	............do.............	K	—	Mont.	—	—	Decomposed gneiss, greenish-yellow to red.
263*	SE¼ SW¼ SW¼ sec. 10, T. 115 N., R. 39 W.	K	—	—	—	—	Decomposed gneiss, white to tan.

APPENDIX D

X-ray diffraction analyses of the less-than-two micron fraction of samples collected by Bickford and Price.

X-ray diffraction analyses of the less-than-two-micron fraction of samples collected in 1947 by Bickford and Price. Data are listed by county and samples from each locality are arranged in descending order.

Asterisk (*) indicates that electron microscope data for these samples are listed in APPENDIX F.

Key:

K	kaolinite	V	vermiculite
I	illite	G	gibbsite
M	muscovite	B	boehmite
Mont	montmorillonite	t	trace

Numbers in APPENDIX D to the right of the kaolinite, muscovite-illite, and montmorillonite columns, e.g., K(8) M-I(1) Mont(1) refer to the ratios of the intensity of first order x-ray peaks for each mineral minus the background count. The ratio indicates, in a general way, the relative abundance of each clay mineral.

Brown County

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
N NW¼ NW¼ NW¼ sec. 3, T. 111 N., R. 33 W. (See Locality 13, APPENDIX B)					
1104-1	K(9)	M	—	4	Clay, light-colored, weathered gneiss.
1105-2	K	M(t)	—	2.7	................do................
1106-3	K(9)	M(1)	—	2.7	Weathered gneiss.
1107-4	K(9)	M(1)	—	3.7	Weathered gneiss; auger sample.

Morrison County

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
BOLUS Cen. sec. 8, T. 127 N., R. 29 W. (See Locality 91, APPENDIX B)					
1165	K	M	Mont.(?) G	.7	Clay, gray, somewhat pisolitic, contains quartz grains, hard.
1166-0	K	—	G	2	Clay, hard, heavy iron stain, pisolitic.
1167-1	K	—	G	2	Clay, hard, iron-stained, pisolitic, light-green.
1168-2	K	—	G	3.5	Clay, pisolitic, hard, iron-stained, light-green, speckled with white clay.
1169-3	K	—	—	2.5	Clay, somewhat pisolitic, green.

Redwood County

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
RAMSEY Cen. of n. edge SE¼ sec. 36, T. 113 N., R. 36 W. (See Locality 16, APPENDIX B.)					
1126-1	K	I(t)	—	4	Clay, yellow, soft; taken from top of bluff.
1127-2	K	I(t)	—	2	Clay, yellow, soft.
1128-3	K	M(t)	—	5	Weathered gneiss; gneissic texture partly preserved; hard and blocky, irregularly iron-stained, quartz present, green clay mineral.
1129-4	K(7)	M(3)	—	6	................do................
1130-5	K	I(t)	—	5	................do................
1131-6	K(9)	M(1)	—	5	................do................
1132-7	K(9)	M(1)	—	4	................do................
1133-8	K	—	—	6.5	................do................
1134-9	K	—	—	6	................do................
1136-10	K	M(t)	—	5	................do................
1135-11	K	I(t)	—	6	................do................
1137-12	K	I(t)	—	5	................do................
1138-13	K	I(t)	—	6	................do................
1139-14	K(9)	M(1)	—	6	................do................
1140-15	K	M(t)	—	5	................do................
1141-16	K	I(t)	—	5.5	................do................
*1142-17	K	M(t)	—	7	................do................

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
PARK SE¼ SW¼ NE¼ sec. 36, T. 113 N., R. 36 W. (See Locality 15, APPENDIX B)					
1159-2	K	I(t)	—	6	Weathered gneiss; gneissic texture partly preserved; blocky; mottled green and yellow.
1160-3	K	I(t)	—	5	...............do...............
1161-4	K	I(t)	—	4.5	...............do...............
1162-5	K	I(t)	—	6	...............do...............
1163-6	K	M(t)	—	5	...............do...............
1164-7	K	I(t)	—	4	...............do...............
SLUMP SW¼ NW¼ NE¼ sec. 36, T. 113 N., R. 36 W.					
1202-15	K	I(t)	—	1	Clay just below soil; sharp contact with sample below; auger sample.
1201-14	K	I(t)	—	6	Weathered gneiss, soft, blocky, greenish-gray, irregularly iron-stained; auger sample.
*1200-13	K	—	—	6	...............do...............
1199-12	K	I(t)	—	6	...............do...............
1198-11	K	—	—	7	...............do...............

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1197-10	K	M(t)	—	7	................do................
1196-9	K	M(t)	—	7.5	................do................
1195-8	K	M(t)	—	5	................do................
1194-7	K	—	—	6	................do................
1193-6	K	M(t)	—	6	................do................
1192-5	K	M(t)	—	7	................do................
1191-4	K	M(t)	—	6	................do................
1190-3	K	I(t)	—	4.5	................do................
*1189-2	K	—	—	3	................do................
MANN SW¼ SW¼ SW¼ sec. 30, T. 113 N., R. 35 W. (See Locality 17, APPENDIX B.)					
1188-12	K	I(t)	—	2	Clay, blue, lignitic.
1187-11	K	—	G	.3	Pisolitic iron oxide layer.
1186-10	K	—	—	1.5	Gradational zone between pisolitic material and clay.
1185-9	K	—	—	5	Clay, grayish-white with round, red spots of iron stain.
1184-8	—	—	—	5	Sample missing.
1183-7	K	—	—	8.3	Clay, yellowish-gray, spotted and streaked.
1177-1	K	I(t)	—	2	Clay, powder-blue, decomposed Precambrian rock; auger sample.

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1178-2	K	M(t)	—	2	................do................
1179-3	K	I(t)	G, V(t)?	1.5	................do................
*1180-4	K	M(t)	—	1.8	................do................
1181-5	K(9)	M(1)	—	1.4	................do................
1182-6	K(9)	M(1)	—	1.3	................do................
RALPH SE¼ SW¼ SW¼ sec. 30, T. 113 N., R. 35 W.					
1210-9	K	I(t)	—	6	Clay, yellowish-gray, spotted and streaked by iron staining; residual product of weathered Precambrian metamorphic rock.
1209-8	K	I(t)	—	7	................do................
1208-7	K	I(t)	—	6	................do................
1207-6	K	M(t)	—	7	................do................
1206-5	K	M(t)	—	8	................do................
———	—	—	—	5	Sample missing.
1205-3	K	M(t)	—	6	See 1209-9.
*1204-2	K	M(t)	—	5	Transitional in composition between 1205-3 and 1203-1.
1203-1	K	M(t)	—	7	Metamorphic rock, decomposed, silver-green, quartz veins and iron oxide stain common.

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
NORTH REDWOOD NE¼ SE¼ SE¼ sec. 30, T. 113 N., R. 35 W. (See Locality 18, APPENDIX B.)					
1247-8	K	—	—	.7	Clay, light-colored, bauxitic.
1246-7	K	—	G	8	Clay, light-gray, iron-speckled; transitional upward.
1245-6	K	—	G?	5	Clay, greenish-brown with iron oxide-coated pisolites.
1244-5	K	I(t)	—	2.8	Decomposed gneiss.
1243-4	K	I(t)	—	3.7	................do................
*1242-3	K	I(t)	—	4.5	................do................
1241-2	K	I(t)	—	9.5	................do................
1240-1	K	I(t)	—	6	................do................
GULLEY NE¼ NW¼ sec. 32, T. 113 N., R. 35 W. (See Locality 19, APPENDIX B.)					
1216-6	K	—	—	1	Clay, light-colored, pisolitic.
1215-5	K	—	—	5	Clay, yellow.
1214-4	K	—	—	4	Clay, bluish-gray.
1213-3	K	—	—	2	Clay, yellow, iron-stained.
1212-2	K	—	—	1.5	Clay, yellow, iron-speckled.
1211-1	K	—	—	2	Clay, light-colored, pisolitic, with quartz pebbles; iron-stained.

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1217-7	K	I(t)	—	3.8	Clay, blue to brown. Auger sample.
*1218-8	K(8)	M(1)	Mont.(t)	1.5	................do.................
CROW CREEK NE¼ SW¼ SW¼ sec. 2, T. 112 N., R. 35 W. (See Locality 46, APPENDIX B.)					
1219-1	K	—	G	.5	Clay, blue, with many iron oxide pisolites.
1220-2	K	—	G?	3	Clay, blue-gray, pisolitic, some iron stain present.
1221-3	K	—	—	6	Clay, yellowish-blue, slightly pisolitic, streaks and spots of iron oxide.
1222-4	K	—	—	1.5	Clay, light-colored.
1223-5	K	—	—	2	Clay, light-blue; auger sample.
1224-6	K	—	—	2	................do.................
1225-7	K	—	—	1.6	................do.................
*1226-8	K	—	—	2.3	................do.................
1227-9	K	I(t)	—	2.3	................do.................
1228-10	K	I(t)	—	1.5	................do.................
1229-11	K	I(t)	—	2	Clay, light-colored.
1230-12	K	—	—	1.5	................do.................
1231-13	K	I(t)	—	4.5	................do.................
HENDERSEN SE¼ SE¼ sec. 34, T. 113 N., R. 35 W. (See Locality 3, APPENDIX B.)					

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1232-1	K	—	Mont.(t)	2	Clay, brown, iron-stained, probably equivalent to nearby pisolitic high-iron clays.
1233-2	K	—	—	3	Clay, light-blue; auger sample.
1234-3	K	I(t)	—	1.7	. . . . .do. . . . .
1235-4	K	I(t)	—	3	. . . . .do. . . . .
1236-5	K	I(t)	—	1	. . . . .do. . . . .
1237-6	K	I(t)	—	1.8	. . . . .do. . . . .
*1238-7	K	M(t)	—	2	. . . . .do. . . . .
1239-8	K(9)	M(1)	—	1.5	. . . . .do. . . . .
M NW¼ NW¼ sec. 2, T. 112 N., R. 35 W. (See Locality 5, APPENDIX B.)					
1091-M	K	—	G	.7	Clay, pisolitic, light-colored.
1092-00	K	—	G	2.3	Clay, light-colored, pisolitic, yellow-stained.
1093-0	K	—	—	2.3	. . . . .do. . . . .
1094-1	K	—	—	4	Clay, light-gray, yellow staining present.
1095-2	K	—	—	4	. . . . .do. . . . .
1096-3	K	—	—	9.5	Clay, somewhat pisolitic, sandy, iron-stained.
1097-4	K	—	—	7	Clay, light-yellow.
1098-5	K	—	—	7	Clay, sandy, yellow-gray.
1099-6	K	—	—	6.3	Clay, some partly light-gray and some partly purplish-pink.

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1100-7	K	—	—	4	Clay, gray with some yellow sand, overlies angular conglomerate which grades downward into 1 foot green clay.
1101-8	K	—	—	1.5	Sand, yellow, grades downward to grayish-green, argillaceous, fine sand which in turn grades downward into conglomerate.
1102-9	K	—	—	2.3	Basal conglomerate, various sizes of quartz granules with small pieces of green clay.
*1103-10	K	M(t)	—	7	Weathered gneiss.
P SE¼ NW¼ NE¼ sec. 8, T. 112 N., R. 34 W. (See Locality 6, APPENDIX B.)					
1108-0	K	—	—	.8	Clay, pisolitic, light-gray.
1109-1	K	—	—	3.5	Clay, pisolitic; pisolites light-colored and iron-stained, matrix light greenish-gray.
1110-2	K	—	—	2	Clay, light-gray, speckled with iron oxide, somewhat pisolitic.
1111-3	K	—	—	2	Clay, light bluish-gray, contains quartz pebbles and a few pisolites; auger sample.
1112-4	K	—	—	.7	................do................
R NW¼ NE¼ NW¼ sec. 8, T. 112 N., R. 34 W.					
1114-1	K	—	G	4	Clay, pisolitic, iron-stained pisolites, light-colored matrix, quartz sand present.

Redwood County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
1115-2	K	—	—	.5	Clay, light-gray, contains much fine to very coarse quartz sand.
1116-3	K	—	—	2	Clay, pisolitic, light-gray, some iron-staining.
1117-4	K	—	—	1.5	Clay, yellow, partly sandy, overlies weathered gneiss.
S SE¼ SE¼ SE¼ sec. 9, T. 112 N., R. 34 W. (See Locality 23, APPENDIX B.)					
1119	K	—	—	4.5	Weathered schist or gneiss, dark-green, contains some iron oxide staining.

Renville County

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Description Sample
	K	M-I	Other		
A SE¼ SW¼ NW¼ sec. 11, T. 112 N., R. 34 W. (See Locality 9, APPENDIX B.)					
1000-0	K	—	G(t)	4	Clay, hard, blocky, light-colored; contains iron-stained pisolites.
1001-1	K	—	—	5.5	Clay, light yellow, hard, blocky, some pisolites.

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
1002-2	K	—	—	1.7	Clay, pisolitic, light-colored, some iron-oxide staining.
1003-3	K	—	—	5	Clay, white with some yellow specks.
1004-4	K	—	—	2	Clay, white to yellow.
1005-5	K	—	—	1.9	Clay, red; auger sample.
1006-6	K	—	—	.7	Clay, transition zone; auger sample.
1007-7	K	—	—	1.5	Clay, light yellow-brown; auger sample.
1008-8	K	—	—	1.5	................do................
B NE¼ NE¼ SE¼ sec. 4, T. 112 N., R. 34 W. (See Locality 22, APPENDIX B.)					
1016-1	K	—	G(t)	1.5	Clay, light-yellow, contains iron-stained pisolites.
1017-2	K	—	G(?)	3	Clay, pisolitic, much iron-staining. Pisolites iron-rich, reddish-yellow, grade downward to greenish-yellow clay.
1018-3	K	—	—	3	Clay, scattered pisolites, greenish-yellow, some specks of iron oxide.
1019-4	K	—	—	3.5	Clay, yellow-brown, flecks of iron-stain, some spots of green clay.
1020-5	K	—	—	2	Clay, yellowish-brown; auger sample.
1021-6	K	—	—	2.3	Clay, blue; thin layer above yellowish-brown clay; auger sample.
1022-7	K	—	—	2	Clay, yellowish-brown; auger sample.
1023-8	K	—	—	1.8	................do................
1024-9	K	—	—	2	................do................

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction: K	M-I	Other	Thickness (in feet)	Sample Description
*1025-10	K	I(t)	—	1.7	. . . . .do. . . . .
1026-11	K	I(t)	—	2	Clay, deep-blue, some quartz veins; auger sample.
1027-12	K	—	—	3.7	Clay, yellowish-brown, iron oxide staining, quartz present; auger sample.
1028-13	K	—	—	.7	Clay, deep-blue; auger sample.
C NE¼ NE¼ NW¼ sec. 10, T. 112 N., R. 34 W. (See Locality 7, APPENDIX B.)					
1029-00	K	—	—	2	Clay, light-gray.
1030-0	K	—	G	5.3	Clay, light-gray with yellow stain.
1031-1	K	—	G(?)	4	Clay, light-gray with yellow stain, lignitic material.
1032-2	K	—	G(t)	.8	Clay, carbonaceous.
1033-3	K	—	—	6.3	Clay, light-colored.
*1034-4	K	—	—	3.3	Clay, hard, light-gray; auger sample.
1035-5	K	—	—	2.9	Clay, yellowish-brown, sandy; auger sample.
1036-6	K	—	—	1.8	Clay, yellowish-brown, contains iron oxide nodules; auger sample.
1037-7	K	—	—	.6	Sand, yellow-brown; auger sample.
1038-8	K	—	—	.5	Clay, pisolitic (?), light-colored; auger sample.
1039-9	K	—	—	.5	Clay, yellow, slightly pisolitic (?); auger sample.
1040-10	K	—	—	.3	Sand, yellow-brown; auger sample.

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
1041-11	K	—	—	2.3	Clay, sandy, light-yellow-brown; auger sample.
1042-12	K	—	—	.8	................do................
1043-13	K	—	—	2.8	Clay, light brownish-gray; auger sample.
1044-14	K	—	—	1.5	Clay, light brownish-gray with quartz granules; auger sample.
1045-15	K	—	—	2	Clay, brown, iron-stained, contains quartz granules; auger sample.
*1046-16	K	—	—	.3	Clay, mottled brown and blue; quartz present; auger sample.
D SE¼ NW¼ NW¼ sec. 4, T. 112 N., R. 34 W.					
1047-1	K	—	—	.7	Clay, light-gray.
1048-2	K	I(t)	—	4.3	Clay, light-gray.
1049-3	K	I(t)	—	.5	Clay, yellow-brown.
———	—	—	—	5.3	Sample missing.
1052-6	K	I(t)	—	2.8	Clay, light yellow-brown, slightly pink-stained; auger sample.
1053-7	K	I(t)	—	2.7	................do................
1054-8	K	I(t)	—	1.4	................do................
E SE¼ NW¼ SE¼ sec. 3, T. 112 N., R. 34 W. (See Locality 8, APPENDIX B.)					
1055-E	K	—	G(t)	.7	Clay, hard, iron-rich, pisolitic.

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
1056-00	K	—	—	4	Clay, iron-coated pisolites, gray centers, matrix yellow-brown to blue-green.
1057-0	K	—	—	2	...............do................
1058-1	K	—	—	2.5	...............do................
1059-2	K	—	—	3.5	...............do................
1060-3	K	—	—	3	...............do................
1061-4	K	—	—	2	Clay, iron-stained, contains gray pisolites, yellow-brown matrix.
1062-5	K	—	—	2	Clay, iron-stained, contains gray pisolites, blue-green matrix.
1063-6	K	Mont.(?)	G	.7	Clay, pisolitic, sandy, lignitic.
1064-7	K	—	GV(?)	1.4	Clay, yellow at top, gray toward base, lower part carbonaceous.
1065-8	K	—	—	1	Clay, light-gray, yellow-stained, somewhat pisolitic.
1066-9	K	—	—	1.5	...............do................
1067-10	K	—	—	4	Clay, light yellow-gray.
1068-11	K	—	—	2.8	Clay, yellow-gray.
1069-12	K	—	—	1.5	Clay, sandy, green to yellow.
1070-13	—	—	—	1.9	Sample missing.
1071-14	K	—	—	2.8	Residual weathered metamorphic rock, greenish-gray to powder-blue clay, auger sample.
1072-15	K	—	—	2.3	...............do................
1073-16	K	—	—	3.5	...............do................
*1074-17	K	—	—	2.3	...............do................

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction			Thickness (in feet)	Sample Description
	K	M-I	Other		
G NW¼ NW¼ SW¼ sec. 21, T. 112 N., R. 33 W. (See Locality 38, APPENDIX B.)					
1075-0	K	—	G(t)	3	Clay, somewhat pisolitic, light bluish-gray, iron-stained.
1076-1	K	—	—	3.7	Clay, iron-stained, light bluish-gray.
1077-2	K	—	—	2.3	Clay, light yellow-gray.
1078-3	K	—	—	7	Clay, light yellow-brown, parts stained.
1079-4	K	M(t)	—	4.3	Clay, yellow-brown; auger sample.
1079-A-5	K	M(t)	—	3.8	................do................
MUNSEL NE¼ NE¼ SW¼ sec. 12, T. 112 N., R. 34 W.					
1143-1	K	M(t)	—	3.5	Clay, powder-blue, residual weathered metamorphic rock; auger sample.
1144-2	K	I(t)	—	6.5	................do................
1145-3	K	M(t)	—	4.5	................do................
*1146-4	K	I(t)	—	3.5	................do................
1147-5	K(9)	M(1)	—	4.2	................do................
1148-6	K(9)	M(1)	—	2.7	................do................
BERG NE¼ NW¼ SW¼ sec. 35, T. 112 N., R. 33 W. (See Locality 40, APPENDIX B.)					
1170-1	K	—	Mont.(?)	5	Clay, pisolitic, matrix light-gray, iron-stained pisolites.

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				
	K	M-I	Other	Thickness (in feet)	Sample Description
———	—	—	—	0.7	Sand, yellow.
1171-2	K	—	—	2	Clay, similar to sample 1170-1 but lighter in color and contains more sand.
H NE¼ SW¼ SE¼ sec. 18, T. 112 N., R. 33 W. (See Locality 29, APPENDIX B.)					
1080-1	K(8)	M(1)	—	6	Clay, buff.
1081-2	K(8)	M(1)	—	5	Clay, yellowish-gray, iron-oxide stained; auger sample.
1082-3	K(9)	M(1)	—	3.1	................do................
1083-4	K(9)	M(1)	—	1.8	Clay, red to brown, much iron oxide; auger sample.
K SE¼ SE¼ SE¼ sec. 35, T. 112 N., R. 33 W. (See Locality 41, APPENDIX B.)					
1085-1	K	—	—	2.5	Clay, yellowish-gray.
1086-2	K	—	—	5.2	Clay, light-gray, sandy at top, grades downward into cream-colored clay.
———	—	—	—	3.3	Clay, cream-colored.
1088-4	K	—	—	3.1	................do................
*1089-5	K	—	—	4.5	Clay, brownish-yellow, sandy, grades downward into white sand; sand grades into clay beneath.
1090-6	K	—	—	.4	Clay, light-colored.

Renville County (continued)

Sample location and designation	X-ray determination of clay mineralogy of $<2\mu$ fraction				Sample Description
	K	M-I	Other	Thickness (in feet)	
RUONA N½ SE¼ sec. 31, T. 112 N., R. 32 W.					
1248-1	K	I(t)	—	5.8	Clay, cream-colored, grades downward to greenish-blue clay; auger sample.
V SE¼ NW¼ NE¼ sec. 18, T. 113 N., R. 35 W.					
1120-V	K	—	—	—	Clay, dark-green; weathered metamorphic rock.
W NW¼ SW¼ SW¼ sec. 28, T. 113 N., R. 34 W.					
1121-2	K	I(t)	—	6.5	Clay, blue, contains quartz and mica; decomposed metamorphic rock.
1122-3	K	—	—	5	................do................
1123-4	K	I(t)	—	5	................do................
1124-5	K	I(t)	—	6	................do................
1125-6	K	M(t)	—	4	................do................

Stearns County

Sample location and designation	X-ray determination of clay mineralogy of <2μ fraction				Description Sample
	K	M-I	Other	Thickness (in feet)	
RICH SE¼ SE¼ NW¼ sec. 8, T. 127 N., R. 29 W. (See Locality 90, APPENDIX B.)					
1149-1	K	—	G	1.8	Clay, pisolitic, light-colored, iron-stained.
1150-2	K	—	G,B	2.2	................do................
1151-3	K	—	—	1	................do................
1152-4	K	—	—	3	Clay, light-blue, somewhat pisolitic; contains quartz grains.
1153-5	K	I(?)	—	3	Clay, blue; contains quartz grains.
1154-6	K	I(t)	—	2	................do................
1155-7	K	I(t)	—	2.3	................do................
1156-8	—	—	—	1.8	Clay, similar to sample 1155-7.
*1157-9	K	I(t)	—	2.2	Clay, blue; contains quartz grains.

APPENDIX E

Electron microscope descriptions of selected samples.

Asterisk (*) indicates that electron micrograph of this sample is shown in main body of report.

Sample number	Description
Brown County	
49*	Well-formed hexagonal kaolinite flakes of 0.5 microns to 4.0 microns in diameter; occur also in well-formed stacks of 2.5 microns to 3.0 microns diameter.
Redwood County	
10*	Hexagonal kaolinite flakes with somewhat irregular edges, 0.5 microns to 1.0 microns in diameter.
33	Thin, wide, irregular montmorillonite flakes.
34	Well-formed hexagonal kaolinite flakes, 0.1 microns to 1.0 microns in diameter; some kaolinite stacks present; a few halloysite tubes present.
38	Well-formed hexagonal kaolinite flakes, very thin, mostly 0.17 microns to 0.5 microns in diameter, some flakes up to 2.0 microns in diameter; a few halloysite tubes present, 0.66 microns length and 0.2 microns width (maximum) and 0.25 microns length and 0.06 microns width (minimum).
39	Hexagonal kaolinite flakes, poor to fair in outline, 0.25 microns to 0.66 microns in diameter; a few halloysite tubes present, somewhat tapered at ends, 0.5 microns length and 0.15 microns width (maximum) and 0.15 microns length and 0.03 microns width (minimum).
40	Irregular kaolinite flakes, 0.25 microns to 0.66 microns in diameter, most particles about 0.33 microns in diameter; a few lath-shaped kaolinite flakes present; moderate amount of halloysite tube fragments with ragged ends, 0.5 microns length and 0.15 microns width (maximum) and 0.25 microns length and 0.06 microns width (minimum).
53	Irregular, thin kaolinite flakes, a very few halloysite tubes present.
54	Stacks of irregular kaolinite flakes formed of small, well-formed kaolinite plates.
55	Hollow halloysite spheres formed of small plates, general polygonal outline of spheres when seen in photos of non-coated preparations, 0.25 microns to 1.0 microns in diameter; some short halloysite tube (?) fragments, 0.5 microns length and 0.25 microns width; a few poorly-formed hexagonal kaolinite flakes present.
58	Thin kaolinite flakes up to 15.0 microns diameter, appear to break up into platelets of 0.25 micron diameter; all flakes have fair to poor hexagonal outline.

Sample number	Description
Redwood County (continued)	
60	Poorly-formed hexagonal kaolinite flakes, mostly 0.5 microns to 0.33 microns in diameter; halloysite tubes present, 0.2 microns length and 0.05 microns width (maximum) and 0.07 microns length and 0.03 microns width (minimum).
69*	Hollow halloysite spheres, general polygonal outline of spheres when seen in photos of non-coated preparations, 0.33 microns to 0.66 microns diameter; spheres composed of small platelets, some wispy ends coming off spheres as if they are peeling.
70	Kaolinite flakes of irregular outline; some kaolinite stacks, larger kaolinite flakes composed of small, well-formed hexagonal plates.
72	Fair to well-formed hexagonal kaolinite flakes, mostly 0.25 microns in diameter; some kaolinite stacks of 2.0 microns diameter; a few halloysite tubes present.
73	Well-formed hexagonal kaolinite flakes and stacks, mostly 0.5 microns to 1.0 microns in diameter; larger flakes of 1.5 microns to 2.0 microns made of aggregates of flakes of 0.25 microns in diameter; individual flakes range from 0.33 microns to 1.0 microns in diameter; some star-shaped particles present.
75	Fair to poorly-formed hexagonal kaolinite plates of 0.13 microns in diameter which form stacks of irregular outline; stacks have alligator-type surface texture; a very few six-pointed star-shaped plates of 0.25 micron diameter on some stacks.
104*	Small and large well-formed hexagonal kaolinite flakes, mostly 0.25 microns to 0.5 microns in diameter, some up to 2.0 microns in diameter; larger kaolinite stacks approximately 3.0 microns diameter and have irregular outlines and alligator surface texture; stacks of 1.5 microns to 2.0 microns in diameter have fair to good hexagonal outlines.
146	Well-formed hexagonal kaolinite flakes with average diameter of 0.5 microns but ranging from 0.25 microns to 1.0 microns in diameter; some larger aggregates composed of smaller flakes.
271	Very irregular kaolinite particle shapes; no regular forms.
272	Very irregular particle shapes; slight development of hexagonal kaolinite forms.
274	Very irregular particle shapes; slight development of hexagonal kaolinite forms; some irregularly-shaped flakes have very thin flat crystal blades extending outward from the flake's edge and lying in the plane of the flake.
275	Some irregularly-shaped large flakes which have very thin flat crystal blades extending outward from the flake's edge and lying in the plane of the flake.

Sample number	Description
Redwood County (**continued**)	
276	Very irregular particle shapes; much fine-sized material.
320	Fair to good hexagonal kaolinite flakes, 0.13 microns to 0.5 microns in diameter; many stacks of kaolinite flakes; halloysite tubes uncommon.
M-1103-10	Irregularly-shaped flakes, probably kaolinite; some large, thick irregularly-shaped particles, possibly muscovite.
S-1119-2	Kaolinite flakes of irregular outline; some well-formed hexagonal flakes present; larger flakes composed of small, well-formed hexagonal flakes; halloysite tubes very rare.
Ramsey 1142-17	All flakes irregular in outline.
Mann 1180-4	Flakes of irregular outline, a few small, well-formed hexagonal kaolinite flakes; halloysite tubes very rare.
Slump 1189-2	Kaolinite flakes of irregular outline, edges show smaller, well-formed hexagonal flakes; an occasional halloysite tube present.
Slump 1200-13	Mostly small kaolinite flakes of irregular outline; halloysite tubes very scarce.
Ralph 1204-2	Mostly small kaolinite flakes of irregular outline; halloysite tubes very scarce.
Gulley 1218-8	Poorly-formed hexagonal kaolinite flakes; irregular darker flakes present, possibly muscovite.
Crow Creek 1226-8	Hexagonal kaolinite flakes; occasional halloysite tube present.
Crow Creek 1231-13	Hexagonal kaolinite flakes; occasional halloysite tube present.
Hendersen 1238-7	Well-formed hexagonal kaolinite flakes mostly 0.33 microns in diameter with lesser amounts of flakes 1.25 microns in diameter; large 2.0 micron diameter flakes appear irregular in outline but break up into smaller well-formed hexagonal flakes; very few halloysite tubes present.
North Redwood 1242-3	Well-formed hexagonal kaolinite flakes mostly 0.5 microns to 0.75 microns in diameter; halloysite tubes very rare.
Renville County	
35	Fair to good hexagonal kaolinite flakes, much material of 0.2 microns diameter, some flakes up to 3.0 microns in diameter; some kaolinite stacks present.
42 (pisolite)	Mostly irregular kaolinite flakes tilted in random fashion; some edges show slight indication of hexagonal shape; some flat regions up to 4.0 microns across.
42* (matrix)	Kaolinite flakes of very irregular outline.
44*	Well-formed hexagonal kaolinite flakes of 0.25 microns to 2.0 microns in diameter; some well-formed kaolinite stacks; most flakes 0.33 microns to 1.0 microns in diameter.

Sample number	Description
Renville County (continued)	
50	Very well-formed hexagonal kaolinite flakes of 0.25 microns to 0.33 microns in diameter; fairly well-formed halloysite tubes 1.5 microns in length and 0.12 microns width (maximum) and 0.4 microns length and 0.07 microns width (minimum).
51	Kaolinite flakes of fair to good hexagonal outline; a very few halloysite tubes present.
B-1025-10	Fair to poorly-formed hexagonal kaolinite flakes.
C-1034-4	Mostly small, fair to poorly-formed hexagonal kaolinite plates; very few halloysite tubes present.
C-1046-16	Poorly-formed, large, hexagonal kaolinite flakes, small hexagonal kaolinite flakes with fair outline; very occasional halloysite tubes present.
E-1074-17	Large kaolinite flakes having poor hexagonal outline but made up of aggregates of small, well-formed hexagonal kaolinite flakes.
Munsel 1146-4	Large kaolinite flakes having poor hexagonal outline but made up of aggregates of small, well-formed hexagonal kaolinite flakes; a few scattered halloysite tubes present.
K-1089-5	Large kaolinite flakes of irregular outline; fine edges show smaller, fair to well-formed hexagonal flakes.
324	Kaolinite flakes of general hexagonal shape of mostly 0.25 microns in diameter.
Stearns County	
Rich 1157-9	Mostly flakes of irregular outline and some well-formed hexagonal kaolinite flakes.
Yellow Medicine County	
247	Small irregular kaolinite flakes, a few hexagonal kaolinite flakes of 0.2 microns diameter, some flakes in stacks, some hollow halloysite spheres and tubular halloysite particles present; hollow halloysite spheres about 0.25 microns in diameter and have polygonal outline; they appear to be made of tiny plates; short halloysite tube fragments (?) from 0.25 to 0.33 microns in length.
260	Very irregular kaolinite particle shapes, no regular forms.
261	Very irregular particle shapes, no regular forms.
263*	Well-formed hexagonal kaolinite flakes; some lath-shaped kaolinite stacks of plates of 2.0 microns to 4.0 microns in diameter; many of the larger kaolinite flakes break into smaller 0.5 micron to 1.0 good hexagonal flakes.

APPENDIX F

Maps showing sample localities.

Figure F-1—Location map showing sample locality maps A through H.
F-2—Map A—Granite Falls area.
F-3—Map B—Redwood Falls area.
F-4—Map C—Morton-Franklin area.
F-5—Map D—Brown County-Renville County area of the Minnesota River Valley.
F-6—Map E—Fort Ridgley area.
F-7—Map F—Mankato area.
F-8—Map G—Richmond area.
F-9—Map H—Mississippi River area of Morrison County.

Figure F-1 — Map of Minnesota showing locations of locality maps A through H.

Figure F-2 — Map A — Granite Falls area.

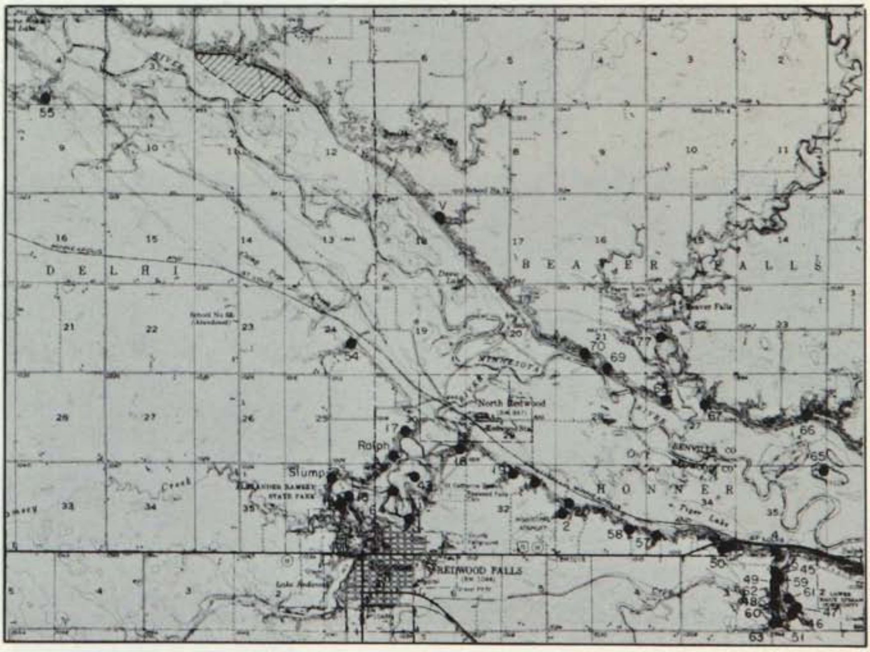

Figure F-3 — Map B — Redwood Falls area. Ruled area represents probable shallow deposits of highly weathered residuum (unit 1).

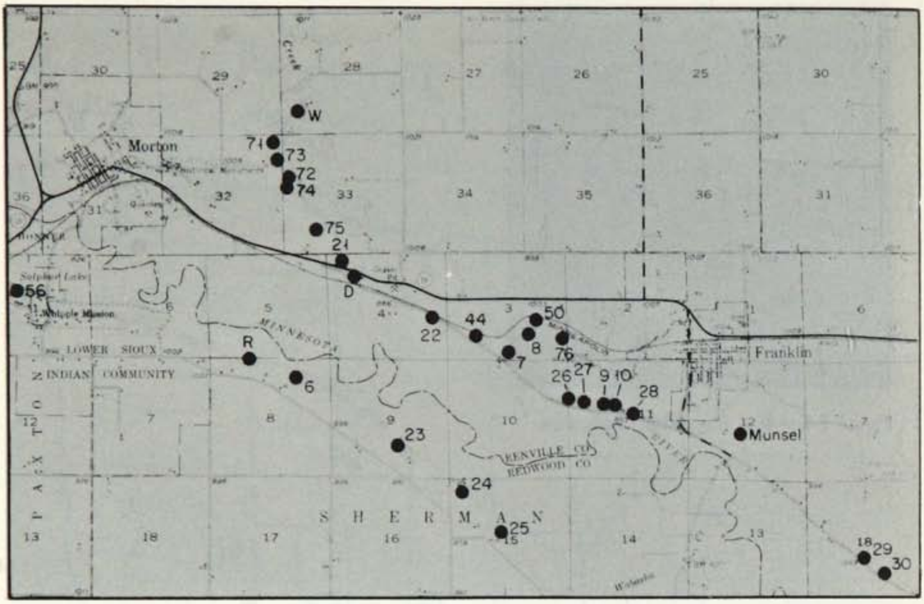

Figure F-4 — Map C — Morton-Franklin area.

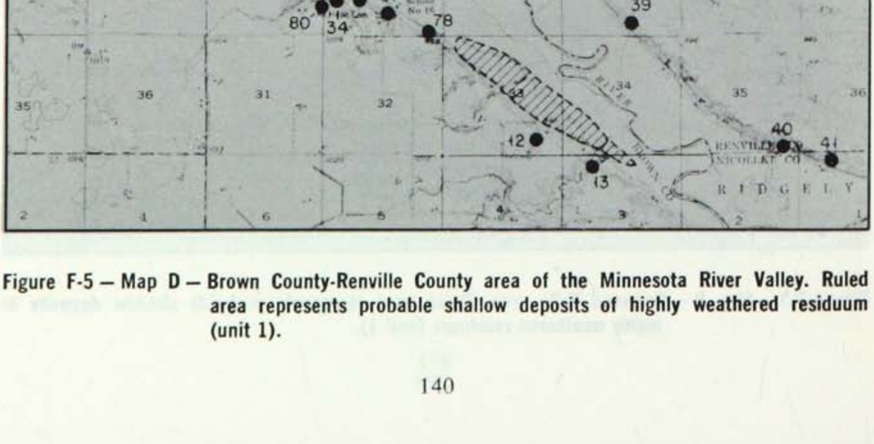

Figure F-5 — Map D — Brown County-Renville County area of the Minnesota River Valley. Ruled area represents probable shallow deposits of highly weathered residuum (unit 1).

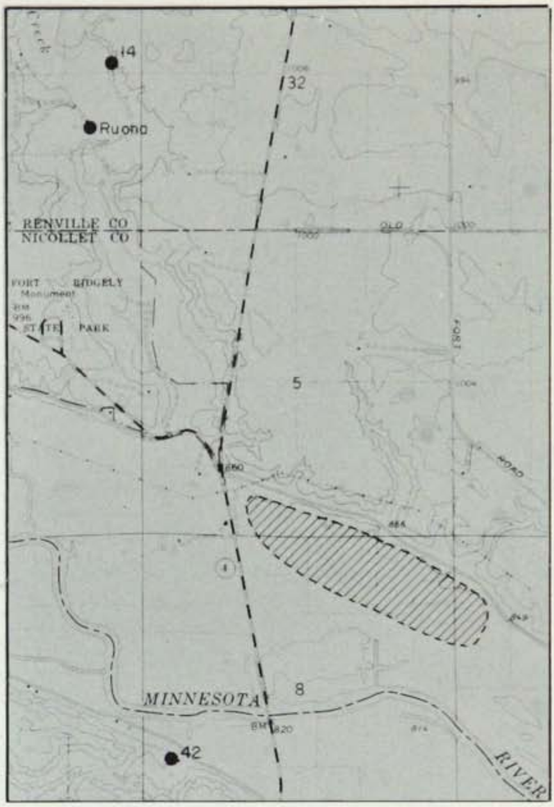

Figure F-6 — Map E — Fort Ridgley area. Ruled area represents probable shallow deposits of highly weathered residuum (unit 1).

Figure F-7 — Map F — Mankato area.

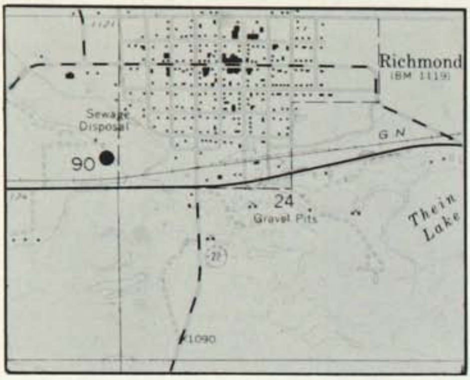

Figure F-8 – Map G – Richmond area.

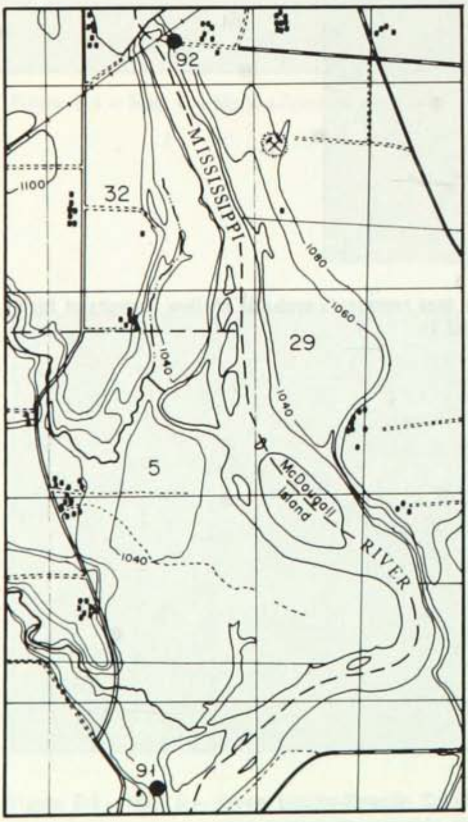

Figure F-9 – Map H – Mississippi River area of Morrison County.

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