U.S. Geological Survey.
Reports: Open file.

GEOLOGY OF THE NORTHERN BLACK HILLS BENTONITE MINING DISTRICT

Sam H. Patterson, 1918-

U. S. Geological Survey
OPEN FILE REPORT
This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

CONTENTS

CONTENTS

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

ILLUSTRATIONS

———

TABLES

———

INTRODUCTION

SCOPE AND PURPOSE OF THE REPORT

Extensive deposits of bentonite are present in the Cretaceous sedimentary rock strata cropping out on the northern flank of the Black Hills. These deposits have been the subject of a study by the U. S. Geological Survey as part of the program of the Department of the Interior for appraisal of natural resources of the Missouri River Basin. This report contains information concerning the geology of the bentonite deposits of the Northern Black Hills district. An attempt is made to explain some of the relations that exist between the physical properties and the mineralogical characteristics of the bentonite. Consideration is given to the occurrence of bentonite deposits and different types of sedimentary rocks and to depositional and post-depositional conditions which these rocks reveal. Evidence for sources of ancestral materials and conditions of alteration are discussed.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the help of Dr. R. E. Grim, formerly of the Illinois Geological Survey, for supervising the laboratory investigations and for many helpful suggestions during the preparation of the manuscript. Grateful acknowledgment is made to M. M. Knechtel of the U. S. Geological Survey for supervision of the field work phase of this investigation. Thanks for assistance in the field work are due Mr. Robert S. Roth and Mr. William J. Sando who worked during the field season of 1950 and to Mr. Leonard G. Schultz and Mr. John C. Hathaway who assisted during the months of June and July 1951.

A considerable amount of work was done while the writer was stationed at the Illinois Geological Survey, Urbana, Illinois. The writer is deeply grateful to Dr. M. M. Leighton, former Chief of the Illinois Geological Survey, for making available certain facilities and for providing space to work. He is also indebted to various members of the Illinois Geological Survey staff, particularly Mr. Arthur W. White.

DEFINITION OF BENTONITE

Bentonite was defined by Ross and Shannon (1926, p. 79) as follows: "Bentonite is a rock composed essentially of a crystalline claylike mineral formed by the devitrification and the accompanying chemical alteration of a glassy igneous material usually a tuff or volcanic ash; it often contains variable proportions of accessory crystal grains that were originally phenocrysts in the volcanic glass. These are feldspar (commonly orthoclase and oligoclase), biotite, quartz, pyroxenes, zircon, and various other minerals typical of volcanic rocks. The characteristic clay-like mineral has a micaceous habit and facile cleavage, high birefringence and a texture inherited from volcanic tuff or ash, and it is usually the mineral montmorillonite but less often beidellite."

Some geologists would include in the definition that bentonite altered from ash deposited in marine waters. This idea is doubtless a consequence of the general acceptance of theories which explain the high magnesium contents of bentonites by adsorption from sea water. Beds of bentonite have been reported from several nonmarine strata of Tertiary age in Western United States. Possibly these deposits accumulated in magnesium rich lakes; nevertheless they provide adequate ground against restricting bentonite to clays of marine origin.

The term bentonite is sometimes used as a trade name to refer to any clay having certain properties notwithstanding its origin. Montmorillonite clays formed by alteration of rocks other than volcanic ash or tuff may have essentially the same composition and properties as bentonite. Such materials should not be classified as bentonite because they do not conform to the definition. Efforts have been made, particularly in certain parts of clay industries, to restrict the term bentonite to clay which swells when placed in water and to classify non-swelling materials of similar composition as sub-bentonite. The use of sub-bentonite as a mineralogic term should be discouraged as it implies a distinct mineral, and there is no sharp boundary between swelling and non-swelling bentonites. Whether a bentonite is classified as swelling or non-swelling may depend upon the judgment of one individual or on the treatment of samples before and during tests.

The term metabentonite has also been used as a general term for both bentonite of Paleozoic age and for all non-swelling bentonites. Metabentonite was originally defined by Ross (1928, p. 164) as including only that bentonite which showed definite evidence of metamorphism. With few exceptions the non-swelling bentonite materials have not been metamorphosed; therefore, metabentonite is unsuitable as a general term for these clays.

Bentonite deposits discussed in this report include both high and low swelling materials which conform to Ross and Shannon's definition. The term bentonite was first proposed by Knight (1898, p. 491) for clay cropping out near Rock Creek, Wyoming. Considerable evidence suggests that the material Knight described came from a bed at the same stratigraphic horizon as the Clay Spur bed. The Clay Spur bed contains the most extensive bentonite deposits in both the northern and western Black Hills and has been the source of most of the much studied "Wyoming type" bentonite.

LOCATION AND IMPORTANCE OF THE NORTHERN BLACK HILLS BENTONITE MINING DISTRICT

The Northern Black Hills Bentonite Mining district includes a 60 mile segment of the outcrop belt on the northern flank of the Black Hills uplift, that lies in the northeast part of Wyoming, southern Carter County, Montana, and western Butte County, South Dakota. The Northern Black Hills Bentonite Mining district is bounded geologically on the east by a broad belt of alluvium and terrace deposits that blanket the bentonite-bearing strata east of Belle Fourche, South Dakota. Western limits of the district are marked by a zone of steep dips along Range 67 W., Wyoming, which forms the boundary between the Black Hills uplift and the Powder River structural basin. These steep dips place the bentonite deposits in positions very unfavorable for mining. The area mapped consists of about 980 square miles and includes about 280 square miles in Butte County, South Dakota, more than three townships in Carter County, Montana, and the remainder in Crook County, Wyoming.

Belle Fourche, the county seat of Butte County, South Dakota, is the largest town in the district. The village of Alzada, Montana is the only other center of population within the district. The abandoned village and present post office of Colony, Wyoming has played a historic role in the development of the bentonite deposits. The Northern Black Hills Bentonite Mining district is crossed by U. S. Highway 212 from which most of the bentonite deposits can be reached over secondary roads, mining roads, and trails. Bentonite deposits in the northeast part of the district can be reached by way of U. S. highway 85, which extends north from Belle Fourche. Most of the bentonite is shipped by way of a spur of the Northwestern railroad which extends from Belle Fourche to the vicinity of Colony, Wyoming.

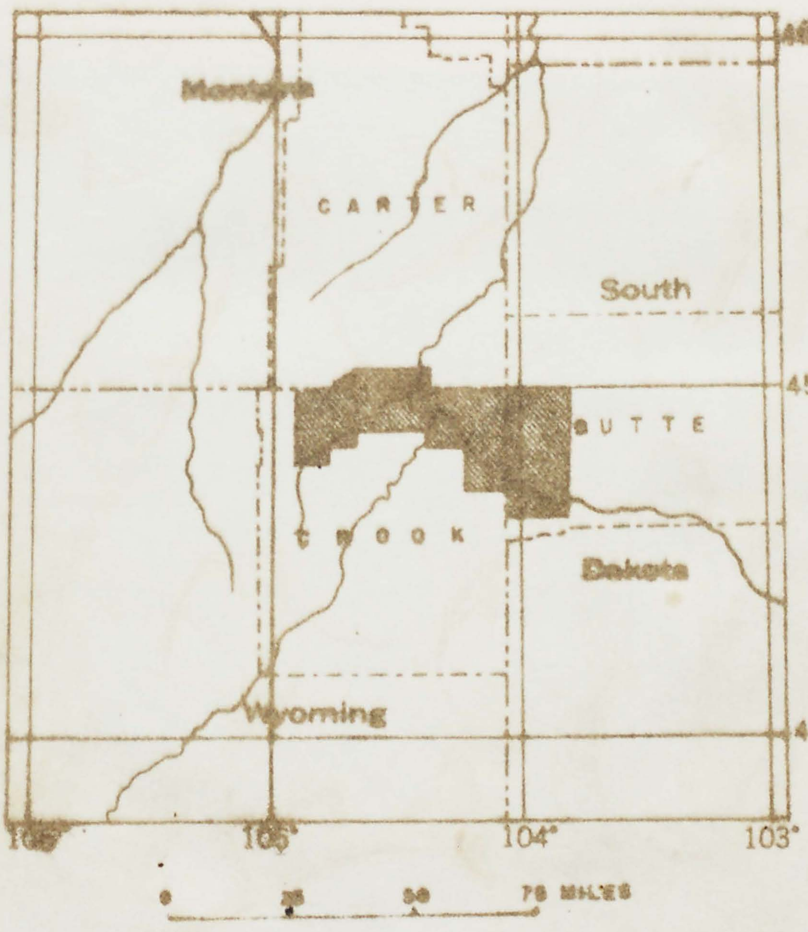

Figure 1. --Index map showing location of the Northern Black Hills Bentonite Mining District.

The Northern Black Hills Bentonite Mining district together with the much smaller Western Black Hills district, contain more than three-fourths of the known deposits of what is now considered commercial grade high swelling or "Wyoming type" bentonite. Importance of the district is emphasized by the 2,000,000 tons of bentonite shipped in the last 10 years.

METHODS OF INVESTIGATION

Bentonite deposits of the Northern Black Hills Bentonite Mining district were sampled with the aid of a hand auger during the field seasons of 1947 and 1950. The deposits and associated strata were mapped on air photos and a study of the bentonite beds and their relations to enclosing rocks was made during the field season of 1950 and the months of June and July 1951. A map was prepared by transferring data from the photos to a base map compiled from the Bureau of Land Management township plats.

Commercial tests of the foundry bond and drilling-mud properties for each sample of bentonite were made in the laboratory. The results of the commercial tests will be published in a report by the U. S. Geological Survey (Knechtel, M. M., and Patterson, S. H.). Thermal analyses were made of a selected group of samples in an effort to determine the relation between the mineralogy of the bentonite and the physical properties. These selected samples include material representative of each bed and of portions of beds having unusual physical properties. Information concerning the amounts and types of non clay materials was obtained by microscopical examination and thermal analyses.

GEOLOGIC OCCURRENCE OF THE BENTONITE BEDS

The bentonite deposits of the Northern Black Hills Bentonite Mining district occur as beds and lenses in sedimentary rocks of both Upper and Lower Cretaceous age. Bentonite strata range from paper thin laminae to beds that are locally more than 20 feet thick. Rocks containing the bentonite deposits described in this report are more than 3,100 feet thick and range from the Newcastle sandstone to the Mitten member about 900 feet above the base of the Pierre formation. Additional bentonite beds are present in the 800 feet of the Pierre formation, which is above the Mitten member. Bentonite beds above the Mitten member were not examined in detail because of their unfavorable thicknesses and impure nature. Sedimentary rock units containing the bentonite dip gently northeast, north, and northwest and crop out in belts paralleling the arcuate northern margin of the Black Hills uplift. As a consequence of gentle regional dips, the bentonite beds lie at or near the surface in narrow but extensive zones along the strike of the strata. Extensive deposits also lie in positions accessible to strip mining on the limbs and axial portions of the several large and many small anticlines which extend throughout most of the district. Bentonite bearing strata are brought to the surface repeatedly by prominent structures in the northeastern part of Crook County, Wyoming, where the Colony, Chicago Creek, Shepard, and La Flamme anticlines and the Kilpatrick Creek syncline extend almost parallel to U. S. highway 212. The importance of these structures is emphasized by the large amount of mining in T. 57 N., R. 61 W., the northeastern half of T. 56 N., R. 61 W. and in T. 57 N., R. 60 W., Crook County, Wyoming.

A second fundamental reason for the large amount of bentonite under light overburden in the district is that two thick and persistent bentonite beds are overlain by thin relatively resistant strata which in turn have superjacent non-resistant beds. These resistant zones above each of the two beds serve as protective cap rocks and cause the bentonite to lie under shallow overburden nearly parallel to local dip slopes. These same two bentonite beds rest on resistant beds which prevent them from being undercut by erosion and increases the length of dip slopes. The combination of resistant beds below and relatively resistant cap rocks above the bentonite beds together with the lack of resistance of the bentonite results in the formation of numerous small outliers, inliers, and long belts of shallow overburden along outcrops where bentonite can be easily removed by strip mining techniques. The relation between the amount of bentonite under light overburden and the nature of enclosing rocks is shown diagrammatically in Fig. 2.

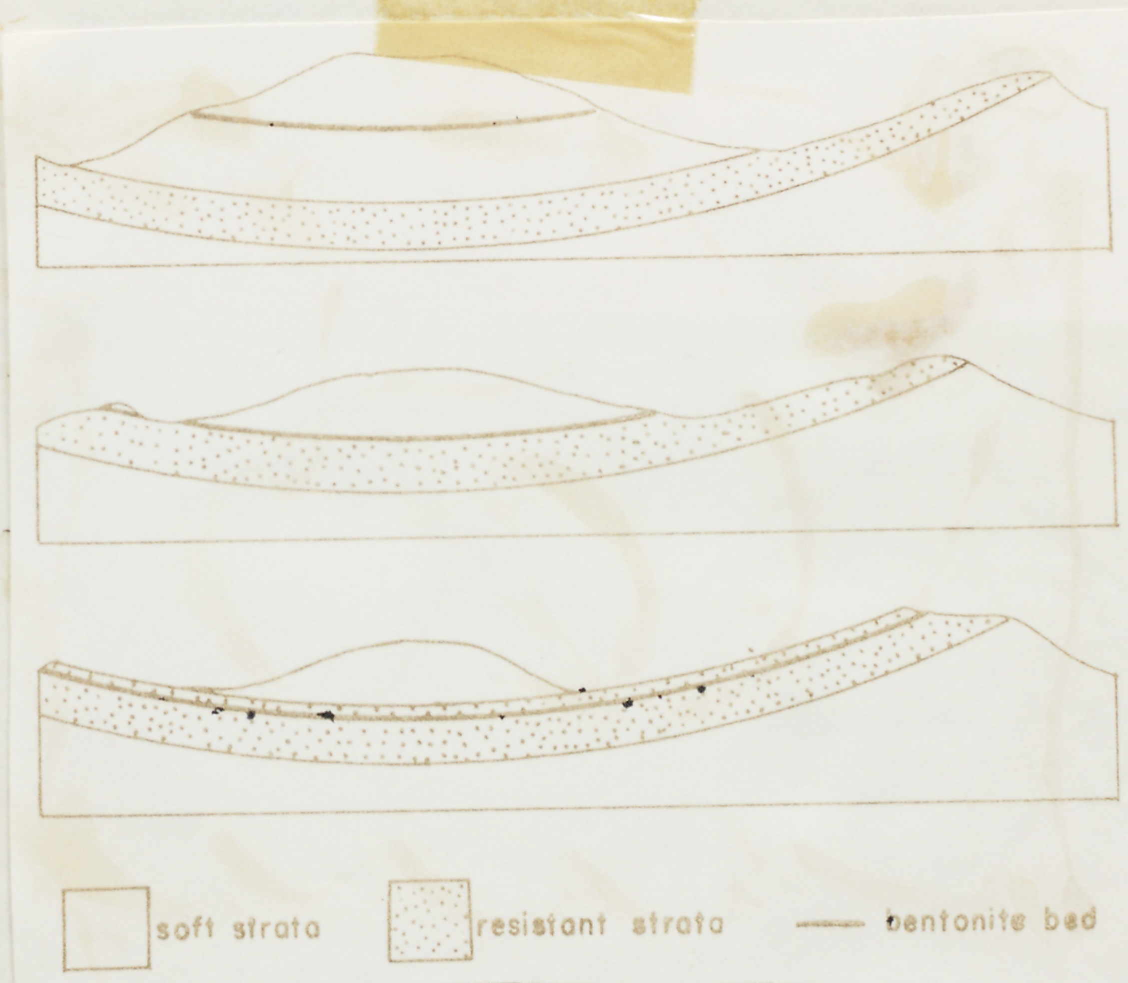

Figure 2.—Diagrammatic representation of the relation between resistance of enclosing strata and the amount of bentonite under light overburden.

STRATIGRAPHY

GENERAL CHARACTER AND AGE OF THE ROCKS

All of the rocks exposed in the Northern Black Hills Bentonite Mining district are of sedimentary origin and range in age from Lower Cretaceous to Recent. Exposed sedimentary formations total more than 4,200 feet in thickness and consist chiefly of marine shale, marl, and argillaceous sandstone (see Generalized Section); shallow water and beach deposits appear to be present in the Newcastle sandstone; nonmarine deposits are represented by the Fuson shale and the lower three-fourths of the Fall River sandstone. Major unconformities are not present, and with the exception of the lowermost Cretaceous formation, the Lakota sandstone, which crops out outside the limits of the district and is not discussed in this report, a fairly complete section of Cretaceous rocks is described. Surficial deposits ranging in age from Oligocene? to Recent form a mantle over the eroded surface of the Cretaceous rocks in many places. These deposits include gravel, sand, silt, soil, and alluvial fill in terraces and along the present streams.

The classification of the sedimentary units used in this investigation is essentially the one published by Rubey (1930, p. 3-9) as modified by Reeside (1944) who dropped the name Graneros shale and elevated its four members to the rank of formations. A ruling by the Committee on Geologic Names transferred the Sage Breaks member to the Carlile shale and restricted the Niobrara formation to the limits of Rubey's Beaver Creek member. The name Beaver Creek was dropped, and the Niobrara formation now conforms to the nomenclature that existed prior to Rubey's classification. Cobban and Reeside (1951, p. 1892-1893) later placed the boundary between the Upper and the Lower Cretaceous series at the top of the siliceous Mowry shale. Faunas of the formations from the Fall River sandstone to the Niobrara formation were listed by Cobban (1951, p. 2170-2198).

CRETACEOUS SYSTEM

Lower Cretaceous series

Inyan Kara group

Fuson formation.--The Fuson formation appears at the surface only in a few deep valleys and small canyons within the area mapped. The best Fuson exposures in the northern Black Hills are in cliffs in Government Canyon in T. 57 N., R. 64 W., Crook County, Wyoming. In this area 109 feet of red, purple, and light gray shale are revealed in a nearly complete section. Dark-gray shale and sandstone strata are present in the formation in the eastern part of the district, and Darton and O'Hara (1909, p. 4) describe 60 to 70 feet as being characteristic thicknesses of the formation in the Belle Fourche quadrangle. Some of the light gray shale has a soft puffy surface which indicates some swelling capacity and suggests the presence of bentonitic material.

Fall River sandstone.--The Fall River sandstone, which has often been referred to as the Dakota sandstone in old reports, is a resistant unit that forms prominent ridges and long dip slopes. The sandstone is fairly massive, but thin bedded sandstone and shale beds are present in both the lower and middle parts. The sandstone is brownish gray or buff and ripple-marks and cross-bedding are common. The upper part of the formation is characterized by thin, hard, ferruginous sandstone beds and many small nodular ferruginous concretions which are commonly hollow. Thicknesses of 75 to 110 feet characterize the formation in the Northern Black Hills.

Rocks younger than Inyan Kara group

Skull Creek shale.--The Skull Creek shale rests on the Fall River sandstone and consists of soft, dark-gray, fissile shale. Because of its soft character, the belts in which the formation crops out are wide and often covered with soil and alluvium. In the few places where the unit can be accurately measured, approximately 250 feet of shale is present. The formation contains several zones of gray, ferruginous, mudstone concretions and large, yellowish-gray, calcareous, cone-in-cone concretions. Thin beds of argillaceous sandstone, carbonaceous shale, and dark bentonitic shale are present near the base of the formation. In some places the Skull Creek shale grades into the subjacent Fall River sandstone. Sandstone dikes occur near the top and also near the base. The dikes near the base consist of gray, medium-grained, poorly consolidated sandstone. These dikes range from paper thin partings to 3 or 4 inches in thickness and can be traced only a few feet.

Dikes in the upper part are restricted to the uppermost 50 feet of the formation. These dikes are composed of sandstone that closely resembles some of the coarser material of the Newcastle sandstone. Thicknesses ranging from a few inches to 12 feet characterize the dikes and many of them can be traced for 200 or 300 feet. Because of erosion, upper and lower limits of dikes cannot be determined, but few of even the thicker dikes appear to exceed 20 feet in vertical dimensions. Some of the largest dikes support high hills and ridges. Slickensides have been noted on outer surfaces of the larger dikes. Some dikes have poorly developed bedding which is not of the same attitude as enclosing shale strata.

The origin of the sandstone dikes in the sedimentary rocks exposed around the Black Hills has caused much speculation by geologists.

Darton (1902, p. 4) observed that dikes in the lower beds of the Graneros shale (Skull Creek formation) contained sandstone which was very similar to parts of the Dakota sandstone (Fall River sandstone). Apparently he thought that sand had been intruded upward from that formation. A similar conclusion was reached by Grace (1952, p. 20) during a study of stratigraphy of the Newcastle sandstone. Grace recognized that lithologies of the dikes in the upper part of the Skull Creek shale were similar to parts of the Newcastle sandstone. He also noted that these dikes occur where the Newcastle formation is missing. Most of the dikes were studied in some detail by Russell (1927, p. 402-408) who concluded that they were formed by the forcing of sandstone, which must have been more plastic than enclosing shale, into fractures formed by stresses during folding. He noted that dikes were not particularly common in anticlines or synclines where stresses and fractures should have been most abundant. Russell recognized that dikes south of Belle Fourche, South Dakota occur about 30 feet below the Newcastle horizon but nevertheless believed that the sandstone originated from a bed in the Mowry shale which is even higher in the section than the Newcastle.

Only a few very fine-grained sandstone beds are present in the Mowry formation of the Northern Black Hills district. Except for the presence of fish remains, the sandstone of the Mowry is lithologically unlike that of the sandstone dikes. Conformable relations of the Mowry sandstone beds with enclosing strata and uniform stratification within the beds also indicate that they could not have been sources of coarser sandstone in the dikes. Absence of dikes or disturbed strata in the middle portions of the Skull Creek shale and the fact that dikes near the base of that formation are much smaller than those at the top oppose the theory that sand was intruded upward from the Fall River sandstone.

Lithologic resemblances of the dikes in the upper part of the Skull Creek shale to certain strata in the lower part of the overlying Newcastle sandstone suggest that the dikes are closely allied to that formation. Evidence for an uplift of the Black Hills in late Skull Creek or early Newcastle time has been presented by Crowley (1951, p. 83-90) and Grace (1952, p. 12-13, 22). It seems most likely that the sandstone dikes consist of the first sandy materials deposited after this uplift. Large cracks formed by stresses related to the uplift, smaller desiccation cracks in low lying mud flats, and possibly narrow stream or tidal channels would have trapped the first available arenaceous sediments. The Fall River sandstone is the most likely source of the first sandy sediments after the uplift and the short distances of transportation involved may account for the similarities between that formation and the dikes. The presence of dikes in places where the Newcastle sandstone is absent may be a consequence of the restriction of limited amounts of sand to crack-like depressions or erosion prior to deposition of basal Mowry sediments. The slickensides on the larger dikes were probably formed after emplacement of the dikes as suggested by Grace (1952, p. 20).

Newcastle sandstone.--The Newcastle sandstone is an extremely variable unit of discontinuous beds of sandstone, siltstone, arenaceous shale, bentonite, carbonaceous shale, and impure lignite. The coarser sandstone beds are commonly cross-bedded and ripple-marked and nearly vertical worm borings are very abundant in some zones. The Newcastle formation is best developed in the western part of the district where it is more than 70 feet thick and contains massive beds of coarse to medium-grained sandstone that appear much like strata in the Fall River sandstone. The beds become less massive and more variable as the formation thins toward the east and feathers out entirely a few miles west of the Wyoming-South Dakota boundary. The stratigraphic position of the formation is commonly indicated beyond its extent by a thin sandy zone in the dark marine shale which contains small phosphatic and gypsiferous nodules. Nowhere in the South Dakota portion of the district is this zone sufficiently developed to constitute a mappable unit. The eastward thinning of the formation is locally interrupted by thick massive sandstone lenses. In sec. 21, T. 56 N., R. 61 W., Crook County, Wyoming, the formation consists of only 18 inches of platy, flexible, sandstone within a thin zone of sandy shale. In section 28 of that same township, which lies in the direction of the thinning, the formation is represented by a lense of cross-bedded sandstone that is 21 feet thick. The Newcastle formation exposed along the axis of the Chicago Creek anticline contains thin, soft, sandstone strata but local massive lenses are also present. In the Colony anticline, less than four miles north of the Chicago Creek structure, the Newcastle formation is represented only by a very thin sandy zone in dark marine shale.

The most detailed studies of the Newcastle formation have been made on the western flank of the Black Hills where one of the units within the formation, the "Muddy sand", has yielded considerable amounts of petroleum from lens shaped stratigraphic traps. Collier (1922, p. 81-82) recognized that the Newcastle sandstone was deposited in a near shore environment and suggested that parts of the formation accumulated along beaches and in lagoons while the sandy shale portions of the unit represented deposition in deeper marine water. Collier's theories have recently been strongly supported by Crawley (1951, p. 83-90) who interpreted much of the Newcastle sandstone as representing near shore and beach deposits and postulated an uplift of the central Black Hills with possible exposure of the central pre-Cambrian core during the period of deposition of that formation. The principal evidence for the magnitude of the uplift is the discovery of a gold nugget in the Newcastle sandstone. This nugget must have originated from pre-Cambrian gold deposits in the central portion of the Black Hills. Crowley also recognized 12 genera of marine fossils proving conclusively that the Newcastle sandstone on the western flank of the Black Hills could not have been deposited entirely under non-marine conditions.

Only plant fossils were found in the Newcastle sandstone of the Northern Black Hills; however, the lenticular nature of the strata, the lateral gradation of the unit into dark marine shale, and the presence of cross-bedding, ripple-marks, worm borings and coal beds provide ample evidence of deposition in a near shore environment. Ripple-marks and cross-bedding are most common in the large lenses of coarser grained rocks. These lenses probably represent beach or bar deposits. The bentonite beds, which have resulted from the alteration of nearly pure fine-grained volcanic ash, as well as the coal and argillaceous strata associated with the bentonite, could have accumulated only in waters protected from vigorous wave action. The possibility that the bentonite was laid down as part of a delta is ruled out by both the pure nature of the clay and the persistence of the relatively thin beds. Areal extent of the bentonite and the associated fine-grained rocks suggest deposition in a lagoon or series of lagoons that were aligned along a sea coast whose shape, though more narrow and arcuate to the north-west, was not unlike the present outline of the northern Black Hills. Nowhere can the bentonite be observed to extend to the extremities of the Newcastle formation. This fact further supports the theory of lagoonal deposition within the near-shore belt in which sandy sediments were accumulating. Massive sandstone lenses that are present in the thinner portions of the formation may even represent the off shore bars that enclosed the lagoons.

Two bentonite beds are present in outcrops of the Newcastle sandstone in sec. 11, T. 57 N., R. 65 W., Crook County, Wyoming. These bentonite beds are separated stratigraphically by 10 1/2 feet of silty shale, but both beds rest on thin impure coal beds and are overlain by argillaceous siltstone. The cyclic characteristics of these two series of strata indicate an unusual repetition of local depositional conditions. These two cycles might have been caused by fluctuations of sea level or two periods of elevations of the land areas. They can also be explained by a migration of lagoons along a coast line during a single period of submergence. Deposition of both coaly material and volcanic ash probably was restricted to the deeper more quiet portions of shallow lagoons. The presence of one coal, bentonite, and sandstone sequence above another may represent only the timing of an ash fall when one migratory lagoon was located above older lagoonal deposits.

Siliceous Mowry shale.— The siliceous Mowry shale is the uppermost formation of the lower Cretaceous series. Because of its relative hardness and resistance to erosion, the Mowry is one of the most conspicuous formations in the Northern Black Hills Bentonite Mining district. The formation consists chiefly of beds of hard siliceous shale interbedded with strata of bentonite and subordinate amounts of silty material. The fresh shale is dark brownish-gray and has a subconchoidal fracture. The weathered material is light silvery-gray, and in most places weathering is accompanied by a slight increase in hardness. Fish remains, consisting of vertebrae, fins, gill covers and scales, are abundant throughout the formation. Powdery yellow sulfur deposits are present along both vertical joints and bedding planes, and sulfurous odors are given off by moist exposures of the fresh shale. More than twenty bentonite beds were measured in one section of the formation. All of these bentonite beds except one near the top of the formation are less than 14 inches thick.

The origin of the siliceous shale was carefully studied by Rubey (1929, p. 153-170) who theorized that "The Mowry shale was formed on the sea floor by the chemical decomposition of slowly accumulated, very fine-grained, highly siliceous volcanic ash in the presence of decaying organic matter." Rubey also observed that the formation is softest in the lower part and hardens progressively upward and that the unit was hardest just below the Clay Spur bentonite bed which is located essentially at the top of the formation. There is no strong evidence against Rubey's conclusions for the Mowry shale as exposed in the Northern Black Hills district. However, the topographic expression of the 30 or 40 feet of shale below the Clay Spur bentonite bed suggests a degree of resistance somewhat less than lower beds. This part of the formation commonly weathers back from the edges of cliffs where lower beds stand in steep faces. The thin zone of Mowry shale occurring above the Clay Spur bed is also less resistant than the more massive strata in the lower part of the formation.

Because of its resistance to erosion, there are many excellent exposures of the upper half of the formation, but the lower part of the unit is nearly everywhere covered by talus or alluvial deposits. The few exposures of the beds immediately above the Newcastle sandstone that are present show that the lowermost Mowry strata consist of 10 to 20 feet of soft, dark-gray, fissile shale which grades upward into siliceous shale. This thin dark shale stratum is at the stratigraphic position of a thicker shale unit that has been named the Nefsy shale by Collier (1922, p. 82) for exposures on the western flank of the Black Hills uplift. The Mowry shale equivalent is included as part of the Mowry shale in the Northern Black Hills because of its thin nature and the poor exposures which show satisfactory boundaries only in a few places. In that portion of the district lying in South Dakota and the eastern part of Crook County, Wyoming, the Newcastle sandstone is not present and it is impossible to separate the lower soft Mowry shale from the lithologically similar Skull Creek shale. In such places the lower Mowry boundary must somewhat arbitrarily be drawn at the base of the lowermost siliceous shale beds which are 10 to 20 feet higher stratigraphically than the top of the Newcastle sandstone. The total thickness of the Mowry formation ranges from 200 to 250 feet, the greater thickness being present in the central and western parts of the district.

Upper Cretaceous series

Colorado group

Belle Fourche shale.--The Belle Fourche shale, named by Collier (1922, p. 85) after exposures along the Belle Fourche River in the southwestern part of Crook County, consists chiefly of very dark-grey fissile shale with subordinate amounts of sandy shale and many beds of bentonite ranging in thickness from that of mere paper-thin seams to 6 feet or more. In the southwestern extremity of the area mapped, this formation comprises two members, lower and upper, with a maximum aggregate thickness of about 825 feet. In the southeastern part of the district near the town of Belle Fourche, South Dakota only the strata equivalent to the lower member, with a thickness of about 425 feet, are lithologically typical of the Belle Fourche shale and accordingly are designated by that name. Here the rocks equivalent to the upper member are largely of a highly calcareous facies so closely allied to that of the Greenhorn that they have been mapped as an undifferentiated part of that formation.

Lower member.—The lower member of the Belle Fourche shale ranges in thickness from about 425 feet near the town of Belle Fourche to about 540 feet in T. 56 N., R. 67 W., Wyoming in the southwestern part of the district. The member is well exposed in a small stream valley southwest of Highway 212, in sec. 22, T. 57 N., R. 62 W., Wyoming, in the central part of the district. At this location the lower member is a little more than 500 feet thick and is subdivisible into three lithologic units. These units are also recognizable in other parts of the district but are not shown separately on the geologic map because their contacts with one another are so extensively concealed by soil and other surficial deposits that they cannot be mapped satisfactorily.

The lowermost unit, which rests on the Mowry shale, ranges in thickness from 30 to 45 feet. This unit, which includes bentonite beds D and E, consists primarily of dark shale which is harder and less fissile than that of the overlying strata. It contains many oblate-spheroidal concretions, commonly corrugated or pit-marked, of hard, gray, finely-crystalline, manganiferous siderite, ranging from about a foot to about 5 feet in equatorial diameter, but rarely measuring more than a foot in their axial dimensions. Weathered surfaces of these concretions are purplish-brown or black from oxidation and they lend to the unit as a whole a striking dark coloration which persists far beyond the limits of this district in exposures of the strata above the Mowry shale. The unit is comparable in this respect to the "oligonite zone" (Spivey, 1940, p. 16), exposed on the south side of the Black Hills in Fall River and Custer Counties, South Dakota, which comprises strata above the Mowry ranging in thickness from 60 to 80 feet. South of Alzada, Montana, within the northern Black Hills

Bentonite Mining district, the lowermost 25 feet of strata also contain ovoid calcareous concretions with an average maximum diameter of about a foot and a half, yellowish-brown on weathered surfaces and showing cone-in-cone structure. Concretions of this kind are increasingly abundant toward the west side of the district.

The medial unit of the lower member is about 215 feet thick as exposed in T. 57 N., R. 62 W., Wyoming, in the central part of the district. The medial unit consists largely of sandy shale intercalated with many beds and lenses of soft, gray sandstone, most of them less than 2 inches thick, and thick layers of dark-gray, soft, fissile shale. Beds of bentonite, ranging in thickness from less than an inch to a foot and a half, occur at numerous horizons within this unit. Ironstone concretions are contained in a thick layer of dark shale in the middle of the lower half of the unit and two higher strata contain lenticular cone-in-cone aggregates. The relative abundance of sandy material in the medial unit no doubt represents deposition related to that of correlative strata of the Frontier sandstone of areas farther west in the region, as on the west side of the Powder River basin of Wyoming.

The rocks of the uppermost unit of the lower member contain less sandy material than do those of the medial unit and they include many more bentonite beds than are enclosed in the upper of the two members of the Belle Fourche shale. The uppermost, or non-sandy, unit is approximately 250 feet thick in T. 57 N., R. 62 W., Wyoming, in the central part of the district. About 20 miles farther southeast, in the vicinity of Belle Fourche, South Dakota, strata believed to be continuous with the upper part of this unit contain so much calcareous matter that they are regarded as belonging to the overlying Greenhorn formation, so that the uppermost unit as there measured is only about 200 feet thick. In T. 57 N., R. 62 W., where the entire unit is well exposed, it consists essentially of soft, dark-grey shale, in part, fissile, including many beds of bentonite and, in its upper part, a few layers containing highly calcareous material in the form of concretions and lenticular cone-in-cone aggregates. Close to the middle there is a thin bed of sandy shale and, 20 feet higher, a zone of shale containing small concretions of brown siltstone. The topmost stratum is bentonite bed F which is about 4 1/2 feet thick in this locality but pinches out about 22 miles farther southeast where the base of the Greenhorn lies directly above beds equivalent to the uppermost unit of the lower member. Among the other beds of bentonite exposed in T. 57 N., R. 62 W., one about 63 feet lower than bentonite bed F is 1 foot, 2 inches thick and another about 10 feet still lower is 10 inches thick; numerous others distributed in various parts of the unit, range in thickness from less than an inch to 6 inches. Possibly the two relatively thick beds just mentioned represent the same epidode of volcanic ash deposition as two even thicker bentonite beds less than 100 feet below bed F, that are exposed about 35 miles farther southwest, in the southwestern part of the district.

Upper member.—The upper member of the Belle Fourche shale is made up almost entirely of soft strata of dark-grey shale, a few of which contain calcareous concretions, and some bentonite, notably, that of bed G. The member rests on Bentonite bed F and is overlain by the Greenhorn formation. The thickness of this member decreases from west to east across the district, largely because a change of lithologic facies whereby the Belle Fourche-Greenhorn contact migrates downward across planes of stratification. Thus, in the southwestern part of T. 56 N., R. 67 W., Crook County, Wyoming, bentonite bed F underlies about 285 feet of strata of the upper member of the Belle Fourche shale, whereas in an easterly direction from that locality, i. e., northwest of Alzada, Montana, bed F is only about 177 feet below the base of a thin limestone stratum which there marks the bottom of the overlying Greenhorn formation. East of Alzada, where the base of the Greenhorn drops to the base of the Orman Lake limestone, the upper member of the Belle Fourche includes only 52 feet of dark shale; near the Wyoming-South Dakota boundary its thickness decreases to 12 feet and is only about 6 feet 4 miles northwest of the town of Belle Fourche, in Butte County, South Dakota, where the bed F dies out. Eastward beyond that locality this member cannot be traced and from there on the Belle Fourche shale is accordingly mapped as an undivided formation.

Greenhorn formation.—The Greenhorn formation consists mainly of brownish-gray calcareous shale and marl, with a few thin beds, lenses and concretions of limestone, some non-calcareous dark shale and a little bentonite. Whereas this formation is only about 70 feet thick as measured in T. 56 N., R. 67 W., Wyoming near the southwestern extremity of this district, about 370 feet of beds are included 40 miles to the east, just west of the Wyoming-South Dakota boundary. The enormous west-to-east increase in thickness thus exemplified is due primarily to a change of lithologic facies, already noted in describing the upper member of the Belle Fourche shale, whereby the lime carbonate content of rocks within the stratigraphic interval occupied by the upper member of the Belle Fourche shale in the southwestern part of the district increases greatly from west to east. As a consequence of this change, the Greenhorn-Belle Fourche contact migrates downward across planes of stratification, whereas the contact of the Greenhorn with the overlying beds of the Carlile formation follows essentially the same stratigraphic horizon from one end of the district to the other. The entire Greenhorn in the southwestern part of the district accordingly represents only the uppermost Greenhorn beds near the Wyoming-South Dakota boundary. The underlying Greenhorn strata at Wyoming-South Dakota boundary are continuous with the upper member of the Belle Fourche shale in the southwestern part of the district.

The lower two-thirds of the Greenhorn formation contains several beds of limestone interbedded with the brownish-gray calcareous shale. The limestone beds are rarely more than one foot thick and are composed of brownish-grey, crystalline limestone that contains abundant sharks teeth and fragments of Inoceramus shells. The lowermost limestone bed, which rests sharply on the Belle Fourche shale, has been named the Orman Lake limestone by Petsch (1949, p. 9-10). The Orman Lake bed extends across the eastern one-half of the district, and is the cap rock that supports prominent ridges paralleling U. S. Highway 212. Other limestone beds in the lower part of the Greenhorn formation are neither as persistent nor as prominently exposed as the Orman Lake bed. The lower two-thirds of the Greenhorn formation was classified as a part of the Graneros shale by Darton (1909, p. 4) and this unit was regarded as a part of the Belle Fourche member of the Graneros shale by Petsch (1949, p. 7-10).

The upper one-third of the formation consists of very light gray weathering marl that contains many zones of limestone concretions, thin beds and lenses of limestone, and thin non-calcareous shale strata. The limestone beds are light brown and form conspicuous brown bands on weathered outcrops. These limestone beds are best developed northeast of Colony, Wyoming and tend to grade westward into zones of closely spaced concretions which in turn become less numerous farther to the west. Lenses of impure bentonite ranging up to nearly two feet thick are present in some outcrops of the upper Greenhorn beds.

Bentonite bed G occurs 55 to 60 feet above the base of the Greenhorn formation in the eastern part of the district where the lower Greenhorn beds are present. Bed G passes into the dark shale facies as the lower Greenhorn strata grade into the Belle Fourche shale. In exposures on the west side of the Little Missouri River valley, bed G is exposed 47 feet below the top of the Belle Fourche shale. Farther to the southwest still greater thicknesses of dark shale are present above the bentonite bed.

Carlile shale.--The Carlile shale on the northern flank of the Black Hills is about 500 feet thick and is made up of three members which can be distinguished readily. The lowermost unit, an unnamed member, is composed of dark-gray, fissile shale in which both calcareous and ferruginous concretions are abundant. The calcareous concretions are subspherical in shape with diameters ranging from 1 1/2 to 3 feet, and most of them are permeated with calcite filled cracks and have poorly developed cone-in-cone structure. The ferruginous concretions are restricted to a zone 10 to 20 feet thick at the top of the member. These flat oval-shaped concretions are ordinarily less than 4 inches by 1 1/2 feet in size. Thin light colored bentonite beds are present in the middle and lower parts of the member in some exposures, but none of the bentonite attains the dimensions demanded of commercial deposits. Because of its soft nature, good exposures of the lower Carlile member are not common. The unit is about 90 feet thick north of Belle Fourche, South Dakota, but it increases to nearly 150 feet in the western part of Crook County, Wyoming.

The Turner sandy shale is the medial member of the Carlile formation. The Turner unit is composed of dark shale that contains many limestone concretions, light-gray sandstone lenses and sandy shale. Locally the unit also contains small lenses of phosphatic nodules and shale pebbles. The middle part of the Turner contains zones of concretions, some of which are more than 6 feet in diameter and form resistant zones in the shale that are expressed in a series of low ridges rising one above the other in step-like fashion. In the eastern part of the district the member is about 200 feet thick, but it thins toward the west. The lower sandy beds appear to interfinger with the subjacent lower Carlile member. Because the thickness of the lower member increases toward the west, the total thickness of the two members remains nearly uniform. Faunal zones of the Turner member do not appear to be preserved in the dark shale but it seems almost a certainty that the upper part of the lower member in western Crook County, Wyoming, was deposited simultaneously with the lower part of the Turner member as exposed north of Belle Fourche, South Dakota. The Sage Breaks shale member ranges from about 200 to 300 feet thick and forms prominent barren outcrops. Dark-gray, non-calcareous shale and light gray limestone concretions make up the member. Most of the shale weathers gray, but a zone near the top weathers light gray and except for its non-calcareous nature could easily be mistaken for a part of the superjacent Niobrara formation. The concretions occur in prominent zones imparting a resistance to the shale that supports prominent ridges and small buttes. Most of the concretions are subspherical or oval shaped and range from 1 to 3 feet in diameter, but some of them are as much as 3 by 8 feet in vertical dimensions and 4 or 5 feet across. Practically all of the concretions are intricately septariate with calcite veins. Dark-brown or black calcite is particularly characteristic of the septaria in those concretions in the upper part of the member. The calcite septaria in the concretions near the middle of the unit are often composed of brown, yellow or orange, and white calcite in concentric layers possibly indicating three separate stages of crystallization or sources of the calcite.

Niobrara formation.--The Niobrara formation consists of grayish-brown marl which weathers to very light shades of gray, yellowish-gray, and orangish-gray. Beds of soft dark-gray shale up to 15 feet thick are usually present in the upper fourth of the formation. Limestone concretions and thin beds and lenses are common in the upper and lower parts of the unit. Fish teeth and bones are sparingly present in the lower part. The thin beds of limestone consist chiefly of poorly cemented accumulations of Ostrea congesta shells. The Niobrara formation erodes easily because of its soft nature and much of its areal extent is covered by alluvium. Thicknesses of the formation throughout most of the district are approximately 200 feet but only 120 feet of Niobrara strata is present in exposures of steeply dipping rocks in T. 56 N., R. 67 W., Crook County, Wyoming.

Many thin beds and lenses of bentonite are present in the upper half of the unit. The thickest of these bentonite beds is rarely more than 6 inches and surface textures indicate that most of the bentonite has low swelling capacities. The bentonitic materials are gray or light gray in color and nearly all of the beds have some iron stains.

Montana group

Pierre shale.--The marine Pierre shale overlies the Niobrara formation and has a thickness of 1,600 to 1,700 feet. The Pierre formation consists of gray and dark-gray shale with a few sandy strata. Because of the great thickness and the low dips that prevail, the outcrop belt of the formation is very wide on the northern flank of the Black Hills. The soft shale is easily eroded and as a rule outcrops are covered with alluvium or soil which prevent accurate measurements of thicknesses. The Pierre shale of the Northern Black Hills was divided into five members by Rubey (1930, p. 3-5) but poor exposures prevented mapping and measurement of the members above the Mitten member.

Gammon ferruginous shale member.--The Gammon member, the lowermost unit of the Pierre shale, consists of about 800 feet of soft gray shale which contains numerous ferruginous mudstone concretions that weather rusty brown. The Groat sandstone bed which ranges from 50 to 150 feet occurs 150 feet below the top of the member. The sandstone is fine-grained, grayish-brown and brown in color and locally contains much glauconitic material. The middle portion of the Groat bed is often sufficiently resistant to cap buttes and to support ridges but both the upper and lower portions are argillaceous and grade into the enclosing shale. The uppermost 150 feet of the Gammon member contains many calcareous concretions as well as the rusty weathering ferruginous concretions. Bentonite bed H which forms persistent ivory colored outcrop bands in the South Dakota portion of the district is 70 to 75 feet below the top of the member. Bed H is also present in the western part of Crook County, Wyoming, but its outcrops are not conspicuous and it was not mapped in that area.

Mitten black shale member.--The Mitten shale member overlies the Gammon shale. This member is characterized by abundant septariate calcareous concretions which weather yellow and brown. The abundant concretions and the cohesive properties of the Mitten shale make it sufficiently resistant to form rounded grass-covered scarps that rise gently above semibarren flats formed by the upper Gammon strata. Bentonite bed I, a thick bed with many shale partings, occurs at the base of the member. Outcrops of this bentonite bed are generally covered, but their position is often marked by a change in slope at the base of the low Mitten scarp. The Mitten member is about 150 feet thick.

Unnamed member.--Superjacent to the Mitten shale is an unnamed unit which is about 450 feet thick and composed of dark-gray shale. The lower half contains much sandy material, and local lenses and beds of friable, fine-grained, gray sandstone are common in the northeast part of the district. Both calcareous and ferruginous concretions are common in the upper one-half of the unit.

Monument Hill bentonitic member.--The Monument Hill member is about 150 feet thick and consists of gray shale. The shale weathers light gray and contains several zones of large light-gray limestone concretions. Thick beds of dark-gray bentonitic shale associated with thin beds of bentonite are present in the upper three-fourths of the unit. The bentonite beds are light-gray and gray in color and as a rule are less than 1 1/2 feet thick. Many biotite flakes and calcite grains are visible in hand specimens of the bentonite and indicate high non-clay mineral contents. Spherical barite concretions of radiating wedge-shaped crystals are commonly associated with the bentonite beds. These concretions average about 1 1/2 inches in diameter. Fibrous calcite fragments are abundant on weathered surfaces of the bentonite beds and the powdery nature of the weathered surfaces suggests that the bentonite has low swelling properties.

Unnamed member.--The uppermost unit of the Pierre shale consists of soft dark-gray fissile shale. A few calcareous concretions are present throughout the unit. This unnamed member is approximately 200 feet thick.

Fox Hills sandstone.--The Fox Hills sandstone overlies the Pierre shale and consists of brown sandy shale and siltstone with beds of sandstone. On the northern flank of the Black Hills the formation ranges in thickness from 150 to 250 feet. Outcrops of the formation are characterized by low grass-covered ridges. The Fox Hills sandstone lies north of the area covered by the geologic map.

TERTIARY AND QUATERNARY SURFICIAL FEATURES

The southern margin of the district under discussion lies within the northern foothills of the Black Hills, a fairly rugged group of mountains in an unglaciated portion of the Missouri Plateau section of the Great Plains province (Fenneman, 1931, Pl. 1) about 150 miles east of the Rocky Mountains. The bedrock underlying the district is largely concealed by soil and by surficial materials deposited by streams during late Tertiary and Quaternary time.

The surface of the district is only moderately dissected, with a total relief of about 1,000 feet. In an overall sense, its slope is gentle and downward toward the north, away from the mountainous area of the Black Hills. There are nevertheless many steep hillsides and a large proportion of the surface slopes in other directions; in fact, much of it actually slopes toward the south and the lowest altitude, about 3,000 feet above sea level along the Belle Fourche River near the town of Belle Fourche, lies within 3 1/2 miles of the most southerly section line of the district.

Extending in a northeasterly direction approximately across the center of the district is a drainage divide, on the west side of which the run-off drains into Little Missouri River and, on the east side, into Belle Fourche River.

The geomorphic history of the district is known only in broad outline. Nearly all the sediments of the exposed Cretaceous bedrock formations were deposited in an epicontinental sea which disappeared in late Cretaceous time. After departure of the sea, and continuing into early Tertiary time, additional sedimentary strata of terrestrial origin (Hell Creek to Wasatch), mostly deposited by aggradational streams, may have accumulated here to a considerable thickness and all the rocks of the neighborhood, including any such younger strata, were later deformed by forces related to the Laramide orogeny. By Oligocene time, however, denudative processes had gained ascendancy and have since continued active until the only rocks remaining today in this district that are younger than the folded and faulted marine Cretaceous bedrock formations are surficial deposits of soil, silt, sand and gravel.

Nearly all of this surficial material is rock derived from outcrops in the central Black Hills and has been transported into the area mapped on the flood plains of streams much older than the present rivers. The pebbles and cobbles in the gravel are most commonly subrounded to subangular, suggesting rather short distances of transportation. The materials of which they are composed are chiefly limestone, quartz, quartzite and ferruginous rocks, and these are commonly intermixed with subordinate amounts of sandstone, chert, and igneous rocks. Most of the material of the coarser gravels is poorly sorted, but in certain layers or lenses the pebbles are uniform in size. In general there is a decrease in particle size of the gravels in the lower terraces and the lower levels contain much material of higher terraces that has been reworked. Isolated boulders as 1-1/2 feet in diameter occur in all of the terraces. Lenses of silt and sand are most abundant in the three lowest terraces. The entire thickness of the terrace deposits is exposed in only a few places and, as a rule, their thickness cannot be accurately determined. Few of them, however, appear to be more than 40 feet thick. Terraces in the valleys of Owl Creek and North and South Indian Creek differ from those in the Belle Fourche

River valley in that essentially all of the gravel is of local origin. Most pebbles in these deposits are angular and less than 2 inches in diameter. The pebbles are chiefly fragments of limestone and ferruginous concretions, which are residual products of the erosion of the soft Upper Cretaceous shales.

By far the most extensive category of surficial deposits is that mapped as "younger alluvium", Qal, which occupies the floodplains along the present streams; the six categories of "older" surficial deposits, ranging from 30 to over 490 feet in height above the Belle Fourche River, are coextensive with remnants of terraces representing, in their order from highest, Tt6, to lowest, Qt 1, six successive stages in the sculpturing of the land surface. Whereas in the part of the district drained by the Belle Fourche River and its tributaries, all of these categories of "older" surficial deposits are associated with terraces, it is noteworthy that in that part lying within the watershed of the Little Missouri River only deposits of the three oldest categories, Qt 4, Qt 5 and Tt 6, are present as terrace cappings. Restriction of the youngest categories, Qt 3, Qt 2 and Qt 1, to the part of the district east of the central divide has to do with a stream-capture that took place at some time during the Pleistocene epoch. As outlined by Darton and O'Harra (1905, pp. 1, 2), the circumstances relating to this incident are as follows:

"One of the most notable topographic features in the quadrangle is the Stoneville Flats, (NW cor. T. 57 N., R. 62 W.) a smooth-bottomed valley that extends completely across the low divide between Little Missouri and Belle Fourche rivers. Originally it was occupied by the upper part of the Belle Fourche, which then flowed northward into the Little Missouri. The flat is floored with a deposit of loam and gravel, some of which continues on the high terraces up the Belle Fourche, and to the north it merges into the alluvium lying along the Little Missouri. This change of course of the stream is a clear case of stream robbery, the lower Belle Fourche, with the advantage of steeper declivity, having cut back the head of its valley until in the present big bend it has captured the stream which originally flowed into the Little Missouri through the Stoneville Flats. Since that time the Belle Fourche Valley has been deepened about 100 feet, for there is a high bank of about that height in the bend of the river. In other words, a dam somewhat over 100 feet in height would turn back the waters of the upper Belle Fourche into the Little Missouri, but, on the other hand, a dam of very moderate height would deflect the waters of the Little Missouri across the Stoneville Flats into the Belle Fourche. There is but little erosion in these flats at present, but it is probable that a stream will eventually develop there that will cut across them and deflect the head of Little Missouri River into the Belle Fourche. Such a stream has already begun the excavation of a valley along the eastern side of the flats."

Each of the terraces on which the "older" surficial deposits lie is assignable to a position on, above or below a sub-horizontal surface that is considered to represent the approximate former position in space of the flood plain of the principal stream that flowed in its immediate vicinity at the time of the capture. In the vicinity of the Belle Fourche River and its tributaries, the terrace deposits designated Qt 3 (see geologic map) lie on such surfaces and so, approximately, do the alluvial materials designated Qal in the stream valleys within the part of the district drained by Little Missouri River and its tributaries. In the present discussion, all such surfaces are termed, collectively, the Stoneville surface because all of them are considered to have developed at the same, or nearly the same time as the Stoneville Flats, where the capture took place. The materials on terraces higher than the Stoneville surface, Qt 4, Qt 5 and Tt 6, may then be classified as pre-Stoneville, and those at lower levels, Qt 2 and Qt 1, as post-Stoneville.

The height of the highest and oldest pre-Stoneville terrace deposits, Tt 6, which on an average are about 525 feet higher than the Stoneville surface, suggests that their origin may have been contemporaneous with that of the Mountain Meadow surface of the Black Hills, believed by Fillman (1929, p. 21-36) to have originated in mid-Oligocene time. If so, they may be outliers of a vast peneplain, the Cypress plain (Alden, 1932,

p. 4-14) which is known to have extended over much of the northern Great Plains region during Oligocene time. However, their correlation with deposits so far outside this district is problematical and the deposits designated Tt 6 can be assigned only tentatively to the Oligocene series; they could be much younger and were considered so by Darton and O'Harra (1905, p. 1-5).

Two stages of stream-erosion in the interval between deposition of these highest surficial materials and those on the Stoneville surface, Qt 5, are represented by terraces about 210 feet, Qt 5, and 150 feet, Qt 4, higher than the Stoneville surface. Most of the remnants of these two pre-Stoneville terraces occur southeast of the central drainage divide but a few are also present in the valley of Little Missouri River.

The terrace deposits that occupy by far the largest aggregate area are those on the Stoneville, Qt 5, surface itself. East of the central divide all Qt 5 deposits are materials that had accumulated essentially at the time of the stream-capture; west of the divide they include also much alluvium that has been deposited in the interval since that time. Some of this younger material is presumably equivalent in age to deposits on the post-Stoneville terraces, Qt 2 and Qt 1, that occur only east of the divide, and the rest is equivalent to the deposits of Recent alluvium, Qal, that occupy the floodplains of Belle Fourche River, Owl Creek and South Indian Creek. The higher of the two post-Stoneville terraces, Qt 2, is about 40 feet below the Stoneville surface; the lower is about 75 feet below that surface. The Recent alluvium along the Belle Fourche River is about 100 feet below the Stoneville surface.

CRETACEOUS HISTORY AND PALEOGEOGRAPHY
OF THE
NORTHERN BLACK HILLS AND SURROUNDING AREA

The Lakota sandstone is the oldest Cretaceous formation in the Black Hills area. It is generally accepted that this formation does not represent the beginning of Cretaceous time, but there is no large unconformity indicated by the contact of the Lakota sandstone and the Jurassic Morrison formation. The Lakota sandstone, the Fuson formation, and the lower three-fourths of the Fall River sandstone consists of non-marine deposits. Marine fossils in the upper part of the Fall River sandstone evidence the first submergence of the Black Hills area in the Cretaceous period. The Skull Creek shale, which rests on the Fall River sandstone, consists of dark marine sediments. The Skull Creek and its equivalent in the Thermopolis shale have a very wide extent which indicates uniform conditions in a broad epicontinental sea. Western limits of this sea as shown by Reeside (1944) extended along a line a short distance west of the Idaho-Wyoming boundary. A local uplift of the Black Hills followed the deposition of the Skull Creek shale. During the relatively short time required for the deposition of the Newcastle formation, the central Black Hills was a low tree-covered land area as indicated by thin coal beds, reworked sandy deposits, and the absence of coarse gravels. The Black Hills area again submerged at the beginning of deposition of the Mowry shale. Widespread uniform conditions are indicated by the fact that uncommonly siliceous shales extend over nearly the entire state of Wyoming, the southern three-fourths of Montana, the western parts of the Dakotas, and western Nebraska. Western limits of this sea probably extended north and south through eastern Idaho, and non-siliceous marine sedimentation may have extended as far east as central Iowa (Fig. 5). By Mowry time sedimentation was much more active in the western part of the sea. Considerable evidence indicates that land areas in Utah, Idaho, and western Montana were being actively uplifted and provided most of the sediment and much of the volcanic material.

Except for a change from siliceous to dark shale type of sedimentation, conditions continued to be uniform throughout the deposition of the lowermost Upper Cretaceous formation, the Belle Fourche shale. Continued uplift of western land areas is indicated by sandy sediments in the equivalent of the Belle Fourche shale to the west. Calcareous deposits of the Greenhorn formation suggest a broad shallow sea extended over much of the High Plains region at that time. To the west the Greenhorn formation passes into a shale facies which in turn grades into sandy shale and continental type sediments. The dark shale and sandy shale of the Carlile unit and the calcareous rocks of the Niobrara formation represent a repetition of conditions that existed in Belle Fourche and Greenhorn time. The thick Pierre shale indicates a long period of rather uniform marine conditions during which continental type sediments tended to increase to the east and the epicontinental sea became somewhat restricted. By Fox Hills time the sea was restricted to the eastern parts of Montana, Wyoming, Colorado, and western Dakotas and Nebraska. At the close of Fox Hills time, the sea withdrew from the Black Hills and surrounding area. Gradual withdrawal of the sea and low elevations of the land areas are suggested by the relations of the Fox Hills to the superjacent continental deposits of the Lance formation. Dobbin and Reeside (1930, p. 9-25) have shown that at some localities the Lance and Fox Hills are separated by a small

Figure 3.—Extent and thicknesses of Upper Cretaceous deposits in the Western Interior of United States. Thickness includes Mowry and Newcastle formations which are now considered lower Cretaceous. From Reeside (1944).

unconformity but in many places the contact between the two formations is gradational. The uppermost Cretaceous is represented by the continental deposits of the Lance formation.

STRUCTURE

The bentonite deposits of the northern Black Hills lie within a belt of low folds which skirts the margin of the Black Hills uplift. Regional dips are gentle toward the northeast, north, and northwest, but in the west and southwest parts of the district where dips of 25 to 30 degrees are common, the rock strata drop sharply into the Powder River structural basin. Folds in the eastern half of the district are characterized by elongate, synclinal and anticlinal flextures whose axes parallel the arcuate northern margin of the Black Hills. Most of these folds are nearly symetrical in outline and range from about 1 mile to 10 miles in length and from 400 yards to 3 miles in width. Folds in the western part of the district tend to be equidimensional and are not as well oriented with the margin of the Black Hills uplift as the anticlines in the eastern part of the district. Some of these nearly equidimensional domes may have cores of igneous rocks, a possibility suggested by the fact that some of them are only a few miles from the monzonitic masses of Devil's Tower and Missouri Buttes.

Many small structural domes and synclinal depressions are superimposed on both the larger structures and on gentle regional dips. Vertical dimensions of most of these small features can be measured in a few feet and their lateral extent in a few yards. These structures are particularly apparent where the lower part of the Belle Fourche and upper part of the Mowry formation are exposed because several light colored bentonite beds in dark shale emphasize local dips. Lack of orientation and small size of of these structures suggests that they have not been formed by diastrophic forces. Structures of similar magnitude in the Minnekahta limestone of Permian age in the Whitewood region of the Black Hills have been attributed by Knasck (1956, p. 20) to uneven compaction and condensation of underlying shales. Differential compaction or movements within the Cretaceous shales probably took place during the folding of the larger structures and the uplift of the Black Hills in the Tertiary period.

There is no strong evidence concerning the date of the folding within the area of the present investigation where upper Cretaceous rocks are all marine and the Cenozoic era is represented only by terrace and alluvial deposits. Farther west in the Powder River Basin the Cretaceous-Cenozoic section is more complete. Dobbin and Reeside (1930, p. 9-25) demonstrated that the withdrawal of the Cretaceous seas at the close of Fox Hills time is not marked by a major unconformity. The fine-grained nature of the thick Lance formation is evidence that land areas remained low in latest Cretaceous time. Paleocene and Eocene units where present in the eastern part of the Powder River basin are also fine-grained, suggesting that the uplift of the Black Hills was more or less gradual and barely exceeded the rate of erosion throughout early Tertiary time. The first evidence of prominent relief in the region is presented by coarse terrace gravels, the oldest of which have been dated by geologists as mid-Oligocene on the basis of rather scanty evidence. Additional uplifts in Pliocene and Pleistocene epochs are suggested by the step-like arrangement of terraces and the tilting of older peneplained surfaces. Doubtless the strata of the Northern Black Hills District were influenced by various stages of uplift that occurred from late Cretaceous to Pleistocene time. However, it seems probable that the most prominent folding took place at the time of the

Figure 4.—Fault exposed in strip mine of the Clay Spur bentonite bed in sec. 15, T. 9 N., R. 1 E., Butte County, South Dakota. Geologist is standing at base of fault scarp. White band near top of cut formed by outcrops of bentonite bed E.

greatest regional uplift which could not have occurred until after the deposition of the fine-grained Eocene sediments.

The rocks exposed at the surface are almost free of large faults, but small faults are common. Normal faults having nearly vertical fault planes and displacements of only a few feet are particularly abundant in the upper part of the Mowry shale where they greatly influence the configuration of outcrops of the Clay Spur bentonite bed. The faults generally cause little difficulty in mining bentonite (Fig. 4) but in a few places excessive thicknesses of overburden are present on the downthrown side of faults.

MINERALOGY OF BENTONITE

STRUCTURE OF MONTMORILLONITE

Montmorillonite is essentially the only clay mineral in the bentonite of the Northern Black Hills district. The most commonly accepted crystal structure of this mineral (Fig. 5) is basically that suggested by Hofmann, Endell, and Wilm (1933, p. 340-347). They believed that the structure consisted of one gibbsite sheet sandwiched between two sheets of silica tetrahedral groups. Unit cells are stacked one above the other in the direction of the c-axis but are separated by different amounts of water. Because of variations in water, the c-dimension of the mineral is not constant; the result is an expanding lattice. Montmorillonite has an ideal composition of $(OH)_4\ Al_4\ Si_8\ O_{20} \cdot n\ H_2O$, but replacements of Si^{++++} by Al^{+++} by Mg^{++} and Fe^{++} or Fe^{+++} are common. All of the replacements except Fe^{+++} for Al^{+++} result in a negative charge. It is generally accepted that these negative charges are balanced by exchangeable cations. The type and amount of substitution within the lattice may have a strong effect on the abundance and possibly the exchangeability of the cations. Type and

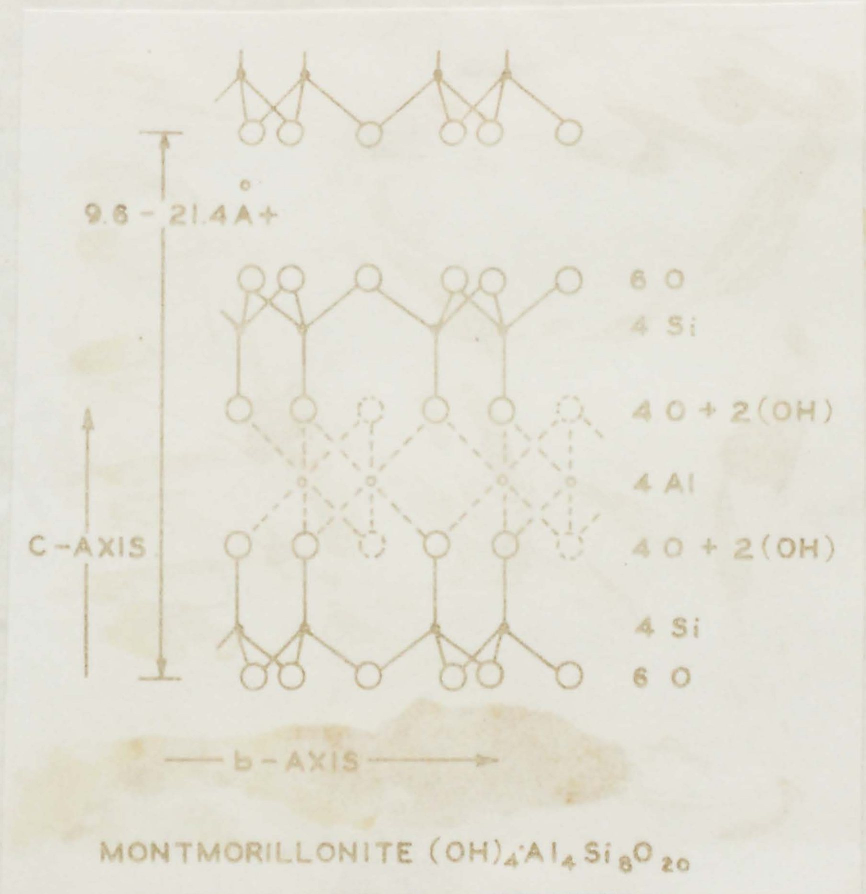

Figure 5.—Schematic presentation of the crystal structure of montmorillonite (after Hofmann, Endell and Wilm, from Grim, Jour. Geol. Vol. 50, 1942, fig. 1, p. 239).

abundance of cations, in turn, greatly influence the physical properties of the clay. In the "Wyoming type" bentonites, sodium is by far the most abundant exchangeable cation, but as a rule some Ca^{++} and Mg^{++} as well as minor amounts of K and H are also present.

Because type and abundance of cations has much to do with the properties of bentonite, location and replaceability of exchangeable ions is very important. Results obtained by Hendricks, Nelson, and Alexander (1940, p. 1457-1464) show that more than 80 percent of the exchangeable cations are located between the silicate sheets rather than around the edges of the montmorillonite flakes. Replaceability of ions is not completely understood, but it is known that it is influenced by several factors. In general divalent ions have more replacing power than monovalent ions. Hydrogen is an exception to this generality as it tends to have much more replacing power than other monovalent ions. Various ions behave differently as the population of exchange positions increases or decreases. Concentration of ions seems to have an important effect, and increased concentrations of a given ion generally causes greater exchange by that ion.

NON CLAY MATERIALS OF THE BENTONITE

Contents of non clay materials in the bentonite beds of the Northern Black Hills district range from 8 to about 65 percent. Percentages of these materials in each bed is within much narrower limits, but proportions of non clay materials vary in different strata and from place to place within a bed. The particle size of the non clay materials is divisable into the following groups: (1) Large fragments, including crystals of calcite and selenite as large as 2 by 5 inches; (2) grit, or sand-sized particles larger than 325 mesh sieve (44 micron opening); (3) particles smaller than grit which can be observed by optical methods; (4) particles too small for observation by optical methods.

Non clay materials consist of unaltered portions of the original ash, detrital materials and precipitates of soluble minerals. The detrital minerals and some of the chemical precipitates were introduced during the deposition of the ash. Some of the soluble salts and iron oxides must have been introduced after deposition. Many of the unaltered minerals of the ash are somewhat arbitrarily distinguished from detrital minerals on the basis of angularity.

Original constituents of the ash are composed chiefly of angular quartz and feldspar. Some biotites and minor amounts of muscovite, volcanic glass shards, and traces of several of the accessory minerals in igneous rocks are usually present. Gruner (1940, p. 587-590) has demonstrated that some bentonites contain as much as 50 percent cristobalite, and that the cristobalite occurs in particles that are smaller than 1.25 microns. No cristobalite was identified by optical methods in the bentonite samples from the Northern Black Hills district. However, x-ray examinations by members of the Geochemistry and Petrology branch of the U. S. Geological Survey have revealed that cristobalite is present in some of the bentonite.

Detrital grains vary greatly in roundness and consist of quartz, feldspar, and biotite with minor amounts of many of the more stable minerals. Many rounded grains of hematite were observed in one bentonite bed, but this material is not common in the bentonite. Detrital minerals are not abundant in most of the light colored high swelling bentonite deposits, but in some of the beds having low colloidal properties, detrital materials make up most of the non clay minerals. Because of shale and silt impurities, detrital minerals are most abundant in the upper dark colored portions of bentonite beds where they are usually associated with some organic materials.

Selenite is the most common chemical precipitate in the bentonite, but other types of soluble salts are doubtless present in most bentonite. Iron oxide and carbonate materials are common in joint deposits. The selenite occurs as small fibrous crystals along joints and both small and large euhedral crystals throughout the clay. Dengo (1946, p. 7-8) concluded from field and microscopic evidence that selenite in bentonite beds near Casper, Wyoming, was a final product of diagenesis and formed later than bentonite. He observed that larger crystals were present at or near the surface and that the selenite has been somewhat changed by weathering. Where the bentonite is mined in the Northern Black Hills district, large crystals of selenite can be observed at distances as great as 50 yards from the nearest natural outcrop. This indicates that the large crystals at the surface of the bed are not residual and oppose the theory that an effect of weathering would be to increase the size of the crystals. Selenite deposited in joints in the bentonite clearly indicate that some of the crystals were deposited after the formation of the bentonite. Crystals along joints also suggest that selenite was introduced by ground water action rather than formed as a final product of diagenesis.

IDENTIFICATION OF THE CLAY MINERALS

There are several methods of identifying clay minerals. Thermal analysis is one of the most practical and rapid methods and is therefore employed in this investigation. The apparatus used is similar to that described by Grim and Rowland (1944, p. 65-68). In order to obtain reproduceable results, care was taken to center the thermocouples and to maintain constant heating rates of approximately 100°C in 10 minutes. All samples were allowed to reach equilibrium moisture conditions in an atmosphere of 46 percent relative humidity before analyses were made.

The thermal technique is particularly valuable in the study of bentonites because it provides a measure of the forces which hold water on the basal plains of the unit cells and a means of identifying common types of exchangeable cations. Loss of water with heating is accompanied by absorption of energy and results in an endothermic reaction and the more tightly bound water requires higher temperature to cause this reaction. It is known from the works of Hendricks, Nelson, and Alexander (1940, p. 1457-1464) that calcium and sodium bentonites yield different thermal curves. At the moisture content at which the samples were analyzed, the loss of interplaner water results in a single sharp peak for sodium bentonite and a double peak for the calcium material. In pure sodium bentonite this reaction begins at about 90°, reaches its maximum near 150°, and is completed at about 180°C. The first peak in the calcium bentonite is commonly broader and occurs at slightly higher temperatures than in sodium bentonite. As a rule the second reaction in calcium bentonite is much weaker than the first. This reaction begins between 170° and 200° and is usually completed before a temperature of 250°C is reached. It is generally accepted that the second peak is a consequence of hydration of calcium ions. Sodium either does not hydrate or has a much weaker attraction for water; hence, there is only a single peak at a lower temperature.

Thermal curves of hydrogen bentonite are characterized by two nearly equivalent endothermic reactions at low temperatures as shown by Barshad (1950, p. 228). The exothermic reaction between 900° and 1000° also tends to be much stronger. The two low peaks occur between temperatures of 150° and 180°C, and the reaction caused by the loss of interlaminar water is ordinarily completed when temperatures of 210°C are reached. During the

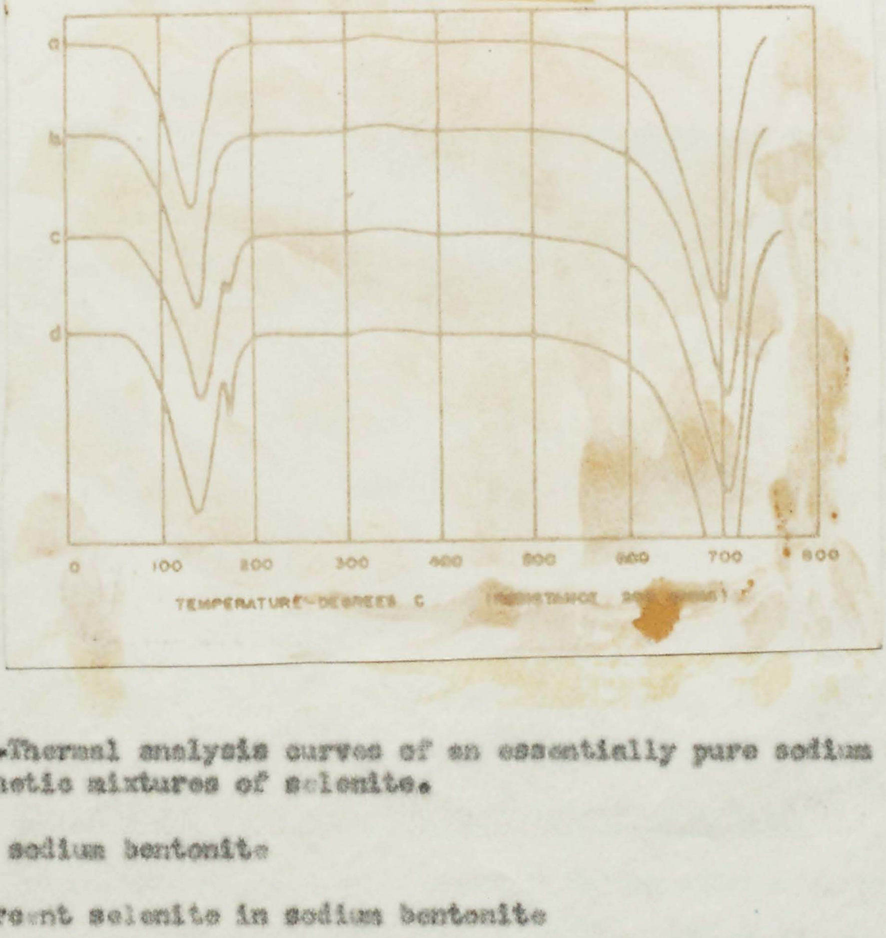

Figure 6.—Thermal analysis curves of an essentially pure sodium bentonite and synthetic mixtures of selenite.

a. Pure sodium bentonite

b. 1 percent selenite in sodium bentonite

c. 5 percent selenite in sodium bentonite

d. 10 percent selenite in sodium bentonite present investigation a correlation was noted between thermal curves and pH determinations. All samples having two nearly equal low temperature peaks have acid pHs which further substantiates the presence of H^+.

Small amounts of selenite, $CaSO_4 \cdot 2H_2O$, give endothermic reactions at temperatures between 150° and 200°C. These reactions are caused by the loss of water from the hydrous selenite and may possibly be confused with reactions caused by loss of water from hydrated exchangeable ions. To furnish a means of recognizing the reaction resulting from varying amounts of selenite, thermal analyses were made of a minus 2 micron fraction of essentially pure sodium bentonite and synthetic mixtures of that clay with 1, 5, and 10 percent selenite (Fig. 6). This suite of curves also provides a means of estimating the amount of selenite in the bentonite. Thermal reactions in the synthetic mixtures may not correspond exactly to equal proportions of natural mixtures. Nevertheless thermal curves of natural mixtures in which the amount of selenite can be estimated microscopically have reactions that are of the same order of magnitude as the equivalent synthetic mixture.

TEXTURES OF WEATHERED SURFACES OF BENTONITE BEDS

In general, textures that are developed on the weathered surfaces of bentonite beds are related to the swelling capacities of the clay. Surfaces of high swelling or "Wyoming type" bentonite beds are characterized by a popcorn texture (Fig. 7). The surface of this bentonite swells many times its volume and becomes a slippery thixotropic mass during rainy periods. Large cracks develop as the material dries. With continued drying and shrinkage, smaller cracks diverge from the larger ones. In the final stages the surface is a rubble of fragments resembling popped corn. The popcorn surface texture can be developed by alternately wetting and drying the bentonite in the laboratory. As a rule individual fragments are more or less angular after the first one or two cycles of wetting and drying, but with additional cycles, particles become rounded and more closely resemble popcorn. Particles which are angular when dry become rounded and irregular in outline as they swell in the presence of water. Presumably there is a tendency for the transfer of very small clay particles away from corners and edges during swelling, and in this manner angular particles become rounded.

The surface of low swelling clay commonly consists of rounded edged polygons resembling alligator hide (Fig. 15), a term used by Kerr and Hulp (1949, p. 61) in describing the surface of a bentonite bed in New Mexico. Because of its low swelling capacity, the shrinkage with drying is only great enough to form polygonal cracks. The rounded edge of the polygon is probably formed in the same manner as the edge of the popcorn particles. Some low swelling bentonite materials have a granular texture similar to cornmeal. This texture is most common an inch or two below the surface and is expressed in a soft puffy soil. This texture is particularly characteristic of impure bentonite zones and calcium type bentonite beds. The significance of this texture is not understood. However, most calcium saturated soils are known to be granular, and it is likely that the granular texture of bentonite is a consequence of the type of exchangeable cations that are present.

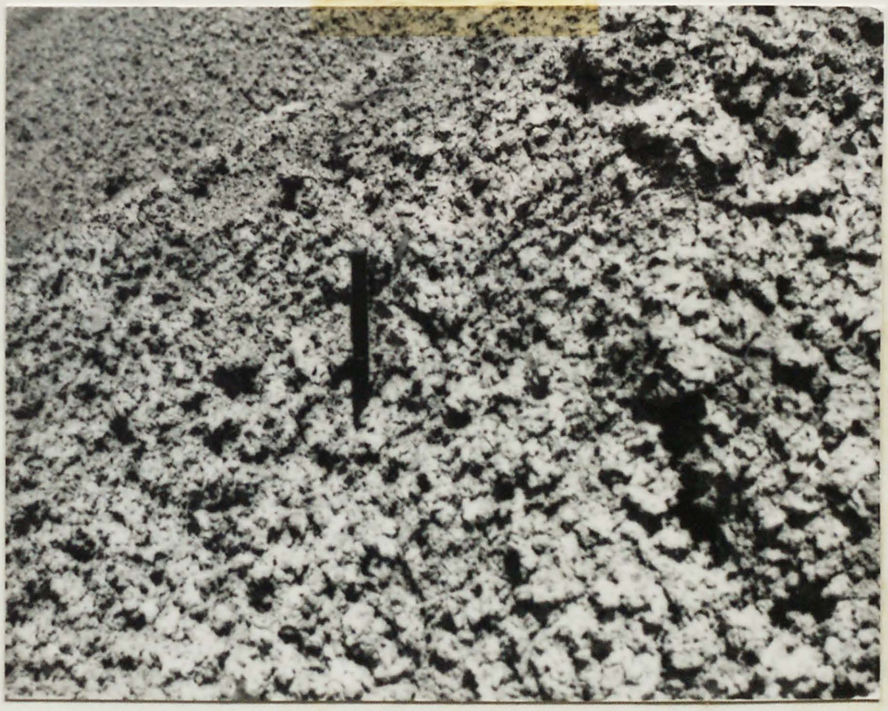

Figure 7.--Popcorn texture on the surface of the Clay Spur bentonite bed.

STRATIGRAPHIC OCCURRENCE AND CHARACTERISTICS OF THE BENTONITE BEDS

BED A

Bentonite bed A occurs in the Newcastle sandstone formation and is commonly called the Newcastle bentonite bed. Bed A has also been referred to by Heathman (1939, p. 8-9) as the bentonite bed at the base of the Mowry shale. Within the district outcrops of bed A are restricted to Crook County, Wyoming, where exposures of the bed appear intermittently over a distance of 30 miles, extending from the northern part of T. 56 N., R. 62 W. to the northeast corner of T. 56 N., R. 66 W. Bed A wedges out completely beneath a covered zone a short distance beyond its easternmost outcrop as that bed is not present in exposures of the Newcastle sandstone in the western part of the next township to the east. The Newcastle formation itself wedges out less than nine miles southeast of the easternmost exposures of the bentonite. Bentonite is known to be present in the Newcastle sandstone beyond the western limits of bed A outcrops in T. 56 N., R. 66 W., but because of poor exposures, stratigraphic uncertainties, and unfavorable mining conditions, the mapping of bed A was not carried beyond that limit.

Bed A is a discontinuous stratum that is not present in some outcrops of the Newcastle sandstone, but over most of its areal extent the bed is characterized by thicknesses of three to five feet and eight feet of bentonite is present in many exposures of the bed. At one locality in sec. 6, T. 56 N., R. 62 W., Crook County, Wyoming bentonite bed A is 30 feet thick. It is unlikely that the 30 foot thickness is very persistent because nearby exposures reveal less than five feet of bentonite. The lenticular nature of the sandstone beds associated with this very thick portion of bed A suggest that the deposit results from concentration of volcanic ash in a channel formed by either stream or tidal currents.

Thicknesses and lithology of the Newcastle strata vary considerably within the district, and the relations of bed A to the top and the base of the formation are not uniform. In sec. 7, T. 56 N., R. 62 W., bed A is less than six feet above the contact between the Newcastle sandstone and the underlying Skull Creek shale, but less than four miles northwest of that place, about 30 feet of Newcastle strata are present below the bentonite bed. Farther west, along the Little Missouri River, the Newcastle sandstone is more uniform, and bed A crops out near the middle of the formation. In most exposures, a bed of platy impure coal or carbonaceous shale is present below the bentonite bed and small fragments of charcoal are common in the lower part of the bentonite. The coaly stratum is unusually hard and weathers to a small but prominent ledge (Fig. 8). Where the carbonaceous stratum is absent, fine-grained sandstone and siltstone are present immediately below the bentonite bed, and the uppermost one to five inches of these arenaceous beds are locally very hard and siliceous, but in most places this sand is almost as friable as sandstone in other parts of the formation. The contact between the bentonite and the underlying rocks is very distinct. The floor of bed A is sufficiently indurated to support heavy mining equipment and to permit the mining of even the lower part of the bentonite without undue contamination of undesirable materials.

In most outcrops bed A is overlain by friable sandstone and siltstone, but in a few places gray, soft, silty shale is present above the bentonite, and at other localities a thin stratum of impure coal overlies the bed. The contact between the bentonite and the superjacent materials is either very distinct or consists of a gradational zone one to six inches thick. The Newcastle beds above bed A range in thickness from 20 to 35 feet and consist of sandstone and siltstone with subordinate amounts of shale.

Figure 8.—Bentonite bed A and enclosing rocks in NW 1/4 sec. 11, T. 57 N., R. 65 W., Crook County, Wyoming.

Figure 9.—Outcrops of bed A and subjacent coal stratum in NE 1/4 sec. 11, T. 57 N., R. 65 W., Crook County, Wyoming.

These strata making up the overburden can easily be removed by heavy mining equipment but are still more resistant than the basal black shale of the overlying Mowry formation. The resistance of these Newcastle strata is sufficient to form small ridges and local dip slopes capping the bentonite bed and is largely responsible for the large amount of bed A bentonite under light overburden. The most favorable mining localities are situated where bed A is capped by gentle dipping Newcastle strata in the northwest part of T. 56 N., R. 62 W., and the southeast part of T. 57 N., R. 66 W., and in the central portions of the broad low North Fork anticline in the western part of T. 57 N., R. 65 W., Crook County, Wyoming.

Most outcrops of bed A are characterized by moderately developed popcorn surfaces, but parts of the weathered surfaces of this bed have an alligator hide texture. Crystals of selenite and fragments of fibrous calcite are common on some outcrops of bed A. The color of the bentonite ranges from olive-green to brownish-grey with intermediate shades of greenish-gray and brownish-gray. Commonly the light colored bentonite extends to the top of the bed and variations in shade that are present are ordinarily lenticular in outline. In places the material adjacent to joints or cracks in the bentonite is much darker than the rest of the bed. This dark material appears to have been stained by small amounts of organic matter. Under considerable overburden the bentonite is bluish-grey, a color that oxidizes near the surface to lighter shades (see further discussion of near surface discoloration of the bentonite under the Clay Spur bed). Because of the porous nature of the superjacent sandstone the oxidized or discolored portions of bed A extend to greater depths and are not as clearly related to the topographic configuration of the land surface as in other beds where the material above the bentonite is composed of comparatively impervious shale.

The non clay materials of bed A range from 10 to about 35 percent of the bentonite. The finer sized particles consist of very angular quartz and feldspar and minor amounts of biotite, selenite, and iron oxides. Traces of volcanic glass and many other accessory minerals are also present. Grit made up as much as 13 percent of the samples tested, and it is probable that in some parts of the bed the proportion of grit is even much higher. Approximately 80 percent of the grit is composed of clear subangular quartz. The remaining 20 percent is made up of rounded masses of limonite, both rounded and euhedral biotite flakes, selenite, and traces of muscovite, garnet, sphene, magnetite, glass shards and small rounded grains of very fine-grained schist. Detrital quartz in large amounts conforms with evidence presented for the near shore deposition of the bentonite. Presumably the rounded biotite flakes are also detrital but the euhedral flakes were probably a part of the volcanic ash. The most likely source of schistose grains is in the central pre-Cambrian core of the Black Hills, and their presence in the bentonite may support the theory that pre-Cambrian rocks were exposed in the central Black Hills during Newcastle time.

Thermal analyses of a sample of bed A bentonite from one locality (Fig. 10, curve c) revealed that sodium is the chief exchangeable ion that influences the water in the montmorillonite, whereas bentonite from a second locality (Fig. 10, curve d) is characterized by much calcium bound water. These results conform with the ion exchange data (Table 4, samples 1 and 2) and commercial tests of the clays. Some of the clay from bed A (samples showing interlayer water chiefly influenced by sodium) has very high swelling capacities and excellent drilling mud properties, but

Figure 10.--Differential thermal analysis curves of samples from bentonite beds A, B, and Clay Spur.

a. Bed A, brownish-gray bentonite 2 feet thick, sec. 8, T. 58 N., R. 63 W., Crook County, Wyoming.

b. Bed A, light colored bentonite 3 feet 9 inches thick, sec. 8, T. 58 N., R. 63 W., Crook County, Wyoming.

c. Bed A, light colored bentonite 4 feet 8 inches thick, sec. 6, T. 56 N., R. 62 W., Crook County, Wyoming.

d. Bed A, light colored bentonite 3 feet 2 inches thick, sec. 8, T. 56 N., R. 62 W., Crook County, Wyoming.

e. Bed B, light colored bentonite 8 inches thick, sec. 34, T. 58 N., R. 63 W., Crook County, Wyoming.

f. Bed B, bluish-gray bentonite 1 foot 7 inches thick, sec. 8, T. 57 N., R. 61 W., Crook County, Wyoming.

g. Clay Spur bed, light colored bentonite 1 foot 9 inches thick, sec. 34, T. 9 S., R. 58 E., Carter County, Montana.

h. Clay Spur bed, light colored bentonite 1 foot 6 inches thick, sec. 34, T. 58 N., R. 63 W., Crook County, Wyoming.

i. Clay Spur bed, dark colored bentonite 11 inches thick, sec. 33, T. 58 N., R. 63 W., Crook County, Wyoming.

j. Clay Spur bed, light colored bentonite 3 feet 1 inch thick, subjacent material analyses in curve i.

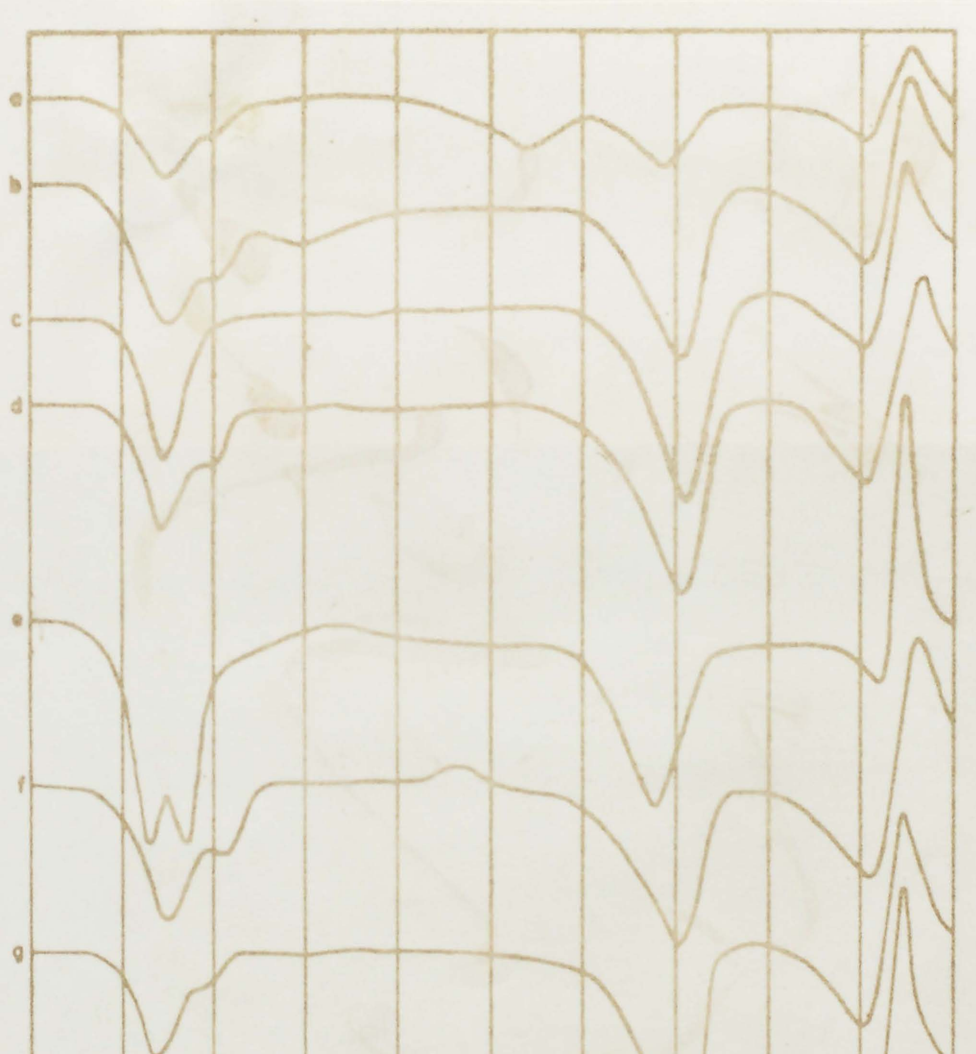
a
b
c
d
e
f
g
h
i
j
0
100
200
300
400
500
600
700
800
900
1000
TEMPERATURE—DEGREES C
(RESISTANCE 200 OHMS)

Figure 10

much of the material from this bed (sample 5 in which interlayer water is influenced by calcium) swells very little and is unsuitable for use in drilling muds. Thermal curves of the lower light colored and upper dark stratum in bed A at a third locality (Fig. 10, curves a and b) indicate that the water in both parts of the bed is influenced by calcium. In the sample from the upper dark bentonite, an endothermic peak at about 540° suggests the presence of some illite.

BED B

Bentonite bed B occurs in the upper part of the Mowry shale 50 to 55 feet below the Clay Spur bed. This Bed B is only 10 to 18 inches thick, but it is very persistent and can be found in almost every exposure of upper Mowry strata. Siliceous shale enclosing the bed stands in steep cut banks and cuesta faces and bed B is rarely present under light overburden. Because of excessive cover and unfavorable thickness, bed B cannot be considered as a possible source of bentonite. The bed is of interest because it was deposited in an environment very similar to that of the Clay Spur bed and the factors influencing the post depositional alteration, other than those resulting from differences in composition of the original ash, must have been almost identical for the two beds. Bed B was deposited on a smooth sea floor below quiet marine water as indicated by the uniform thickness and persistence of the bed and the presence of marine fossils in the enclosing shale. The bentonite bed is characterized by a sharp basal contact but grades upward into superjacent shale through a thin zone of interlaminated shale and bentonite. The floor of the bed consists of a zone of chertlike material that is approximately one inch thick. The chertlike material is distinctly harder than the subjacent siliceous shale.

As a rule outcrops of bed B are light yellowish gray and are characterized by powdery or alligator hide textures. Undiscolored shades of bluish-gray bentonite commonly persist to within a few inches of the surface of this bed. This persistence of the undiscolored clay near the surface seems to be more than a function of the heavy overburden and probably indicates that the iron and the clay are more intimately associated and, therefore, the iron cannot be as easily oxidized as in other bentonite beds. Thermal curves (Fig. 10, curves e and f) and ion exchange data (Table 4) of samples of this bed from two localities show that the proportion of exchangeable sodium in the clay is very low and that calcium and hydrogen are the dominant exchangeable cations. Presence of a large proportion of hydrogen in a sample of bed B bentonite from one locality is indicated by the pH of 5.4 and the dual character of the low temperature peak in the thermal curve. The two endothermic reactions occur at the same temperatures as the two peaks shown for hydrogen saturated montmorillonite by Barshad (1950, p. 228). This sample of acid clay was obtained by channel sampling near the surface of the bed and it is likely that calcium was replaced by hydrogen during weathering.

The bentonite in bed B has very low swelling capacity, and it has essentially no value for use in drilling muds. As with most calcium bentonites, the foundry bond properties of the clay in bed B is characterized by very high green strength and low dry strength.

CLAY SPUR BED

Nomenclature and occurrence

The name Clay Spur was introduced by Rubey (1930, p. 4) for outcrops of the bentonite bed in the western Black Hills. Since 1930 this bed has been referred to as Type I bentonite (Wing, 1940, p. 12, 20) and the Upper Mowry bed (Moore, 1940, p. 27). This same bentonite stratum is also termed the Commercial bed by producers of bentonite. The Clay Spur is by far the most important bentonite bed in the northern Black Hills. It has been the source of more than 95 percent of all bentonite shipped from the district, and still contains the largest known reserves of commercial grade bentonite.

The Clay Spur bed is commonly regarded as occurring at the top of the siliceous Mowry shale, and locally the top of the bentonite does mark the upper limit of that formation. In many places, particularly where the Clay Spur bed is thick, a zone above the bentonite, ranging in thickness from six feet to a knife edge, contains siliceous shale laminae. The lithology of this siliceous zone clearly indicates that it is closely related to the Mowry shale and, therefore, it is considered to be the uppermost part of that formation.

Rocks comprising the overburden above the Clay Spur bed consist chiefly of the manganiferous siderite concretion zone of the lower member of the Belle Fourche shale. This concretionary zone is distinctly more resistant than the overlying portions of the Belle Fourche formation. As a consequence of this difference in resistance, the concretion zone serves as a cap rock above the Clay Spur bentonite bed. The cap rock, in turn, causes the bentonite to lie under light overburden in rather broad belts where upper Mowry and lower Belle Fourche strata are exposed. Numerous elongate spurs, small outliers, and inliers are formed where the bed and its protecting strata are cut by local drainage patterns.

Outcrops of the bentonite commonly appear as conspicuous light colored bands that can be seen for several miles. Weathered surfaces of the lower light colored part of the Clay Spur bed are characterized by a well developed popcorn texture except in portions of the bed deficient in colloidal properties or partially covered by soil. Dry surfaces of the bed are nearly white in color but when wet they become much darker and appear to have green or yellow shades. Surface textures of the dark portions of the bed commonly resemble alligator hide or are covered by soft soil. Moisture contents of the light colored clay in the natural state usually range from about 15 to 40 percent with an average of about 30 percent. In places particularly accessible to the movement of ground water, moisture contents may be as high as several hundred percent. When the moisture content is less than about 40 percent, the clay tends to part with a subconchoidal fracture but as the moisture content increases, the clay becomes very plastic and finally a thixotropic gel. As the moisture content is reduced below about 20 percent, the conchoidal fracture is replaced by a hackley parting and the bentonite becomes almost as hard as the fingernail.

Relation of thicknesses of the bed to enclosing strata

Characteristics of both the bentonite and enclosing strata vary with the thickness of the bentonite bed. Variations in these characteristics can best be understood by first examining the two extremes of conditions that are present. In places the Clay Spur bed is only two inches thick (Fig. 12), but no locality was found where bentonite was completely missing at the stratigraphic position of the bed. The thin bentonite is characterized by very light-gray colors and usually much iron staining is present. The bentonite grades into the superjacent shale through a zone of bentonitic shale one to two inches thick. Contact between the bentonite and subjacent material is not so sharp as is characteristic of those portions of the bed that are sufficiently thick to be mined. The lower part of the thin bentonite commonly consists of a zone of dark bentonitic shale one-half to one inch thick. No chertlike floor is present beneath thin portions of the bed. Subjacent material, though composed of siliceous shale, is much softer than similar material under thicker portions of the bentonite bed.

In many places the Clay Spur bentonite bed is four feet thick and in a few localities as much as seven feet of bentonite are present. Where the bentonite is thick (Fig. 14) there is a prominently developed chertlike floor beneath the bed and its contact with the bentonite is very sharp. The cherty floor ranges from two to about eight inches in thickness and its lower limits are as a rule poorly defined, marked only by a gradual downward decrease in hardness. In a few places the Mowry siliceous shale below the chertlike floor is harder adjacent to vertical joints suggesting that the origin of the cherty material is related to downward movement of ground water. The bentonite is readily divisible into a lower light colored stratum and an upper dark colored layer. The light bentonite ranges in thickness from 2 1/2 to 4 feet and is characterized by waxy textures and pronounced color-banding exhibiting shades of yellow, olive green, greenish gray, and light gray. The lowermost one-fourth to one-half inch of the bentonite invariably has a cornmeal texture and an abundance of large selenite grains as well as small biotite flakes. The light bentonite grades into the superjacent dark bentonite through a zone of increasing dark laminae. The dark bentonite strata range from one to one-half feet thick and are composed chiefly of dark-gray bentonite but light colored laminae are always present in the lower part, and in places they extend nearly to the top. Siliceous shale laminae appear in the upper part of the dark bentonite which in turn grades upward into a prominent zone of siliceous shale interlaminated with dark bentonite and dark shale. The zone of siliceous laminae is usually four to six feet thick, and interlaminated shale is more abundant in the upper part as the zone grades into dark shale.

Characteristics of the thick portions of the bed are replaced laterally by those of the thin parts of the bed. The chertlike floor beneath the bentonite becomes less prominent as the thickness of the bed decreases and this floor is rarely discernible where the bentonite is less than 10 inches thick. Thicknesses of both the light and dark colored portions of the Clay Spur bed decrease in approximate proportion to the total thickness of the bed, The dark colored material appears to grade into a thin bentonitic shale zone in thin portions of the bed. The zone of siliceous shale laminae above the bentonite also decreases laterally and is rarely present where the bentonite is less than one foot thick. The extent of both the thick and thin portions of the bed is very irregular; therefore the gradation from one extreme to the other is also not uniform. In places intermediate thicknesses of the Clay Spur bed extend for at least a mile, but in other localities thicknesses of more than three feet decrease laterally to three inches within 40 or 50 yards.

Total thickness of the Clay Spur bed and the superjacent zone of siliceous laminae ranges from about three inches to nearly 12 feet. Where the bentonite is unusually thick, the superjacent zone of siliceous laminae is also thick; where the bentonite is moderately thick, the siliceous zone is only moderately thick; where the bentonite is exceptionally thin, the siliceous zone is missing. This relation of strata (Fig. 11) indicates that the deposition of volcanic ash from which the bentonite formed began on an undulating sea floor. The sea floor had a local relief of at least 12 feet. Either the accumulation of the ash tended to be restricted to the lows of the uneven surface or most of the material laid down on the highs was soon shifted to the lows by the leveling action of gentle currents. A relief of about six feet must still have been present after the deposition of most of the ash because the zone of siliceous laminae above the bentonite appears to be entirely restricted to the lows. The sharp basal contact of the Clay Spur bed that is present in thicker portions of the bed throughout the district indicates that deposition of ash must have begun simultaneously over a wide area. The presence of thin bentonitic shale zones beneath thinner parts of the bed suggests either a mixture of ash with subjacent shale by the action of waves or currents or that the rate of accumulation of ash on the highs was at first very slow in respect to that of the normal dark sediments. There can be no reason for assuming that the rate of deposition of normal dark sediments was greatly decreased during the accumulation of the ash; therefore, the ash from which the light bentonite has been formed must have accumulated at a very rapid rate to have avoided discoloration by the dark mineral particles and the small amount of organic matter associated with the normal sediments. Upward gradation of light bentonite into dark colored bentonite is evidence that the rate of accumulation of the ash gradually slowed and was finally surpassed by that of the normal dark sediments.

Origin of the undulating surface below the Clay Spur bed

The undulating surface below the Clay Spur bed extends with more or less uniform relief throughout both the northern and western Black Hills area, and similar surface is present under the Clay Spur bed along the east flank of the Big Horn Mountains. Obviously the surface resulted from

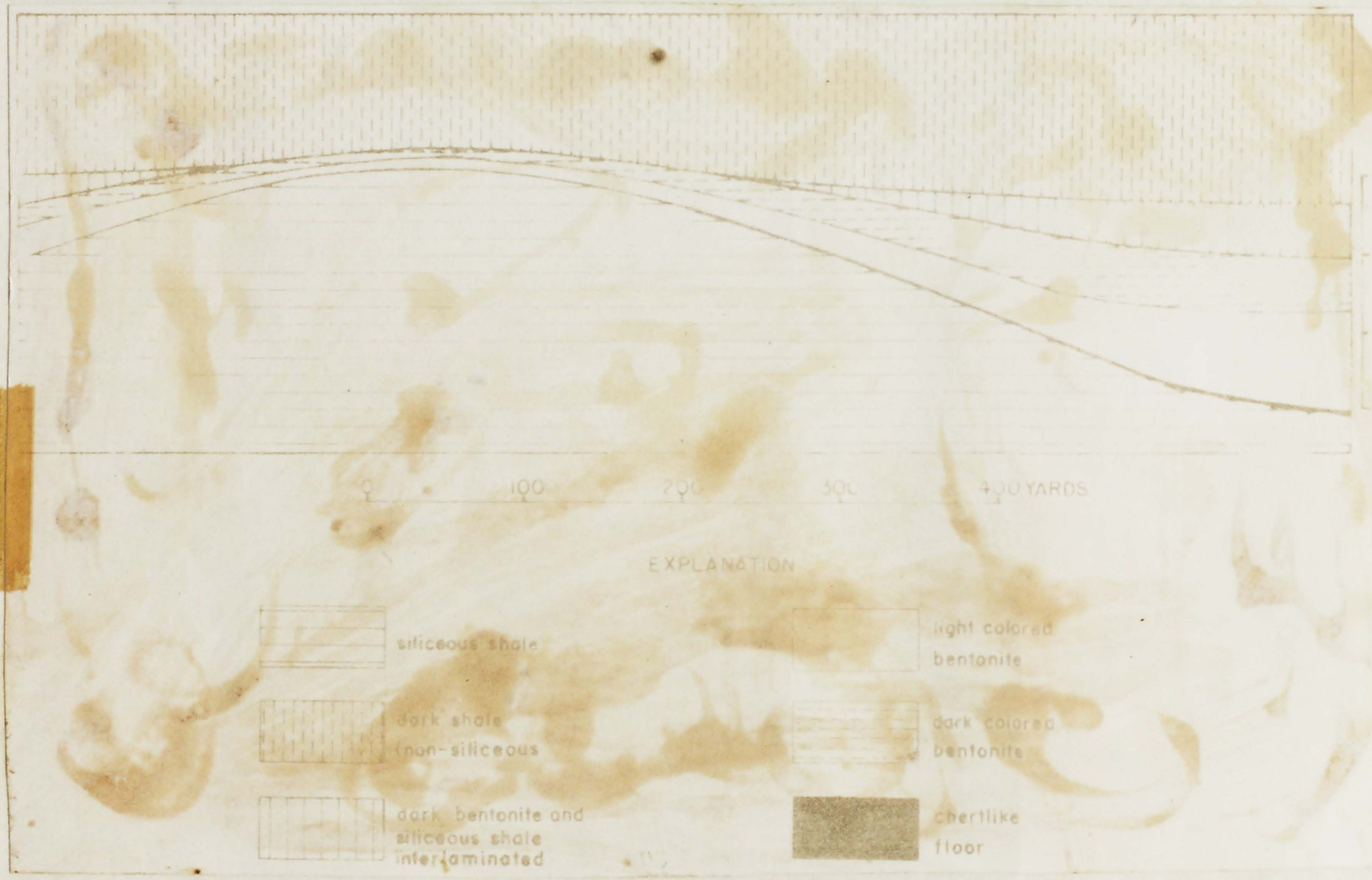

Figure 11. Diagrammatic representation of relation of thickness of Clay Spur bentonite bed to enclosing strata.

Figure 12.--Exposure where the Clay Spur bentonite is thin. The bed is 2 inches thick at point of spade, near center of sec. 19, T. 56 N., R. 60 W., Crook County, Wyoming.

Figure 13.--Exposure of intermediate thicknesses of the Clay Spur bentonite bed. The bed is about 18 inches thick, SW 1/4 sec. 6, T. 56 N., R. 61 W., Crook County, Wyoming. Black bed above shrubs is the Clay Spur bed.

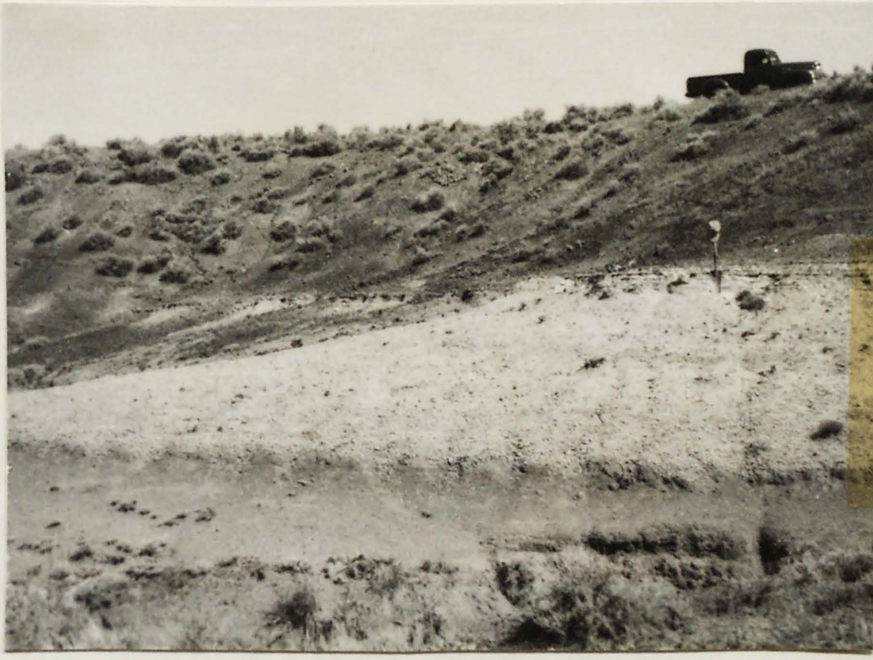

Figure 14.—Clay Spur bentonite bed and siliceous laminae zone in SE 1/4 sec. 7, T. 56 N., R. 61 W., Crook County, Wyoming. Bentonite is 5 1/2 feet thick.

Figure 15.— Interlaminated gray bentonite, bentonitic shale, and siliceous shale above the Clay Spur bed in SE 1/4 sec. 7, T. 56 N., R. 61 W., Crook County, Wyoming. Bentonite strata have alligator hide texture.

Figure 16.—Siliceous laminae zone above the Clay Spur bed in SE 1/4 sec. 7, T. 56 N., R. 61 W., Crook County, Wyoming.

very uniform conditions over an extremely wide area. This surface does not represent an erosional unconformity. The reasons are as follows: (1) Strata below the bentonite have not been truncated by erosion. (2) Shallow water or continental deposits are not present either above or below this surface. (3) Magnitude of relief is much too uniform throughout a very large area for the undulating surface to represent an erosional unconformity.

Proof that the undulating surface was not formed by waves is furnished by the following: (1) Absence of cross-bedding in the siliceous shale below the Clay Spur bed. (2) Apparent lack of orientation of both the highs and lows. (3) Sharp contact between the bentonite and the subjacent shale could not have been preserved if deposition had taken place where waves were active. (4) The fact that the zone of siliceous laminae above the bentonite is restricted to the lows can only mean that relief features remained stationary much longer than could be possible in the presence of active waves. Where the zone of siliceous laminae is six feet thick the lows must have remained in place for at least 10,000 years if Rubey's computation (1930, p. 48) of 0.2 millimeter for the average thickness of the annual pairs of laminations in the Black Hills can be assumed to be applicable. Because deposition of siliceous laminae was restricted to the lows, the rate of accumulation may have been nearly twice as fast as continuous strata. Some bentonite which probably accumulated very rapidly is present in the zone of siliceous laminae; therefore, it is likely that 2,000 to 5,000 years would be more nearly correct for the time of accumulation of this zone.

Differential compaction of underlying shales might have caused the formation of an undulating surface in part of the area. This possibility seems most logical where the formation below the Mowry shale, the Newcastle sandstone, contains numerous lenses of shale and sandstone. However a surface formed by differential compaction could not be expected to have such a uniform relief, and it is stretching imagination too far to postulate that this phenomena was responsible for the formation of the undulating surface over such a wide area.

Present state of knowledge in the field of oceanography does not rule out the possibility that an undulating surface of deposition exists today where fine-grained sediments are being deposited in marine water by or in the presence of very gentle currents. Giant ripples have been observed by Rich (1948, p. 767-779) on the sandy floor of the Bahama Banks. He describes the ripples as being vaguely aligned and as much as 600 to 750 feet across. These ripples occur on shallow banks which are swept by the currents of the Gulf Stream. Very large irregularly aligned ripple-marks in shallow water sandy sediments have also been described by Haentzschel (1938, p. 1-48). These occurrences of large ripple-marks in sandy sediment make it seem even more logical that ripple-marks form where fine-grained materials accumulate in the presence of weak currents. Such conditions would most likely have been present in the moderately deep Cretaceous epicontinental sea.

If the undulating surface does represent large ripple-marks, the evidence presented for the stationary nature of the relief features indicates that the ripples either did not migrate or moved at an exceedingly slow rate. Uniform deposition on such ripple-marks would result in rolling bedding. Rolling strata on a much smaller scale have been observed by McKee (1938, p. 77-83) in the Colorado River flood deposits and by Andersen (1931, p. 21-31) in glacial deposits. In both occurrences, the bedding is thought to have originated from deposition on stationary ripple-marks. The theory that undulating surface below the Clay Spur bentonite bed represents rolling bedding is supported by the fact that a stratigraphic interval between the floor of that bentonite bed and a thin bentonite zone approximately 2 1/2 feet lower in the Mowry shale maintains nearly constant thicknesses throughout much of T. 57 N., R. 61 W., and T. 56 N., R. 61 W., Crook County, Wyoming. This bed is essentially the same thickness in outcrops of both the highs and the lows.

If it is true that the undulating surface is an expression of rolling bedding, then the restriction of ash and the zone of siliceous laminae to the lows must be explained. Formation of stationary ripples would require a delicate balance between the supply of fine-grained sediments and the transporting power of gentle currents. Possibly rapid influx of large amounts of volcanic ash destroyed the equilibrium conditions which formed the stationary ripple-marks. A less likely possibility is that depth of the sea was changing about this time and different currents were introduced. A change in conditions of sedimentation is suggested by differences in lithologies between the siliceous Mowry shale and soft dark shale of the overlying Belle Fourche unit. Apparent lack of orientation of highs and lows could be a consequence of irregular outcrops and discontinuities of exposures, and these features may actually have some vague orientation. In outcrops, distances from lows to highs may be only a few yards in one direction and several hundred yards in the opposite direction. This may be in part a consequence of the asymmetry of ripple-marks. Persistence of thick portions of the bentonite bed over a distance of a mile may be the result of orientation of the outcrop with a trough of a large ripple.

The nature and significance of the light and dark laminae in the Clay Spur bed

The varve-like light and dark bentonite laminae in the upper part of the Clay Spur bed (Fig. 17) range from tissue thin layers to more than one-fourth inch in thickness. Frequently even the thinnest layers can be traced for several yards within the limits of fresh exposures in strip mines, but often groups of laminae extend only a few inches and some groups appear to be truncated by younger layers. As a rule the thinner laminae are distinctly separate units, light and dark layers tend to be about equal in thickness, and there is no gradation from one color to the other. Some thicker layers are characterized by a mixing of the light and dark colors and a blurring of the boundaries between laminae. Some zones as much as one-half inch thick, enclosed in uniform and continuous laminate zones, appear to be slightly distorted or are almost free of layering. Small irregular masses of the light bentonite are sometimes enclosed in the dark material but fragments of the dark clay are rarely found in the light clay. These tiny blocks of light material are most common in the thicker poorly stratified dark layers. Optical examinations of thin sections have revealed that the dark colors result chiefly from small amounts of organic matter dispersed through the clay. Most of the organic material is present in the form of blotchy coatings on the non clay mineral grains but there are small irregular masses of organic matter throughout the clay. Most of these organic particles are elongate parallel to the laminations. The dark bentonite also contains an average of 25 to 30 percent non clay materials, whereas the light laminae like the thick light colored portion of the Clay Spur bed contains only about 15 percent non clay materials. The non clay materials are composed chiefly of fine-grained angular quartz and feldspar, but some sub-rounded grains are also present. Most of the non clay grains are too equidimensional to have marked orientation, but the small amount of biotite and other elongate minerals that are present are roughly oriented parallel to the laminae.

The presence of thin persistent laminae prove conclusively that these sediments accumulated in very quiet water. The dark bentonite layers show contamination by the type of non clay minerals and organic materials that are found in the shale above the bentonite bed, but the light bentonite laminae are composed of relatively pure montmorillonite and are closely allied to the thick light colored bentonite present in the lower portions of the Clay Spur bed. Mixing of colors in laminae, truncation of some groups of laminae, slight distortion of some layers enclosed by undistorted zones, and inclusion of some small blocks of light clay in dark can best be explained by very small sea floor mud flows. Such flows must have taken place on extremely gentle slopes and in places only very thin layers of sediments were displaced.

Thicker dark colored zones most commonly rest with sharp contact on subjacent light clay but upper limits of the dark clay are most commonly indistinct. This relationship together with the presence of small light colored blocks within the dark clay suggests that the dark material was deposited in the form of an exceedingly plastic clay or as partially compacted masses of flocculated clay particles. The ancestral material of the light clay tended to form more coherent layers which were more likely composed of more or less unaltered volcanic ash.

Obviously this interlaminated light and dark material represents a type of cyclic sedimentation that cannot be explained by periodic outbursts of volcanic ash. These laminae do closely resemble seasonal varves.

Figure 17.— Varvelike interlaminated light and dark bentonite from the upper part of the Clay Spur bentonite bed. Natural size.

The laminae differ from glacial varves in that the coarser material is confined to the dark layers and there are no gradations between the thinner layers. If it is correct to assume that the accumulation of volcanic ash was continuous but decreased at a rather uniform rate, a seasonal influx of shale material and organic matter would explain the origin of these varve-like deposits. Such material would most likely be introduced during the warm months of the year when rainfall on the land areas would be reflected in an increase of fine-grained sediments in moderately deep marine water. A possible explanation for the apparent original plasticity of the dark clay is that it may have contained ash which had been more or less completely altered to montmorillonite during a delay in its transportation to the site of final deposition.

Near surface discoloration in the Clay Spur bed

The color of bentonite in the Clay Spur bed situated under more than a few feet of overburden is predominantly bluish gray, a color which oxidizes at or near the surface to olive green, yellow and light gray. Discoloration from blue to lighter shades takes place in a zone governed largely by thickness of overburden and distance from the nearest natural outcrop. As a rule all of the bentonite under more than 25 feet of cover is undiscolored and that part of the bed that is less than 12 feet below the surface is completely discolored; however, the blue clay may still be present under as little as 12 feet of cover where situated at distances of several hundred feet from the nearest natural exposures and the discolored portions of the bed may be found under extraordinary amounts of overburden where the land surface rises sharply above exposures of the bentonite. This relation of the discoloration of bentonite to the amount of cover and topographic configuration of the surface above the bentonite bed indicates that discoloration takes place both laterally and vertically within the bed. The color change begins along a system of nearly horizontal and nearly vertical joints that intersect in a criss-cross fashion. As the change progresses, the exterior portion of joint blocks are altered first to greenish gray, then to olive green so that a given block may have an undiscolored bluish-gray core enveloped in concentric layers of greenish gray and olive green. Because of their oval shape, bluish-gray cores are often referred to as "eggs". The ease with which "eggs" can be separated from enclosing layers indicates that some physical change must accompany the discoloration process. Chemical analyses by Margaret D. Foster (1948) of the U. S. Geological Survey have shown that discoloration results from oxidation of ferrous iron to the ferric type. This oxidation is no doubt related to the slight increase of limonitic material along joints in the discolored material. Oxidation has been attributed by M. M. Knechtel (1947, p. 1201) to have taken place through the agency of surface water seeping into the joint systems.

The evidence at hand indicates that the time required for this discoloration of the bluish-gray bentonite varies considerably. The zone of color change is known to be present under overburden ranging from 12 to 18 feet in places where local drainage patterns and topography are in maturity, and it can be concluded that the present land surface has not been altered greatly during the last several hundred or few thousand years; therefore, it must take at least several hundred years for the oxidation process to progress under more than a few feet of overburden. The color change can be brought about in the laboratory within a few weeks by alternately wetting and drying the clay, and where the blue material has been exposed in the faces of strip mines the discoloration has been observed to extend inward about two inches in the solid blocks and nearly one foot along joints during the period from one summer's mining season to the next. Blue grey bentonite that has been placed in stockpiles with light colored clay frequently changes color throughout the entire stock pile in a period of about one year. Apparently the oxidation takes place rather rapidly at the surface but the rate is greatly reduced by the compacting effect of the overburden and the impervious nature of both overburden and bentonite.

In general the colloidal properties of the blue clay are much lower than those of the discolored bentonite and in most instances where the color change has been induced artificially, it is accompanied by an increase in colloidal properties. The nature and cause of the increase in colloidal properties is of considerable economic importance and will become more important in the future as reserves of high colloidal discolored clay are depleted. It is generally recognized that a fundamental reason for high colloidal properties of bentonite is the tendency for montmorillonite to break down to flake-shaped particles approaching the unit cell in size. A decrease in particle size in the discolored clay is indicated by the increase in wall building capacities, swelling properties, foundry sand bonding dry strengths and viscosities.

Although the oxidation of ferrous to ferric iron is no doubt the explanation for the color change, it does not seem possible that this change in valency of the iron could be the major cause for the increase in colloidal properties, and it seems most likely that other physical or chemical processes are active during the period the color change takes place. The reasons that the change in valency does not seem sufficient to account for the increase in colloidal properties are as follows:
(1) Bentonite in the Clay Spur bed rarely contains as much as four percent

Fe_2O_3 and FeO, and this small amount of iron does not seem sufficient to account for much change in colloidal properties. (2) Much of the iron present in the bentonite is in the form of thin limonite films along joints and cracks in the clay and such iron could act only as a dilutent reducing colloidal properties of the clay. (3) For oxidation of the iron to be responsible for the increase in colloidal properties, the iron would have to be closely associated with the clay mineral structure. It would seem that if the iron is to be considered as an integral part of the clay mineral lattice, it would be bound in such a way that the oxidation and change in valency could not take place so easily. (4) Drilling mud and foundry bond tests of the discolored material surrounding blue "eggs" (Table 1, sample A) have failed to show increased colloidal properties over undiscolored cores but tend to show a gradual increase in colloidal properties from bluish-gray to the completely discolored clay. (5) The fact that some of the blue undiscolored clay has been found to be of drilling mud quality and much of the bluish-gray bentonite is now processed for foundry sand bonding purposes indicates the unoxidized clay containing ferrous iron has high colloidal properties and the oxidation to ferric iron is not the chief cause for the increase in colloidality of the bentonite.

A study was made in an effort to determine the reason for the increase in colloidal properties accompanying the color change. A suite of four samples representing various stages of the discoloration process was collected from a strip mine of the American Colloid Company located in sec. 13, T. 9 N., R. 1 E., Butte County, South Dakota. Fresh samples were sealed in glass jars to preserve natural moisture and prevent oxidation before testing. The natural moisture content of samples tested ranged from 27 to 32 percent. Results of the drilling and tests of these samples (Table 1) show that the colloidal properties of the oxidized bentonite are much higher than the unoxidized blue clay. Thermal curves of both the raw sample and the minus two micron fraction of the unoxidized blue bentonite (Fig. 18, curves a and c) do not indicate that the water in the montmorillonite is influenced by exchangeable ions other than sodium. The curve for the whole sample of oxidized olive-green bentonite (Fig. 18, curve c) also fails to indicate the presence of exchangeable ions other than sodium. The curve of the minus 2 micron fraction of the oxidized clay (Fig. 18, curve d) however has a small endothermic peak at about 175° suggesting that some exchangeable calcium or magnesium is influencing the retention of water in the clay. The pH of 9.9 for the blue clay and 9.5 for the discolored clay also suggests that the influence of sodium is not as great in the oxidized material as in the undiscolored blue bentonite. Ion exchange data for the whole sample of discolored, olive-green, bentonite (Table 4, sample 11) and the undiscolored, blue bentonite (Table 4, sample 12) fail to indicate major differences between the two clays. The exchange capacity of the olive-green bentonite (100 m.e./gm) is considerably higher than the capacity of the blue bentonite (78 m.e./gm.). This difference in exchange capacity may be chiefly a consequence of the finer particle size in the oxidized material, which increases the total surface area of the mineral flakes and, therefore, increases the number of available exchange positions.

An experiment on the effects of artificial weathering was carried out on a sample of bluish-gray bentonite from the Clay Spur bed as exposed in a strip mine of the Eastern Clay Products Company in sec. 36, T. 57 N., R. 62 W., Crook County, Wyoming. The fresh sample was sealed in wax in

Table 1.—Drilling mud tests of a suite of samples representative of the bluish-gray to olive-green color change in the Clay Spur bed. Samples are from a strip mine of the American Colloid Company in sec. 13, T. 9 N., R. 1 E., Butte County, South Dakota. All tests were made on slurries of 6 percent bentonite in distilled water, and samples were prepared by air drying and grinding to approximately 200 mesh.

Sample		A	B	C	D
Wall building (in mils)	2 minute	4.8	4.6	4.0	3.8
	15 minute	12.8	11.2	10.2	9.8
	30 minute	17.	16.	14.	13.8
Viscosity (in centepoises)		12	14	18	42
Yield (Barrels of 15 cps. drilling mud per ton of bentonite)		85	88	97	117
Gel Strength (grams)	Initial	5	5	5	10
	10 minute	5	5	15	75
pH		9.9	9.9	9.8	9.5

A. Undiscolored bluish-gray bentonite.

B. Undiscolored bluish-gray bentonite, sample secured between A and C.

C. Partially oxidized bentonite containing "eggs".

D. Discolored yellow bentonite.

the field to prevent any effects of weathering prior to testing. In the laboratory a portion of the sample was air dried and crushed to one-fourth inch size or smaller. This sample was then alternately wet with distilled water and air dried approximately 12 times over a period of four months. During this period the color changed from bluish-gray to lighter shades of olive green and yellow. A sample of the artificially oxidized clay and one of the unoxidized clay were air dried, ground, and tested for use as drilling mud. The results of the tests (Table 2) show that the drilling mud properties were increased considerably by the artificial oxidation process. A thermal curve of a portion of the clay that was not oxidized (Fig. 18, curve e) suggested the presence of a small amount of iron sulfide material as evidenced by a small exothermic peak at about 450°, and it is perhaps significant that small iron sulfide concretions were present in the lower part of the Clay Spur bentonite bed near the location where the sample was collected. The thermal curve of the artificially oxidized material (Fig. 18, curve f) does not show any indication of the presence of iron sulfides. Loss of small amounts of iron sulfide during the artificial oxidation process suggests the possibility that weak acid may form by ground water action on the sulfide and that colloidal properties of bentonite may be improved by a natural acid treating process. The pH of 9.2 for the unoxidized and 8.9 for the artificially oxidized material would also conform with this postulation. Ion exchange data for the fresh clay (Table 4, sample 14) and the artificially oxidized clay (Table 4, sample 15) indicate that the exchange capacities of the two materials are essentially the same. The oxidation was accompanied by a marked increase in exchangeable magnesium (.05 m.e./gm. in the unoxidized and .24 m.e./gm. in the oxidized) and a decrease in sodium (.48 m.e./gm.

Table 2.—Drilling mud tests of fresh and artificially oxidized samples of bentonite. Samples are from a strip mine of the Eastern Clay Products Company in sec. 36, T. 57 N., R. 62 W., Crook County, Wyoming. Unless otherwise designated, tests were made on slurries of 6 percent bentonite in distilled water.

Sample		fresh	artificially oxidized
Swelling capacity of 2 grams of bentonite in distilled water (in mls.)		34	37
Wall building (filtrate in mls)	2 minute	7.4	5.5
	15 minute	18.5	13.4
	30 minute	26	17
Viscosity (centepoises)	6% clay	7	9
	6 1/2% clay	10	14
	7% clay	14	21
Yield (barrels of 15 cps. drilling mud per ton of bentonite)		76	83
Gel strength (in grams)	initial	3	4
	10 minute	4	8
pH		9.2	8.9

Figure 18.—Thermal analysis curves of samples of undiscolored and discolored bentonite from the Clay Spur bed. Curves a - d are of samples from a strip mine of the American Colloid Company in sec. 15, T. 9 N., R. 1 E., Butte County, South Dakota. Curves e and f are of a sample from a strip mine of the Eastern Clay Products Company in sec. 36, T. 57 N., R. 62 W., Crook County, Wyoming. Commercial tests of samples are given in Tables 1 and 2.

a. Undiscolored bentonite (whole sample)

b. Discolored bentonite (whole sample)

c. Less than 2 micron fraction of undiscolored bentonite shown in curve a.

d. Less than 2 micron fraction of discolored bentonite shown in curve b.

e. Undiscolored bentonite

f. Artificially oxidized portion of material shown in curve e.

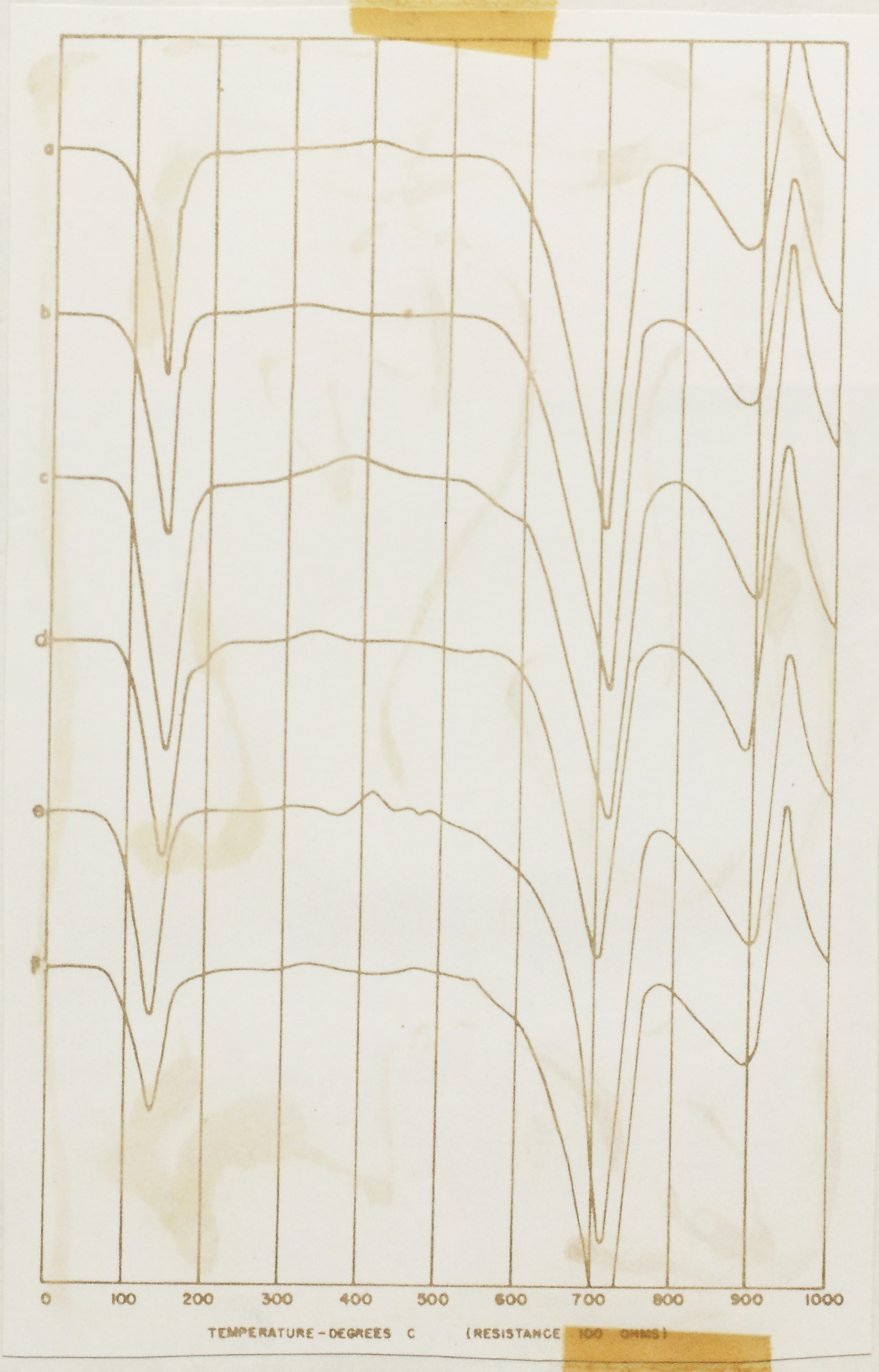
a
b
c
d
e
f
0
100
200
300
400
500
600
700
800
900
1000
TEMPERATURE - DEGREES C
(RESISTANCE 100 OHMS)

Figure 16

Table 5.—Drilling mud tests of a sample of undiscolored bentonite in distilled water and a range of weak concentrations of sulphuric acid. All slurries are of 6 percent clay.

Normal Concentration of Acid	0	1/200	1/100	1/75	1/50	1/10
Viscosity in centepoises	25	25	35	45	55	35
Gel strength (grams)						
initial	2	5	15	40	70	35
10 minute	4	8	30	75	175	35
Wall building (30 minute)	13.8	12.8	12.4	13.8	14.6	22.4

Table 4.—Results of ion-exchange capacity determination

	Bed	Cations					Total cation exchange m.e./gm. (less soluble anions)	Determined cation exchange m.e./gm.
		Ca	Mg	Na	K	H		
1.	A	.53	.24	.13	.02	tr.	.79	.77
2.	"	.18	.23	.35	.01	-	.80	.81
3.	B	-	-	.01	.01	.52	.54	.69
4.	"	.59	.26	.07	.03	-	.89	.91
5.	Clay Spur	.12	.28	.36	.01	.02	.79	.83
6.	" "	.31	.24	.31	.02	-	.87	.80
7.	" "	.03	.12	.81	.02	-	.91	.84
8.	" "	.26	.21	.35	.01	.02	.85	.89
9.	" "	.16	.19	.49	.02	-	.85	.82
10.	" "	-	.14	.48	.03	-	.65	.64
11.	" "	.20	.03	.76	.02	-	1.00	.85
12.	" "	.20	.06	.65	.01	-	.78	.78
13.	" "	.31	.24	.29	.02	-	.76	.68
14.	" "	.28	.05	.48	.01	-	.79	.72
15.	F	.67	.24	.42	.02	-	1.35	.87
16.	"	.12	.27	.42	.02	-	.82	.83
17.	G	.22	.33	.42	.03	-	1.00	.93
18.	I	.54	.16	.18	.01	.06	.95	.88
19.	"	.64	.44	-	.02	-	1.06	.95

Determinations made by John C. Hathaway, Gerald Otzelberger, Carol Parker, and Dorothy Carmol of the U. S. Geological Survey.

1. Bed A, light colored bentonite 3 feet 9 inches thick, sec. 8, T. 58 N., R. 63 W., Crook County, Wyoming (Fig. 10, curve b).

2. Bed A, light colored bentonite 3 feet 2 inches thick, sec. 8, T. 56 N., R. 62 W., Crook County, Wyoming (Fig. 10, curve d).

3. Bed B, light colored bentonite 8 inches thick, sec. 34, T. 58 N., R. 63 W., Crook County, Wyoming, (Fig. 10, curve e).

4. Bed B, bluish-gray bentonite 1 foot 7 inches thick, sec. 8, T. 57 N., R. 61 W., Crook County, Wyoming (Fig. 10, curve f).

5. Clay Spur bed, light colored bentonite 1 foot 6 inches thick, sec. 34, T. 58 N., R. 65 W., Crook County, Wyoming (Fig. 10, curve h).

6. Clay Spur bed, light colored bentonite 2 feet 7 inches thick, sec. 5, T. 57 N., R. 65 W., Crook County, Wyoming (Fig. 19, curve b).

7. Clay Spur bed, light colored bentonite 2 feet 9 inches thick, sec. 4, T. 56 N., R. 66 W., Crook County, Wyoming (Fig. 19, curve f).

Table 4.—continued

8. Clay Spur bed, light colored bentonite 1 foot 10 inches thick, sec. 26, T. 56 N., R. 61 W., Crook County, Wyoming (Fig. 19, curve h).

9. Clay Spur bed, light colored bentonite 1 foot 10 inches thick, sec. 10, T. 55 N., R. 61 W., Crook County, Wyoming (Fig. 19, curve i).

10. Clay Spur bed, dark colored bentonite 2 feet 10 inches thick, overlying material 9. above (Fig. 19, curve j).

11. Clay Spur bed, olive-green bentonite, from strip mine of American Colloid Co. sec. 15, T. 9 N., R. 1 E., Butte County, South Dakota (Fig. 18, curve b).

12. Clay Spur bed, undiscolored blue bentonite, near 11. above (Fig. 18, curve a).

13. Clay Spur bed, artificially oxidized from strip mine of Eastern Clay Products Co., sec. 36, T. 57 N, R. 62 W., Crook County, Wyoming (Fig. 18, curve f).

14. Material 13. above before artificially oxidized (Fig. 18, curve e).

15. Bed F, light colored bentonite 4 feet 5 inches thick, sec. 26, T. 9 S., R. 57 E., Carter County, Montana (Fig. 21, curve f).

16. Bed F light colored bentonite 5 feet 9 inches, sec. 9, T. 56 N., R. 67 W., Crook County, Wyoming, (Fig. 21, curve i).

17. Bed G, gray and brownish gray bentonite 2 feet 4 inches thick, sec. 9, T. 57 N., R. 62 W., Crook County, Wyoming (Fig. 23, curve b).

18. Bed I, yellow and yellowish brown bentonite 5 feet 1 inch thick, sec. 35, T. 12 N., R. 2 E., Butte County, South Dakota (Fig. 23, curve d).

19. Bed I, greenish-gray bentonite 2 - 7 inches thick, sec. 35, T. 12 N., R. 2 E., Butte County, South Dakota (Fig. 23, curve f).

in the unoxidized and .29 m.e./gm. in the oxidized).

In order to check the plausibility of the theory that natural acid leaching may beneficiate the bentonite, drilling mud tests were made on suspensions of the undiscolored material in different concentrations of sulphuric acid (Table 5). Concentrations of acid up to an optimum of about 1/50 N increased the viscosity but both viscosity and gel strength dropped in more concentrated acid. At the optimum of about 1/50 N acid the viscosity was more than doubled and gel strength was many times greater than suspensions mixed with distilled water. Wall building capacities were slightly improved in the low concentrations but were lower in the 1/50 N slurry than in distilled water. Wall building capacities were very poor in the 1/10 N acid, but viscosity and gel strength were higher than most untreated bentonites.

Theory of increase in colloidal properties accompanying discoloration of Clay Spur bed

The hypothesis that best explains the increase in colloidal properties accompanying the change in color of the bentonite from blue-gray to olive-green is the destruction of equilibrium conditions in the hydrated clay. Presumably water is very evenly distributed throughout the clay with a high degree of uniformity in the thicknesses of layers of water molecules between montmorillonite particles, and in this condition there is considerable stability of the clay water system. Because of this stability the bentonite tends to remain in aggregates of montmorillonite flakes that are not easily separated. It seems likely that the hydrated clay would be most stable where one particular exchangeable ion is essentially the only ion influencing the water between montmorillonite particles, so that the water molecules would be oriented in layers of uniform thickness and bonding forces evenly distributed. During the process in which the blue-gray bentonite is oxidized to olive-green ion exchange and other geochemical phenomena are active in destroying the equilibrium that exists in the clay water system. As the stability of the clay water system is destroyed aggregates of montmorillonite flakes are much easier separated, and the colloidal properties are greatly increased.

Essentially all bentonite that is not dried at elevated temperatures contains appreciable amounts of water. Much of this water must have some definite configuration. The geometric arrangement of water molecules in clay has been visualized by Hendricks and Jefferson (1938, p. 865-875) as being a hexagonal net. This net is tied to the external sheet of the clay mineral by the attraction of hydrogen atoms not involved in the binding of the water net with the oxygen of the silicate sheet. This theoretical arrangement of the water molecules has been criticized because it fails to account for the effect of exchangeable ions (Mackenzie, 1950, p. 115-120), and seems probable that the packing of water about such ions has much to do with the orientation of water between montmorillonite particles.

X-ray studies by Hofmann and Bilke (1936, p. 239-251) and by Hendricks, Nelson, and Alexander (1940, p. 1457-1464) have shown that at a given water vapor pressure the cleavage spacing for Na^{+} montmorillonite is lower than for H^{+} or Ca^{++} types. Above 50 percent moisture content the spacings of Na type increases to the limit detectable by present methods much faster than does Ca^{++} or H^{+} montmorillonite. It has been established by Bradley, Grim, and Clark (1937, p. 216-222) in the case of H^{+} montmorillonite and by Mooney, Keenan, and Wood (1952, p. 1371-1374) for Ca^{++} and Na^{+} montmorillonite that water does not penetrate between the cleavage spaces of the mineral but enters in integral layers. That is, a layer of water molecules does not begin to form until the previous layer has developed throughout essentially all of the montmorillonite. Presumably where Na^{+} is the only cation present between two adjacent flakes of montmorillonite there is a definite number of more or less stable layers of oriented water at any given low content of moisture. In the presence of about the same amounts of moisture there would be a different number of stable layers in Ca^{++} montmorillonite and H^{+} montmorillonite might have a tendency to reach still a third equilibrium condition.

The colloidal properties of calcium bentonites are very low and those of sodium bentonites are very high; however, the producers of bentonite have known for several years that a small amount of calcium is present in essentially all bentonite that has very high colloidal properties. Roth (1951, p. 77) suggested that a certain amount of exchangeable Ca^{++} ions are needed in sodium bentonite to produce a good drilling mud. On the basis of x-ray evidence he theorized that calcium rich montmorillonite layers would form double water layer particles, and such particles would create a little disorder in the clay water system and allow a thixotropic suspension to form more easily.

Results of thermal analyses made in the present investigation indicate that Na^{+} is essentially the only ion influencing retention of water in the blue-gray undiscolored clay (Fig. 18, curves a and c). Most of the Ca^{++} and Mg^{++} ions, indicated by the ion exchange measurements (Table 4, samples 12 and 14) are probably located on the surfaces of montmorillonite particles not enveloped by water, or where mineral particles may be separated only by exchangeable Ca^{++} and Mg^{++} without the presence of water molecules. The likelihood that the kind of exchangeable ions on the surface of one particle are different from those on another is supported by the studies of Byrne (1955, p. 30) that revealed montmorillonites to be mixed layer sequences with adjacent layers differing from one another in composition, structure, or some other factor.

Where the orientation of water molecules in aggregates of montmorillonite flakes is influenced only by Na^{+}, any ion exchange reaction which replaces Na^{+} by some other ion would reduce stability of the clay water system and increase colloidal properties. The effect would be to disturb the arrangement of water and make it much easier for additional water molecules to enter between mineral flakes. Na^{+} is most commonly replaced by Ca^{++}, Mg^{++}, and H^{+}. H^{+} is available in weak acids that are introduced by ground water and formed by ground water action on sulfides in the bentonite. An ample supply of Ca^{++} is available in the soluble selenite which is common throughout the bentonite. Both Ca^{++} and Mg^{++} are very common exchangeable ions in the bentonite, and perhaps some Mg^{++} in the montmorillonite lattice is released by octahedral substitution whereby the Mg^{++} is replaced by other ions. The possibility that octahedral substitution may have an important bearing on the swelling properties of clays has been discussed by Foster (1954, p. 1-28). Calcium, magnesium and hydrogen bentonites all have very low colloidal properties as compared with sodium bentonite, and therefore the exchange of Na^{+} by these ions can be carried too far. Too much replacement of sodium by these ions is probably the reason that much of the weathered bentonite does not conform with the specifications for drilling mud bentonite.

In addition to supplying H^{+} ions, weak sulfuric acid may attack the edges of aggregates of montmorillonite particles and aid in splitting them into individual flakes. Partial solution of the silicate sheets of two adjacent flakes might disrupt the forces holding the flakes together and provide space for the large water molecules to enter.

Relation of colloidality of the Clay Spur bentonite to terrace deposits

The time required for the discoloration of the Clay Spur bentonite to progress under more than a few feet of overburden suggests that large deposits of the discolored clay are present under terrace deposits. All terrace gravels must have been deposited on older land surfaces, which means that some of the bentonite may have been oxidized and developed desirable colloidal properties prior to burial. Furthermore, terrace deposits are very pervious and bentonite beneath terraces may have more continuous supplies of water than deposits not overlain by terrace gravels. In general the producers of bentonite hold that bentonite below terrace deposits is not of the quality demanded for commercial purposes. A possible reason for the low properties of this bentonite is that the exchange of Ca^{++} for Na^{+} has been carried too far. Terrace gravels throughout the district contain much weathered calcareous material which could serve as a source of an abundant supply of Ca^{++}. Samples of bentonite from below terrace deposits have been secured only where the overburden is relatively thin. It seems likely that high quality bentonite will eventually be located below terrace deposits. It is probable that such material will be found at greater depths than where terraces are not present.

Mineralogy of the Clay Spur bed

Differential thermal analyses of the dark colored bentonite of the Clay Spur bed (Fig. 10, curve i and Fig. 19, curve j) show that it is composed of montmorillonite with varying amounts of impurities and very small contents of organic matter. Thin sections of some of the interlaminated light and dark bentonite from the lower part of the dark zone reveal that dark laminae are chiefly composed of layers of organic discolored clay in which grit sized particles are particularly abundant. Dark minerals, chiefly biotite, are more abundant and tend to be less angular in the dark zone than in the subjacent light bentonite.

Thermal curves of the light colored portion of the Clay Spur bed reveal that montmorillonite is essentially the only clay mineral present. Chief variations in the thermal curves result from differences in exchangeable ions and non clay impurities. Na^+ is the most common ion which influences the orientation of water in the bentonite (Fig. 19, curves c-f, i and j), but several of the curves show that Ca^{++} or Mg^{++} or both have an important bearing on the retention of water (Fig. 10, curves g and j; Fig. 19, curves a, b, and h). Na^+ is the dominant exchangeable ion in all but one of the 10 samples for which ion exchange measurements were made (Table 4, samples 5-14). Presence of H^+ in one of the samples (Fig. 10, curve h) is indicated by two small low temperature peaks and a pH of only 4.7.

Proportions of non clay materials of the Clay Spur bed are lower than in most bentonite deposits. Grit materials rarely make up as much as five percent of the clay and as a rule total non clay contents are below 10 percent. Most of the non clay materials consist of angular quartz and feldspar, but biotite and selenite are particularly common and at a few localities selenite constitutes almost five percent of the bed. Cristobalite was identified in four of eight samples examined by x-ray methods by members of the Geochemistry and Petrology branch of the U. S. Geological Survey. It was possible to establish that the amounts of cristobalite were as great as 10 percent in only one of the samples.

Figure 19.--Differential thermal analysis curves of samples from the Clay Spur bentonite bed. All samples are from Crook County, Wyoming.

a. Light colored bentonite, 2 feet 6 inches thick, sec. 5, T. 57 N., R. 65 W.

b. Light colored bentonite, 2 feet 7 inches thick, sec. 5, T. 57 N., R. 65 W.

c. Light colored bentonite, 2 feet 1 inch thick, sec. 33, T. 57 N., R. 62 W.

d. Light colored bentonite, 11 inches thick, sec. 4, T. 56 N., R. 66 W.

e. Light colored bentonite, 6 inches thick, underlying material analyzed in curve d.

f. Light colored bentonite, 2 feet 9 inches thick, includes both materials analyzed in curves d and e.

g. Light colored bentonite, 2 feet 8 inches thick, sec. 17, T. 56 N., R. 61 W.

h. Light colored bentonite, 1 foot 10 inches thick, sec. 26, T. 56 N., R. 61 W.

i. Light colored bentonite, 1 foot 10 inches thick, sec. 10, T. 55 N., R. 61 W.

j. Dark colored bentonite, 2 feet 10 inches thick, superjacent to material analyzed in curve i.

k. Light colored bentonite, 1 foot 9 inches thick, sec. 23, T. 55 N., R. 61 W.

BED D

Bed D is a thin stratum of bentonite that occurs near the base of the Belle Fourche shale. Throughout much of the district, bed D is only three to four feet above the Clay Spur bentonite bed, but where the thick laminated siliceous shale zone is present above the Clay Spur bed, the shale interval separating the two beds is much greater. Bed D is commonly less than four inches thick, but in a few places in the western part of the district, the bed is as much as 14 inches thick. Locally there appears to be a correlation between the thick portions of the Clay Spur bed and bed D, and it is possible that some of the lows in which the thick portions of the Clay Spur bed accumulated may have persisted through the period of deposition of bed D.

Because of its unfavorable thickness, bed D is of no economic importance and the bed is removed with the overburden where the Clay Spur bed is mined. Bed D is of interest because of its stratigraphic proximity to the Clay Spur bed, and because bed D was deposited in a marine environment that was unlike that in which the Clay Spur bed and enclosing siliceous shale were deposited. Bed D consists chiefly of very light gray or cream colored bentonite, but at many places it has a reddish brown or salmon colored stratum near the base and a darker gray layer in the upper part. The bed rests sharply on soft dark shale and grades upward into superjacent strata through a thin dark colored zone of interlaminated shale and bentonite. Both the characteristics of weathered outcrops and laboratory tests indicate that bed D consists of high swelling bentonite. Drilling mud and foundry bond tests as well as thermal analyses (Fig. 21, curve a) indicate that bed D is composed chiefly of Na type bentonite of the purity demanded for commercial purposes. The unfavorable thickness is the only reason that this bed cannot be considered a source of bentonite.

BED E

Bentonite Bed E is a very dark colored impure bed that occurs in the lower part of the Belle Fourche shale. Because of its color and impure nature, this bed is often called the "Mud bed". Nowhere in the Northern Black Hills Bentonite Mining district is Bed E sufficiently thick or pure to constitute reserves of commercial bentonite, but a small amount of Clay is mined and processed from stratigraphical equivalent of this bed in the Western Black Hills district. In the northern Black Hills bed E is very useful as a reference stratum in determining the amount of overburden above the Clay Spur bed. In the Wyoming portion of the district bed E ranges from about 27 to 30 feet above the important Clay Spur bentonite bed; therefore, the 30 feet overburden limit above that bed nearly coincides with the outcrops of bed E. In Butte County, South Dakota, the shale interval separating these two bentonite beds thins from about 27 feet near the Wyoming boundary to 18 feet near the town of Belle Fourche.

In many places bed E is covered by soil and alluvium but as a rule the bed can be found wherever lower Belle Fourche rocks are at least moderately well exposed. The stratigraphic position of the bed in covered areas is often indicated by a zone of soft puffy soil. Bed E ranges in thickness from one to about three feet and in a few places it is represented by only a thin zone of dark bentonitic shale. Both the upper and lower limits of bed E grade into the enclosing shale through zones of interlaminated shale and bentonite. The bentonite is dark-gray, gray, and brownish-gray with thin strata of light gray near the middle of the bed. The lower part of the bed is heavily iron stained resulting in a rusty appearance of most outcrops. Weathered surfaces of the thicker portions of the bed exhibit a poorly developed popcorn texture but powdery or alligator hide textures are more characteristic of the bed as a whole.

Although the dark shale strata enclosing bed E have yielded no identifiable fossils, the bentonite appears to have been deposited in moderately deep marine water. Variations in thickness suggest that the sea floor on which the volcanic ash was deposited was characterized by undulations similar to those described for the Clay Spur bed but on a much smaller scale. Thicknesses of bed E do not correlate with variations in thicknesses of the Clay Spur bed and although the uneven surfaces of deposition of both beds may be a consequence of similar phenomena, the forces causing the undulations appear to have been active at different times. The dark color of the bentonite is the result of admixture of shale and organic materials similar to that found in the enclosing shale and suggests that deposition of bed E was much slower than other bentonite beds in the district.

Because of its impure nature and unfavorable thickness, bed E was sampled only at two localities. The non clay minerals averaged more than 20 percent of the bentonite and were particularly abundant in the darker more impure parts of the bed. The non clay minerals consist chiefly of quartz and feldspar but field observations revealed that biotite flakes were very abundant along some bedding planes and that some selenite was present in nearly all of the clay. Differential thermal analyses of the samples (Fig. 21, curves b - d) revealed that they were composed chiefly of sodium type montmorillonite, although the water in one of the samples appeared to be influenced by a small amount of calcium.

A thin light colored stratum within the bed at one locality tested very high in drilling mud properties but the dark material making up most of the bed proved to be deficient in colloidal properties according to present standards for drilling mud. The samples tested had adequate dry strengths but only moderate to low green strengths.

BED F

Because of its conspicuous gray and red colors, bed F was called the Gray Red bed by Rubey and Bramlette (R. C. Moore, 1949, p. 27). This same bed has also been referred to by Wing (1940, p. 25) as occurring " *** approximately 9 feet below the Middle Creek limestone***" in the Western part of Butte County, South Dakota. As a consequence of Wing's description the bed is sometimes referred to as the Middle Creek bentonite bed, a name which has been geologically preoccupied. Bed F first appears as a thin wedge about six feet below the top of the Belle Fourche shale in sec. 29, T. 9 N., R. 2 E., Butte County, South Dakota. Less than two miles northwest of that place, bed F is more than two feet thick. Although its outcrops are locally covered with soil and alluvium, bed F is a continuous stratum in the Montana and Wyoming parts of the district. Locally the bentonite is as much as seven feet thick but it averages four to five feet in outcrops of the upper Belle Fourche strata throughout the western three-fourths of the district. The shale enclosing bed F is soft and the overburden could easily be removed by heavy mining equipment. Large reserves of bentonite are present in this bed, but that portion of bed F under light overburden is restricted to narrow zones along outcrops except in a few small outliers and inliers.

East of the Little Missouri River bentonite bed F crops out in the faces of cuestas supported by the resistant Orman Lake limestone bed, the lowermost bed of the Greenhorn formation. The dark shale interval between Bed F and the Orman Lake limestone bed increases from six feet where bed F first appears in Butte County, South Dakota to 12 feet near the Wyoming-South Dakota boundary and to 32 feet on the eastern side of the broad alluvial plain of the Little Missouri River near Alzada, Montana. As a consequence of a facies development, the Orman Lake limestone is not present on the west side of the alluvial plain in Little Missouri River Valley, where bed F crops out 177 feet below the base of the Greenhorn formation in that neighborhood. The Belle Fourche shale strata above bed F continue to increase in thickness to the southwest to more than 330 feet in the southwest part of T. 57 N., R. 67 W., Crook County, Wyoming.

Like most bentonite beds the contact between bed F and the underlying shale is very distinct. In most places the shale subjacent to the bentonite is soft but locally this shale is distinctly more resistant in a zone one to four inches thick than in lower strata. The bentonite bed grades upward into superjacent shale through a zone of interlaminated shale and bentonite, which as a rule is only eight to ten inches thick and contains very little bentonite in the upper half. The lower light colored portion of bed F averaged four feet 2 inches in thickness at the 16 localities at which it was drilled with a hand auger. The brownish-red color of the clay is largely confined to the lower half of the light colored portion of the bed. Red colors are best developed in the western three-fourths of the district. These red shades are less conspicuous in the eastern part of Crook County and are represented only by yellow and brown iron stains in the gray bentonite in the South Dakota part of the district. Where the red colors are prominently developed, the lower part of the superjacent gray bentonite commonly contains tiny red mineral specks which are locally present in sufficient numbers to produce shades of purple or a reddish-gray transition zone between the gray and the red clay. These red specks oxidize readily at or near the surface and are never present in the outcrops. The true red colored bentonite, on the other hand, weathers to the distinctive brownish red colors of the outcrops of this bed. Much of the weathered surfaces of bed F has well developed popcorn textures in crusts one to three inches thick, and below the crusts, there is commonly a zone of loosely compacted granular material. Most of the unweathered bentonite is characterized by a waxy texture. Small flakes of biotite and grains of feldspar, quartz, selenite and carbonates and traces of other minerals as well as soluble salts make up most of the non clay minerals in bed F. Crystals of selenite up to six inches long weather out of the bentonite. Veinlike deposits of light yellowish-gray, fibrous calcite up to two inches thick are common in bed F in the western part of the district. The calcite appears to have been deposited in joints in the bentonite that extend irregularly through the bed. The fibers in the calcite are oriented perpendicular to the joint. Locally the calcite is so abundant that weathered fragments nearly cover outcrops of bed F (Fig. 20); such large amounts of non clay materials greatly reduce the economic potentialities of the bentonite.

The fibrous calcite appears to be a consequence of the original composition of the ash rather than having been introduced by ground water as indicated by: (1) Absence of fibrous carbonates in the dark shale enclosing the bentonite bed; (2) The fact that fibrous calcite is not abundant in bed F in the eastern part of the district where the bed is situated a few feet below the calcareous strata of the Greenhorn formation which is the most likely source of calcite introduced by downward percolating ground water. Calcite must be a product of the alteration

process by which the ash was devitrified to form montmorillonite and indicates that alteration was still taking place after joints had formed in the bentonite bed. Joints could not have formed in soft submarine sediments; therefore, the presence of fibrous calcite in joints appears to support the theory that alteration of the ash to clay was still taking place following orogenic movements that raised the Cretaceous marine strata above sea level in late Cretaceous time.

A sparse marine fauna in the enclosing shale strata indicates that the volcanic ash which later altered to bed F bentonite accumulated in a marine environment. The uniform sharp contact of the bentonite with the subjacent shale as well as the uniform thickness of the bentonite bed and color stratifications within the bed suggests that the sea floor on which deposition took place was a nearly smooth surface well below the depth of vigorous wave action. The absence of dark laminae in the light colored portion of the bed and the thin zone of interlaminated bentonite and dark shale in the upperpart of the bed suggests that deposition of the ash was at first very rapid and that the tapering off of the accumulation of the ash took place in a shorter period of time than for most other thick bentonite beds. The fact that bed F is uniformally thick in the western part of the district but wedges out toward the east together with thickening of the enclosing shale strata toward the west suggests that the source of both the ash and the enclosing sediments was from the west.

Differential thermal analyses were made on six samples of the light and one sample of the upper dark parts of the bed F (Fig. 21, curves e - j). The curve obtained for the dark sample supports the field conclusion that the dark color is a consequence of shale impurities. Though composed chiefly of montmorillonite, the dark material showed rather low endothermic peaks corresponding to the loss of absorbed and lattice water indicating much dilution by non clay materials. The thermal curve of the dark material also showed that it contained about 5 percent gypsum, some organic material and a little iron sulfide. Thermal curves and ion exchange data (Table 4, samples 15 and 16) of the light bentonite showed that bed F is composed chiefly of montmorillonite and at some localities sodium is the dominent exchangeable ion, but at other localities exchangeable calcium seems to be more abundant than sodium. One sample having high drilling mud properties produced a curve (Fig. 21, curve i) which, at temperatures below 900°C, is very similar to thermal curves of commercial type bentonite from the Clay Spur bed. The exothermic reaction between 900 and 1000°C in this sample and other samples from bed F was neither as large nor distinct as for most sodium montmorillonite, indicating a difference in bulk composition or a slight structural variation. Curves of samples of low colloidal properties show marked variations in the characteristics of the low temperature adsorbed water peaks resulting from the ease with which water is released by the clay. Sodium and calcium are the dominate exchangeable ions indicated by the thermal analyses, but ion exchange measurements (Table 4, samples 15 and 16) indicate that magnesium is common and some hydrogen is present in bed F. Considerable calcium carbonate was present in one sample (Fig. 21, curve f) as indicated by a large endothermic peak between 775 and 890°C. Even the samples of the reddest bentonite failed to show peaks that are characteristic of nontronite, the montmorillonite mineral, which is rich in iron. It must be concluded that there is very little, if any, nontronite in bed F.

Figure 21.—Differential thermal analysis curves of samples from bentonite beds D, E, and F.

a. Bed D, 1 foot 1 1/2 inches thick, sec. 26, T. 56 N., R. 61 W., Crook County, Wyoming.

b. Bed E, 5 feet 5 inches of dark colored bentonite, sec. 27, T. 58 N., R. 65 W., Crook County, Wyoming.

c. Bed E, 6 inches of light colored bentonite subjacent to that material shown in curve b.

d. Bed E, 1 foot 5 inches thick, sec. 21, T. 57 N., R. 62 W., Crook County, Wyoming.

e. Bed F, 9 inches of dark colored bentonite from upper part of bed, sec. 26, T. 9 S., R. 57 E., Carter County, Montana.

f. Bed F, 4 feet 5 inches of light colored bentonite, subjacent to that material shown in curve e.

g. Bed F, 6 inch stratum of reddish-brown bentonite from lower half of bed, sec. 25, T. 57 N., R. 62 W., Crook County, Wyoming.

h. Bed F, 4 inch stratum of reddish-brown bentonite below that material shown in curve g.

i. Bed F, 5 feet 9 inches of light colored bentonite, sec. 9, T. 56 N., R. 67 W., Crook County, Wyoming.

j. Bed F, 2 feet 2 inches of light colored bentonite, sec. 17, T. 56 N., R. 60 W., Crook County, Wyoming.

BED G

Bed G occurs 65 to 85 feet stratigraphically above bentonite bed F. East of the alluvial plain of the Little Missouri River, bed G is about 55 feet above the base of the Greenhorn formation. Bed G crops out intermittently in the lower Greenhorn strata that extend approximately parallel to U. S. Highway 212 between Alzada, Montana and the Wyoming-South Dakota boundary. In the central part of the district bed G occurs five to six feet below a thin limestone bed which protects the bentonite from erosion and causes it to lie under light overburden over considerable areas. West of the Little Missouri River, the lower Greenhorn strata enclosing bed G grade laterally into dark-gray Belle Fourche shale, and as the Greenhorn-Belle Fourche contact rises stratigraphically toward the west increasing thicknesses of Belle Fourche shale occur above bed G.

Bed G possesses about the same degree of resistance to erosion as the shales above and below it; therefore, the bed does not form ledgelike outcrops as do most other bentonite beds. Weathered surfaces of the bed are characterized by loosely compacted, granular, bentonitic soil which supports scanty vegetation and even the best exposures of the bentonite in bed G appear to swell very little when wet. The conclusion based on field evidence that bed G bentonite has low swelling properties is verified by results of laboratory tests. Locally the position of the bed is marked by white alkali efflorescence which has been precipitated from ground water trapped by the relatively impervious bentonite stratum. Oval shaped limestone concretions up to eight inches in diameter are present in some parts of the bed, and in several places pockets of loosely compacted powdery calcite were observed near the base of the bed. The calcareous nature and rounded outline of these pockets suggests that they are remnants of former concretions.

As a rule bed G is three to five feet thick and is composed of gray or brown colored bentonite and is commonly heavily iron stained in the middle and upper part. Parts of the bed appear to have a waxy texture but the bed as a whole is characterized by an earthy texture more like that of ordinary clay. As much as 10 percent grit and 30 percent total non clay material is not uncommon in the bed. The non clay material consists of biotite and calcite in unusually large proportions with minor amounts of fine-grained, angular quartz, feldspar, selenite, and traces of volcanic glass and other minerals. The biotite is sufficiently abundant along some bedding planes to cause them to appear almost black. Soluble salts are probably very abundant in this bed, particularly where alkali efflorescence appears on weathered surfaces.

The contact of bed G with subjacent shale is distinct but the bed grades into the superjacent shale through a transition zone 6 to 12 inches thick. West of the Little Missouri River, where the bed is enclosed in dark shale, the transition zone appears to be marked by an upward decrease in the number of bentonite laminae. East of the Little Missouri River the color and texture of the upper part of bed G is very similar to that of the superjacent calcareous shale and in many places the gradation consists of a continuous decrease in the amount of bentonite rather than a decrease in the number of bentonite laminae. Macrofossils have not been preserved in the shale enclosing bed G but the thin limestone bed occurring five to six feet above the bed G is very fossiliferous. The limestone contains sharks teeth and many fragments of pelecypods. These fossils together with ripple-marks indicate rather shallow marine conditions. It is likely that bed G and its enclosing calcareous shales in the eastern part of the district was deposited in a sea that was not much deeper than the shallow depth suggested by the limestone bed. Consistent thicknesses of bed G, the limestone bed, and the shale interval between the limestone and the bentonite indicate uniform deposition which in view of the evidence for shallow water deposition suggests a quiet sea and a mild climate. Where bed G is enclosed in dark shale west of the Little Missouri River, the sea probably was slightly deeper but the fact that horizons at rather uniform intervals can be traced from the calcareous facies into the dark shale indicates that the dark shale accumulated at about the same rate as the limestone.

Thermal analyses of samples of bentonite from bed G (Fig. 25, curves a and b) indicate that the bentonite is composed chiefly of montmorillonite with considerable amounts of calcite, selenite and other impurities. Nearly seven percent of one sample is composed of selenite and the content of calcium is probably as much as 10 percent. Microscopic examinations of the clay reveal that the calcite is present in very irregular grains most of which show evidence of solution by ground water. The thermal curves suggest that sodium and calcium are the dominant exchangeable ions; however, the ion exchange measurements of one sample (Table 4, sample 17) indicate more magnesium than sodium or calcium.

BED H

Bed H, a thin but conspicuous stratum of very impure clay of volcanic origin, occurs 70 to 75 feet below the top of the Gammon member of the Pierre shale. Bed H is only about 1 1/2 feet thick, but it is very persistent in the northern part of Butte County, South Dakota and is present in a few exposures in the western part of the district in T. 58 N., R. 67 W., Crook County, Wyoming. Presumably the bed also appears in outcrops of the Gammon unit which extend many miles to the north of the Black Hills between these two localities. Bed H is composed of light brownish-gray, hard, platy clay which weathers light gray or ivory. The bed commonly contains as much as 25 percent silt size particles and a total of 55 to 65 percent non clay minerals. Weathered surfaces of this bed are characterized by alligator hide textures and are commonly littered with small plates of hard clay.

Swelling and foundry bond tests made on a sample from bed H indicate that this material has practically no colloidal properties, which is no doubt a consequence of its impure nature. Thermal analysis curve of one sample (Fig. 25, curve c) also shows by low intensities of characteristic reaction that clay minerals do not make up a major portion of the bed. Samples of bed H studied by optical methods revealed that the non clay minerals consist chiefly of angular feldspar and quartz grains with traces of volcanic glass and biotite. The bed does not appear to have any economic value and is described only to complete the study of the bentonite deposits of the district and because it does serve as an excellent stratigraphic marker in a thick succession of shale where diagnostic horizons are otherwise missing.

BED I

Bentonite bed I occurs at the base of the Mitten member of the Pierre shale. The bed consists of several strata of bentonite separated by dark, fissile shale partings. Bed I is best developed and exposed in the drainages of the North and South Indian Creeks in the northwestern part of Butte County, South Dakota, where it ranges in thickness from 8 1/2 to 12 feet. In the western part of the Indian Creeks neighborhood, the Mitten shale exposures trend in a northwesterly direction. This trend continues well into Montana far beyond the area of the present investigation and is diverted to the southwest so that bed I is again present within the area of this report in the northwest part of Crook County, Wyoming. Bed I is known to be present near the northern extent of lower Mitten outcrops several miles northwest of Albion, Montana, and the bed has also been mapped in T. 7 S., R. 56 E., Carter County, Montana on the western limb of the arcuate outcrop pattern. Bed I is much thinner in the western part of the district and is represented in Crook County, Wyoming by less than three feet of bentonite interstratified with two thin shale layers. The nature of the thinning from east to west is illustrated graphically in Fig. 22. If bed I is a continuous stratum as is suggested by its persistence in the areas in which it has been examined, this bed must be present under light overburden in a narrow zone along the 100 mile long, arcuate outcrop pattern of the basal beds of the Mitten shale member.

Because bed I is composed of very low swelling bentonite and is enclosed in soft dark shale, good exposures of the bentonite bed are very rare. In fresh exposures the upper Gammon strata below bed I and the dark Mitten shale above the bed appear very much alike, but on weathered surfaces the Gammon strata are characterized by rusty gray colors and tends to support less plant growth than does the Mitten unit which weathers to a dark-gray soil. Color contrast between soils developed on the two units is often sufficient to determine the boundary between them and, therefore, to locate the position of bed I; this color contrast is particularly apparent on aerial photographs. The Mitten shale is distinctly more resistant than upper Gammon beds, and as a consequence bed I frequently occurs under a thin alluvial cover at the base of a low scarp.

Thick portions of bed I in Butte County, South Dakota consist of as many as eight bentonite strata interstratified with shale layers up to nine inches thick. The most persistent bentonite stratum which averages nearly three feet in thickness occurs at or near the base of the bed. A bentonite stratum in the upper part of bed I is more than three feet thick in a cutbank of North Indian Creek, but most bentonite strata in the middle and upper part of bed I tend to be much thinner and less persistent than the thick layer at the base. As a rule the basal contact of bed I as well as the lower limits of bentonite strata within the bed are very distinct and form rather smooth surfaces. Unlike most other bentonite beds upper boundaries of both the bed and bentonite strata within the bed tend to be sharp or marked only by a thin transition zone of interlaminated shale and bentonite. Locally some of the thin bentonite and shale strata coalesce laterally into thicker units so that a succession of bentonite and shale strata at one place may be represented a few hundred yards away by a single thicker bentonite unit enclosed in shale strata. Such variations in bed I increase the difficulty in determining which parts of the bed are minable deposits.

Undiscolored bentonite in Bed I is greenish gray but this material oxidizes readily at or near the surface to iron stained shades of yellow and orange. In the eastern part of the district the thick lowermost stratum of bentonite in the bed is darker greenish gray and tends to retain its color at the surface more than thinner strata higher in the bed. This retention of the green color at the surface indicates that iron in this stratum is less easily oxidized and may reflect a more intimate association of iron with clay minerals. When the water content is rather high the texture of the bentonite in bed I is waxy but with slight drying, the clay assumes a granular texture. Small flakes of biotite are common throughout the bed. Many of the flakes are water rounded and most of them are oriented parallel to the bedding planes indicating that the biotite was concentrated by sedimentary processes rather than formed authigenically. Small fibrous selenite crystals are present in much of the bentonite and are particularly abundant along joints. In the eastern part of the district irregularly shaped concretions are common in the upper part of the bed; these concretions range from eight inches to two feet in diameter and are composed of masses of heavily limonite stained gypsum and fibrous calcite.

Concretions in shale strata above and below bed I contain marine fossils indicating that this bentonite bed was deposited in a marine environment. The dark fine-grained nature of the enclosing shale strata together with widespread occurrence of the Mitten member of the Pierre shale and its stratigraphical marine equivalents in that formation suggests that bed I was deposited in rather deep marine water at a considerable distance from shore. However, the interstratification of shale with bentonite and interfingering of strata within the bed do not conform with the characteristics of deep ocean or fondo sediments as outlined by

Rich (1951, p. 9). The pure bentonite must be concluded to represent relatively rapid accumulation of volcanic ash thus preventing contamination and discoloration by the dark marine shales whose rate of deposition could not have been greatly slowed by the influx of ash. Interstratification of more persistent bentonite and shale layers no doubt is a consequence of periodic accumulation of volcanic ash with intervening periods of deposition of normal marine shale, but this fails to explain the local interfingering of some of the strata of pure bentonite with shale and the presence of local partings of shale within the bentonite layers. Absence of contorted bedding in the bentonite and shale strata opposes the possibility that all of these strata were involved in submarine mud flows but does not rule out the theory that the shale partings enclosed in bentonite were deposited by density currents of viscous mud. Such density currents may have originated in submarine mudflows on sloping sea floors at considerable distances from the northern Black Hills. Lithologic differences between shale above and below the bentonite bed suggests a change in source of sediments or in sea level, either of which would likely have been accompanied by some orogenic movement which could have created conditions favorable for mud flows. Presumably the sea during and following the accumulation of bed I was somewhat deeper than in the preceding time interval as suggested by the uniform fine-grained nature of the shale in and above the bentonite bed and the presence of many ferruginous and calcareous concretions and some arenaceous materials in shale below the bed.

Non clay materials average about 25 percent of bed I. Finer non clay materials are composed chiefly of angular quartz and feldspar grains. Some gypsum, iron oxides, and calcite are present as well as traces of volcanic glass shards and many other minerals.

Grit makes up more than 50 percent of the non clay materials, most of these silt and fine sand-sized particles consist of sub-rounded and frosted quartz grains. Small grains of pyrite and euhedral magnetite are also present in the grit. The large amount of water rounded particles is most probably a consequence of sandstone facies developed in equivalent rocks farther west. Restriction of Cretaceous seas in Montana time was marked by a progressive eastward shifting of continental deposits as outline by Reeside (1944) and it is likely that the west shore of the sea in which bed I was deposited was much closer to the Black Hills than at the time of deposition of older bentonite beds.

Thermal analyses (Fig. 25), ion exchange measurement (Table 4, samples 18 and 19) and commercial tests of bed I bentonite indicate it is composed chiefly of calcium type bentonite. Low temperature endothermic reactions reach their optimum at about 150°C, but most of them are not completed until temperatures of 250°C are reached. The majority of curves show some indication of a second reaction at about 200°C corresponding to loss of water from the hydrated exchangeable calcium ions. Endothermic reaction caused by loss of lattice water begins at about 400°C and following a slight intermediate peak or a slowdown of the reaction reaches its maximum at about 675°C. In most sodium bentonite this reaction begins at much higher temperatures and is much sharper. Loss of OH water over such a broad range of temperatures in bed I bentonite indicates that some of the hydroxyls are bound more securely than others and suggests some structural differences between bentonite in bed I and that in other beds in the Northern Black Hills district. Bed I bentonite has very high green but low dry foundry sand bonding strengths as do most calcium bentonites.

Figure 25.—Differential thermal analysis curves of samples from bentonite beds G, H, and I.

a. Bed G, brown and brownish-gray bentonite 6 feet 9 inches thick, sec. 29, T. 58 N., R. 62 W., Crook County, Wyoming.

b. Bed G, gray and brownish-gray bentonite 2 feet 4 inches thick, sec. 9, T. 57 N., R. 62 W., Crook County, Wyoming.

c. Bed H, ivory colored bentonite 1 foot 2 inches thick, sec. 8, T. 11 N., R. 5 E., Butte County, South Dakota. (Sample locality is east of the area shown on the accompanying map.)

d. Bed I, yellow and yellowish-brown bentonite 5 feet 1 inch thick, sec. 35, T. 12 N., R. 2 E., Butte County, South Dakota (whole sample).

e. Less than 2 micron fraction of sample shown in curve d.

f. Bed I, greenish-gray bentonite 2 feet 7 inches thick, sec. 35, T. 12 N., R. 2 E., Butte County, South Dakota (whole sample).

g. Less than 2 micron fraction of same sample as curve f.

h. Bed I, yellowish-brown and greenish-gray bentonite, sec. 10, T. 11 N., R. 2 E., Butte County, South Dakota.

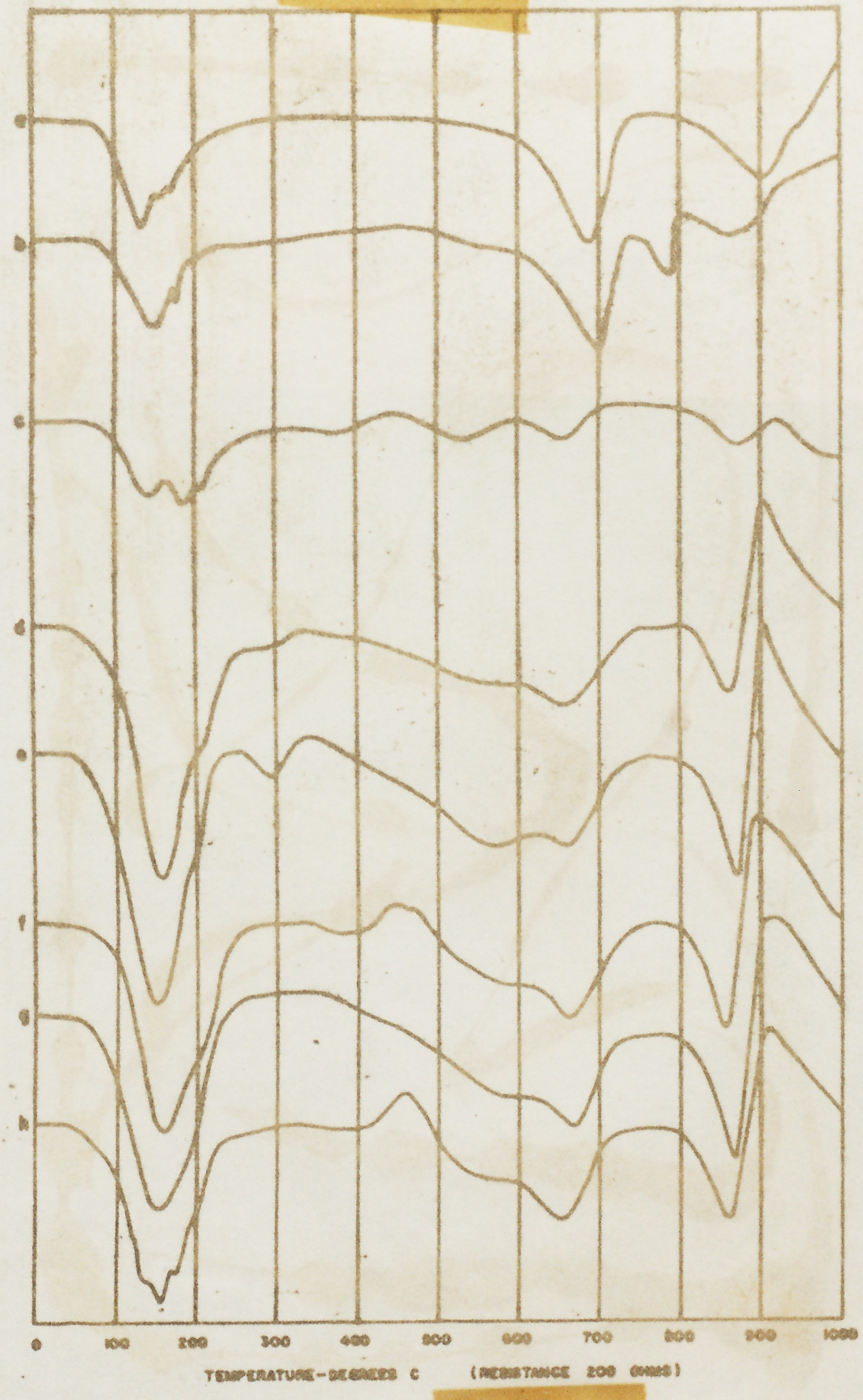
a
b
c
d
e
f
g
h
0 100 200 300 400 500 600 700 800 900 1000
TEMPERATURE-DEGREES C (RESISTANCE 200 OHMS)

Figure 23

A few small crystals of pyrite were observed in grit washed from undiscolored portions of this bed. This mineral is also recognizable in thermal curves of the undiscolored bentonite by a double exothermic reaction between 400° and 500°C which corresponds to the reaction for pyrite given by Grim and Rowland (1944, p. 69). Pyrite probably makes up less than two percent of the bentonite and the mineral does not occur in finely divided particles as indicated by the absence of thermal reactions in the minus two micron fraction of the undiscolored bentonite.

The presence of limonite in discolored bentonite is indicated in the thermal curves (Fig. 25, curves d and e) by endothermic reactions at about 300°C corresponding to the peak for that mineral shown by Grim and Rowland. Only a very weak reaction for limonite occurred in the undivided sample but a reaction of moderate intensity occurred in the minus two micron fraction of this material. Apparently the limonite occurs in very fine particles and is closely associated with the clay. Absence of pyrite in the discolored portions of bed I (Fig. 25, curves f and g) indicates that some of the limonite is formed by oxidation of that mineral. Some limonite also must form during the oxidation of green ferrous iron of the undiscolored clay to ferric iron in the yellow bentonite.

ORIGIN OF THE BENTONITE

SOURCE OF VOLCANIC ASH

With few exceptions, marine strata enclosing the bentonite beds thicken westward, and many of the formations intertongue in that direction with still thicker terrigenous units. Land west of the present deposits was the principal source of sediments and only a relatively small volume came from land areas in the continental interior. Volcanic ash derivatives and tuffaceous material in Cretaceous rocks also increase westward, apparently toward centers of vulcanisms in Idaho, northwestern Utah, or western Montana. The Mowry formation is 250 feet thick or less and contains about 15 percent bentonite and bentonitic shale in much of eastern Wyoming and western South Dakota. In Teton County, Wyoming, in the western part of the state, the Mowry formation has been described by Foster (1947, p. 1575-1577) as about 1,070 feet thick and as containing as much as 25 percent bentonitic materials. The Aspen formation which is in part the correlative of the Mowry in westernmost Wyoming and eastern Idaho consists of up to 2,000 feet of terrigenous deposits in which tuff and ash derivatives are very abundant. In Upper Cretaceous strata, terrigenous sediments tend to extend much farther to the east, but there is no evidence for assuming that there was any major shift in the sources of the volcanic materials.

Satisfactory correlation of the bentonite beds from the Black Hills to the mountain ranges lying to the west has been possible only for the Clay Spur bentonite bed. The Clay Spur bed along the eastern flank of the Big Horn Mountains averages only a few inches thicker than in the Black Hills region. The Clay Spur bed in both regions is composed chiefly of the same type of montmorillonite. This emphasizes the fact that ash of rather uniform composition must have been spread over a very broad area. Other bentonite beds of both Upper and Lower Cretaceous age in the Big Horn region tend to be distinctly thicker and are more numerous than bentonite strata at comparable stratigraphic positions in the Black Hills.

Rubey (1929, p. 155) noted a westward increase in thickness and in the amount of sand sized particles in the Clay Spur bed throughout the

Black Hills region. In the Northern Black Hills area there is only a slight westward increase in thickness of this bed. The Clay Spur is about average thickness in a few places in the eastern part of the district, but such thicknesses are less persistent than in the central and western parts of the district. A westward increase in sand sized particles was not supported by more than 60 grit analyses of the Clay Spur bed made during the present investigation. These analyses suggest that grit materials are controlled by local conditions of deposition. The amount of grit varies from place to place within each of the lows in which the thicker portions of the bed were deposited and in most places the grit tends to be more abundant in the thinner portions of the bed.

Bentonite bed F does thicken markedly westward and there is some westward increase in the amount of grit materials. Bed I, however, is characterized by a pronounced eastward thickening which contrasts with all other evidence for the source of the ash. Apparently original ashes of the bentonite beds in the Northern Black Hills district were deposited so far from their sources that thicknesses and distribution of sand-sized particles were controlled more by conditions of depositions than by distances from source and modes of transportation.

INFLUENCE OF CONDITIONS OF DEPOSITION ON THE FORMATION OF BENTONITE

All of the bentonite beds in the Northern Black Hills district except bed A have altered from ash that was deposited in marine environments. Bed A was originally laid down in lagoons which may have contained some fresh or brackish water. Parts of the lagoons were well ventilated by oxygen bearing water as indicated by the cross-bedded, ripple-marked, sandy beds which enclosed bed A at many places. All other bentonite beds with the possible exception of bed G accumulated in oxygen deficient environments as indicated by the dark color of the shales and thin sulphurous material along joints and bedding planes. The lagoonal basins in which bed A accumulated must have been rather small; therefore, the fact that bed A is locally very thick suggests that part of the ash came from outside the small basins. It is unlikely that fine-grained ash could have been transferred from open seas into the lagoon, but it seems probable that some of the ash fell on nearby land surfaces and was carried to the lagoons by streams.

The rocks enclosing bentonite beds in true marine strata indicate three variations of marine conditions. Bed B and the Clay Spur bed were deposited in the unusually siliceous environment represented by the Mowry shale. Beds D, E, F, and I are enclosed in more common dark marine shale. Bed G in the lower part of the Greenhorn formation indicates accumulation of ash in relatively shallow quiet water in which calcareous shale and marl were being deposited. Thermal analyses and base exchange measurements show that both calcium and sodium type bentonite are enclosed in rocks representing the lagoonal and the unusually siliceous, calcareous, and common black shale conditions of deposition. The conclusion must follow that differences in lagoonal and the variations in marine environments have very little effect on the formation of bentonite. The possibility that bed A accumulated in brackish or fresh water suggests that sea water may not be required for the formation of bentonite.

In a few localities bed A contains bentonite in which sodium is by far the most abundant exchangeable ion and in other localities exchangeable calcium is dominant, but in most places the bed probably consists of more or less even mixtures of the two types. The variability of the bentonite is no doubt partly the result of irregularities in deposition including sedimentary differentiation of the parent materials. Much of the calcium may have been introduced by ground water because most of the strata enclosing the bentonite are very pervious. Possibly the original composition of the ash was much more sodic than is indicated by the bentonite.

The uppermost 40 feet of Mowry strata and basal few feet of the Belle Fourche shale are of particular interest because they contain three bentonite beds, two of which were deposited in unusually siliceous environment and one in more normal conditions of marine sedimentation. The thick Clay Spur bed near the top of the siliceous Mowry shale is chiefly a sodium type bentonite, but bed B which occurs 30 feet lower in the formation is essentially a low swelling calcium bentonite. Both beds were deposited in the same environment and apparently their post depositional histories have been identical. Bed D, though occurring only a few feet above the Clay Spur bed, is enclosed in soft non-siliceous shale representing conditions of sedimentation somewhat different from the lower two beds. Bed D has essentially the same mineralogical characteristics and physical properties as the Clay Spur bed. The occurrence of both a bed of calcium and a bed of sodium type bentonite in identical depositional and diagenetic condition can be explained most logically by variations in the original composition of the ash. Sodium bentonites in the siliceous and non-siliceous shales is most likely a consequence of similarities in the original compositions of the ashes.

Where bed G is enclosed in the calcareous shales of the lower Greenhorn formation its exchangeable ions consist of much magnesium, a moderate amount of sodium, and a relatively small amount of calcium. Bed G everywhere contains much calcium carbonate that would provide a large supply of calcium ions. The fact that magnesium and sodium are both more abundant than calcium in the presence of an abundant supply of calcium ions indicates that there must be some structural reasons for the montmorillonite retaining sodium and magnesium. Perhaps the sodium and magnesium are related to the composition of the ash from which bed G formed.

STRATIGRAPHIC RANGE OF CALCIUM AND SODIUM TYPE BENTONITES

Sodium or "Wyoming type" bentonite is restricted to the uppermost 525 feet of Lower Cretaceous rocks comprising the Newcastle and Mowry formations and the lowermost 600 feet of the Upper Cretaceous rocks which include the Belle Fourche shale and lower part of the Greenhorn formation. Most persistent and purest sodium bentonite beds are found within a few feet of the Lower-Upper Cretaceous boundary. Sodium bentonite decreases in younger rocks and is not common in the Northern Black Hills district above the lower Greenhorn beds. Low swelling calcium type bentonite has a much greater stratigraphic range. In addition to being stratigraphically coextensive with the sodium type, it occurs at intervals throughout 1,500 feet of Upper Cretaceous rocks extending to the upper part of the Pierre formation. Restriction of sodium type bentonite to older rocks may be a reflection of the original composition of the ash. The sodium and calcium contents of bentonite need to vary as little as one percent to change the properties from one type of bentonite to the other. The volcanic ejectaments that accumulated in the Black Hills near the end of the Lower Cretaceous and in the early part of Upper Cretaceous period may have contained slightly more sodium than at any other time.

ORIGINAL COMPOSITION OF THE ASH

Attempts have been made to estimate the original composition of the ash from microscopic determination of the non clay minerals in the bentonite. The amounts of such minerals that can be accurately determined are rarely as much as ten percent and are commonly less than three percent of the bentonite. Estimates of this type follow the assumption that composition of phenocrysts in porphyritic igneous rocks are representative of the whole; therefore the identifiable minerals in bentonite are taken to be indicative of the composition of the parent rock. The validity of the method as applied to bentonite is not beyond question for the following reasons: (1) Most so-called ash particles in bentonite are characterized by marked angularity and rarely show the effects of alteration and solution, whereas in most deposits only traces of volcanic glass remain in bentonite. It is not logical to assume that the composition of small percentages of unaltered fine-grained material is representative of very large proportions of material which has been almost completely altered. (2) Angularity is the only criteria for separating many detrital non clay minerals from grains that were original constituents of the ash. It is assumed that angular grains are part of the ash and that sub-rounded grains are detrital. Many non clay grains are sufficiently small to be angular in most conditions of sedimentation. If the larger grains alone are considered the proportions available for the estimates are greatly reduced, and there is still the possibility that some of the larger angular grains are detrital. (3) Any non vitric ash would vary in composition with distance from source and mode of transportation because of differences in specific gravity of minerals. The composition of mineral grains in bentonite in the Black Hills area could not be expected to be identical with that of phenocrysts in the parent igneous material if it is assumed that the ash originated as far west as central Idaho.

Any ash from which bentonite has altered would contain at least as much silica as the bentonite, and probably the ash would be even more silicic than its alteration product. Nearly all of the more acid igneous rocks contain more silica than do most bentonites. Certainly the vulcanisms producing sufficient ash to form bentonite were very explosive, and there is some evidence that acid lavas are much more explosive than basic ones. In two places where the parent tuff of bentonite is definitely known, analyses given by Nutting (1945, p. 185) show that the parent material contains from 12 to 15 percent more silica than does the bentonite.

Chemical analyses of the bentonite from the Northern Black Hills district that are available are all from the Clay Spur bed. These analyses suggest a composition similar to latite except the proportions of magnesium are too high. Because the original ash must have been richer in silica than the bentonite, the original material was probably more like quartz latite or rhyolite in composition.

Composition of the ash ejected by Cretaceous volcanoes could not be expected to have remained the same throughout the period and minor variations in composition might result in much greater variabilities in the bentonite. Likewise similar bentonites might result from ashes of different composition by the removal of different oxides during the alteration processes. If the conclusion that the fibrous calcite in bed F is an alteration product is correct, the original composition of that bed was much more calcic than any other ash accumulation in the northern Black Hills. The large amount of angular silt-sized particles in bed H suggests that the original material contained much less volcanic glass than most other ash falls in the district. Evidence at hand concerning the original composition of the other bentonite beds indicates only slight variations in compositions that have been outlined elsewhere in the text.

ALTERATION OF THE ASH

Volcanic glasses are known to be soluble in alkaline solutions, and no doubt fine-grained ash lying unburied on the sea floor would soon be altered. It is probable that the alkaline attack on the ash would begin even as the ash settled in the sea water and alteration would be more or less advanced in ash that was suspended for some time in the ocean before deposition and burial. Evidence has been presented suggesting partial alteration of the ash in the siliceous laminae zone of the Clay Spur bed prior to final deposition. However, the presence of very small glass shards in beds B and Clay Spur is proof that alteration of the thicker and hence the more rapidly buried portions of the ash has not been completed in all of Upper Cretaceous and Cenozoic time. The correlation of the thicknesses of the siliceous floor and the bentonite in the Clay Spur bed indicates that the silica was leached downward from the bentonite by the movement of ground water. Ross and Hendricks (1945, p. 67) have pointed out that downward movement of water could not take place in the standing water of the lake and sea. Presumably most of the silica was leached from the bentonite after the elevation of the Black Hills area above sea level in late Cretaceous time and most of the alteration of the ash took place during the leaching.

Further evidence that alteration of the ash took place chiefly after uplift above sea level is present in the fibrous calcite joint deposits which occur in many bentonite beds but are most abundant in bed F. The absence of fibrous carbonates in the shales enclosing the bentonite beds suggests that the calcite is a product of the alteration of the ash. Those portions of the ash that were rich in calcium would probably be among the first altered because calcic rich rocks are relatively unstable as indicated by the mineral stability series in weathering by Goldich (1938, p. 55-68). Presence of calcite joint deposits up to two inches thick suggests that prominent joints were formed in the ash and that there was some lateral movement of water within the bed before the alteration had progressed very far. Prominent joints could not form in soft subaqueous sediments, nor is it likely that cracks as much as two inches across would form in ash or tuff under several thousand feet of rock strata. Joints may have formed in bed A at the close of Newcastle time when conditions ofdeposition changed from near shore to moderately deep marine. All bentonite beds above bed A are overlain by thick successions of rocks representing continuous marine deposition until the close of Fox Hills time. Prominent joints were not likely to have been formed in these beds until the uplift of the Black Hills in late Cretaceous or early Tertiary time. It is even more likely that the periods of greatest uplift did not occur in the northern Black Hills until after the Eocene epoch and by that time part of the Upper Cretaceous strata had been stripped from the region so the bentonite beds were not so deeply buried.

ORIGIN OF CHERTLIKE FLOORS BELOW BENTONITE BEDS

In the Northern Black Hills district a hard chertlike floor is most prominently developed beneath the Clay Spur bed but strata 2 to 4 inches thick below beds A, B, and F also have been locally reinforced with silica. Siliceous floors have also been noted under bentonite beds throughout thick sections of Cretaceous rocks in parts of Montana and central Wyoming. Relation of thickness of the Clay Spur bed to the siliceous floor below the bed and unusual hardness of Mowry shale adjacent to joints just below the floor indicates that silica was leached from bentonite by ground water during or after alteration of ash to bentonite. Similar relations between prominence of the floor and thickness of bentonite have been noted by the author in bentonite beds of both Upper and Lower Cretaceous age on the northeast flank of the Big Horn Mountains.

Development of the siliceous floor depends on the following factors: (1) Amount of silica in original ash and thickness of the bed, both of which are more or less proportional to the amount of silica contributed to the floor. (2) Original silica content of strata below the bentonite. One of the chief reasons for the prominent floors below the Clay Spur and other thinner beds in the Mowry shale is that these strata originally contained as much as 80 percent silica. Only small additions of silica are necessary to make such strata hard and chertlike, whereas similar small additions to other types of dark shales might not be noticed. (3) When very pervious strata occur below the bentonite, the silica is likely to be so dispersed that no prominent floor is formed. Where bed A rests on sandstone, the rock is commonly only slightly less friable than sandstone elsewhere in the formation. Where carbonaceous shale underlies bed A, it is much harder and more platy than at places where the bentonite

Table 5.—Summary of the characteristics of the bentonite beds of the Northern Black Hills district

Bed	Swelling capacity	Characteristic exchangeable ions	Percent non clay materials	Environment of deposition	Economic value
I	very low	Ca	10-20	normal marine (dark shale)	small reserves of very high green strength bonding clay
H	very low	?	45-65	normal marine (dark shale)	none
G	low	Mg, Ca, Na	20-35	calcareous marine	none
F	low to high	Na, Ca	15-25	normal marine (dark shale)	large reserves of bonding clay
E	high	Na?	20-35	normal marine (dark shale)	none
D	very high	Na?	10-20	normal marine (dark shale)	none
Clay Spur	high to very high	Na, Ca, Mg	10-20	unusually siliceous marine	large reserves of both high colloidal and bonding clay
B	very low	H common in weathered clay	15-25	unusually siliceous marine	none
A	low to very high	Na and Ca	10-40	near shore lagoonal	small reserves of high colloidal clay and large reserves of bonding clay

bed is not present.

CONCLUSIONS

Montmorillonite is essentially the only clay mineral present in the bentonite of the northern Black Hills. Nontronite, the iron rich mineral of the montmorillonite group, is not present in sufficient amounts, even in the reddest bentonite, to be recognized by thermal analysis methods. Nearly all physical properties of bentonite are directly related to mineralogical characteristics. Sodium is the dominate exchangeable ion in high colloidal bentonite but the presence of some exchangeable calcium, magnesium or hydrogen appears to be essential. As amounts of exchangeable ions other than sodium increase beyond a few percent, there is a tendency for colloidality to decrease, and the colloidal properties of essentially pure calcium, magnesium, and hydrogen bentonites are very low as compared to sodium bentonite. Non clay materials act as dilutants, and in beds containing commercial quality bentonite, these materials commonly make up as little as 15 percent but rarely more than 25 percent of the clay. Influence of non clay materials is commonly obscured by development of colloidal properties controlled by other factors.

Sodium bentonite is present in rocks that range from the Newcastle sandstone to the lower Greenhorn beds. The purest and most persistent sodium bentonite beds occur within a few feet stratigraphically from the boundary between the Lower and Upper Cretaceous series. Calcium bentonite is coextensive with the sodium type and in addition occurs in 1,500 feet of younger rocks.

The bentonite beds and enclosing strata indicate that volcanic ash was deposited in lagoons and in variations of marine environments representing unusually siliceous, calcareous, and dark shale types of sedimentation. Both sodium and calcium bentonite occur in all of the conditions of deposition represented; therefore, these variations have little effect on the formation of bentonite. Presence of both sodium and calcium bentonite within strata representing identical conditions of deposition and post depositional histories points to differences in original composition of ashes. Cretaceous paleogeography and regional stratigraphy indicates that sources of volcanic ash were from the west. Variations in thicknesses and non clay contents of bentonite within the district were controlled by local conditions of deposition rather than distances from source.

Small portions of the bentonite may have been altered prior to burial, but most of the alteration probably took place after the Eocene epoch. Movement of silica downward to form chert-like floors below bentonite beds could only have taken place after uplift above sea level in the latter part of the Cretaceous period. Fibrous calcite joint deposits may represent one of the first alteration products because calcic rich minerals are among the least stable constituents of igneous rocks. Fissures and joints in which the calcite accumulated were most likely formed during periods of diastrophism after part of the thick sedimentary cover had been stripped from the region. Greatest uplift of the Black Hills came after the Eocene epoch and by that time much of the Upper Cretaceous strata had been stripped from the northern Black Hills.

Low colloidality of the undiscolored portions of the Clay Spur bed is probably a consequence of the purity of the exchangeable cations or equilibrium conditions that exist between the exchangeable ions and the water in the clay. Colloidality is increased when small proportions of sodium are replaced by calcium, hydrogen, or possibly other cations.

This exchange process commonly takes place during the oxidation by which the bentonite is discolored to olive green. The effect of small amounts of calcium, hydrogen or other ions is to create disorder in the orientation of the water layers between adjacent montmorillonite flakes which would allow additional water to enter more easily.

Varvelike interlaminated light and dark colored bentonite in the upper part of the Clay Spur bentonite represent seasonal accumulations. The dark laminae were formed by discoloration of volcanic sediments by organic and shale impurities. Dark materials were probably introduced during the warm months of the year when rainfall on land areas was heaviest. Thicknesses of the Clay Spur bed and the superjacent zone of siliceous laminae vary in direct proportion to each other, this relationship indicates that they were deposited on an undulating surface. This surface must have had a relief of at least 12 feet and may represent the upper surface of giant ripple-marks.

REFERENCES CITED

Alden, W. C., 1932, Physiographic and glacial geology of eastern Montana and adjacent areas: U. S. Geol. Survey Prof. Paper 174, p. 1-133.

Anderson, S. A., 1931, Om Aase og Terrasser inden for Susaa's Vandomraade og deres Vidnesbyrd om Isafsmeltningens Forlb: Danmarks Geol. Untersgoles, II Raekke Nr. 54, p. 21-31.

Barshad, Isaac, 1950, The effect of the interlayer cations on the expansion of the mica type crystal lattice: Am. Mineralogist, v. 35, p. 225-238.

Bradley, W. F., Grim, R. E., and Clark, W. L., 1937, A study of the behavior of montmorillonite upon wettings: Zeitschr. Kristallographie, Band 97, p. 216-222.

Byrne, P. J. S., 1955, Some observation on montmorillonite - organic complexes: Am. Geol. Inst., Geol. Abstracts, v. 1, no. 4, p. 30, (presented at Second National Clay Minerals Conference, 1953).

Cobban, W. A., 1951, Colorado shale of central and northwestern Montana and equivalent rocks of the Black Hills: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 2170-2198.

Cobban, W. A., and Reeside, J. B. Jr., 1951, Lower Cretaceous ammonites in Colorado, Wyoming, and Montana: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 1892-1893.

Collier, A. J., 1922, The Osage oil field, Weston County, Wyoming: U. S. Geol. Survey Bull. 736, p. 81-82.

Crowley, A. J., 1951, Possible Lower Cretaceous uplifting of Black Hills, Wyoming and South Dakota: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 83-90.

Darton, N. H., 1900, U. S. Geol. Survey, 21st Ann. Rept., pt. IV, p. 558.

————————, 1902, U. S. Geol. Survey Geol. Atlas (no. 85), Oelrichs folio, South Dakota - Nebraska, p. 1-6.

Darton, N. H., and O'Hara, C. C., 1905, U. S. Geol. Atlas (no. 128), Aladdin folio, Wyoming-South Dakota, p. 1-8.

————————————————, 1909, U. S. Geol. Atlas (no. 164), Belle Fourche folio, South Dakota, p. 1-9.

Dengo, Garbiel, 1946, Geology of bentonite deposits near Casper, Natrona County, Wyoming: Wyoming Geol. Survey Bull. no. 37, p. 1-28.

Dobbin, C. E., and Reeside, J. B. Jr., 1930, The contact of the Fox Hills and Lance formations: U. S. Geol. Survey Prof. Paper 158, p. 9-25.

Fenneman, N. M., 1931, Physiography of Western United States: McGraw-Hill Book Co. Inc., p. 1-534, map.

Fillman, Louise, 1929, Cenozoic history of the Black Hills: Iowa Univ. Studies in Nat. History, v. 8, no. 1, p. 21-56.

Foster, Helen L., 1947, Paleozoic and Mesozoic stratigraphy of northern Gros Ventre mountains and Mount Leidy highlands, Teton County, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1537-1593.

Foster, Margaret D., 1954, The relation between composition and swelling in clays: U. S. Geol. Survey, Open file report, p. 1-28, (presented at Third National Clay Minerals Conference, 1954).

Goldich, S. S., 1938, A study in rock-weathering: Jour. Geology, v. 46, p. 17-58.

Grace, R. M., 1952, Stratigraphy of the Newcastle formation, Black Hills Region, Wyoming and South Dakota: Wyoming Geol. Survey Bull. 44, p. 1-44.

Grim, R. E., and Rowland, R. A., 1944, Differential thermal analyses of clays and shales a control and prospecting method: Journ. Am. Ceram. Soc., v. 27, p. 65-76.

Gruner, J. W., 1940, Cristobalite in Bentonite: Am. Mineralogist, v. 25, p. 587-590.

Haentzschel, Walter, 1938, Bau und bildung von gross-rippeln im Wattenmeer: Senckenbergiana, Naturf. Gesell. Abh., 20, p. 1-42.

Heathman, J. A., 1939, Bentonite in Wyoming: Wyoming Geol. Survey Bull. 28, p. 1-20.

Hendricks, S. B. and Jefferson, M. E., Structures of kaolin and talc-pyrophyllite hydrates and their bearing on water sorption of the clays: Am. Mineralogist, v. 23, p. 863-875.

Hendricks, S. B., Nelson, R. A., and Alexander, L. T., 1940, Hydration mechanism of the clay mineral montmorillonite, saturated with various cations: Amer. Chem. Soc. Jour., v. 62, p. 1457-1464.

Hofmann, U., Endell, K., and Wilm D., 1933, Kristallstruktur and Quellung von Montmorillonit: Zeitschr. Kristallographie, band 86 (A), p. 340-347.

Hofmann, U., and Bilke, W., 1936, Uber die innerkristalline quellung und das basenaustauschvermogen des montmorillonits: Kolloid Zeitschr. Band 77, p. 239-251.

Kerr, P. F., and Kulp, J. L., 1949, Reference clay localities, United States: Am. Petrol Inst. Project 49, Clay Mineral Standards, Prelim. Rept. 2, p. 1-101.

Knaack, R. L., 1956, The origin of certain structures of the Minnekahta formation in the Whitewood region of the northern Black Hills unpublished thesis, Univ. of Iowa.

Knechtel, M. M., 1947, Association of colloidality with near-surface discoloration of bentonite in Black Hills district (abstract): Geol. Soc. America Bull., v. 58, p. 1201.

Knechtel, M. M., and Patterson, S. H., The northern Black Hills bentonite mining district: U. S. Geol. Survey, Min. Invest. Map (in preparation).

Knight, W. C., 1898, Bentonite: Engineering and Mining Jour., v. 66, p. 491.

Mackenzie, R. C., 1950, Some notes on the hydration of montmorillonite: Mineralogical Soc. Gr. Britain Clay Mineral Bull. 4, p. 115-120.

McKee, E. D., 1938, Original structures in Colorado River flood deposits of Grand Canyon: Jour. Sedimentary Petrology, v. 8, p. 77-83.

Mooney, R. W., Keenan, A. G., and Wood, L. A., 1952, Adsorption of water vapor by montmorillonite. II. Effect of exchangeable ions and lattice swelling as measured by x-ray diffraction: Am. Chem. Soc. Jour., v. 74, p. 1371-1374.

Moore, R. C., 1949, Meaning of facies, in Longwell, C. R., chm., Sedimentary facies in geologic history (symposium): Geol. Soc. Am. Mem. 39, p. 1-34.

Petsch, B. C., 1949, North part of the Whitewood anticline: South Dakota Geol. Survey Rept. Inv. 63, p. 1-30.

Reeside, J. B. Jr., 1944, Maps showing thicknesses and general character of the Cretaceous deposits in the western interior of the United States: U. S. Geol. Survey Prelim. Map 10, Oil and Gas Inv. Ser.

Rich, J. L., 1948, Submarine sedimentary features on Bahama Banks and their bearing on distribution patterns of lenticular oil sand: Am. Assoc. Petroleum Geologists Bull., vol. 32, p. 767-779.

————, 1951, Three critical environments of deposition and criteria for recognition of rocks deposited in each of them: Bull. Geol. Soc. Am. v. 66, p. 9.

Ross, C. S., 1928, Altered Paleozoic volcanic materials and their recognition: Am. Assoc. Petroleum Geologists Bull., v. 12, p. 143-164.

Ross, C. S., and Hendricks, S. B., 1945, Mineral of the montmorillonite group, their origin and relation to soils and clays: U. S. Geol. Survey Prof. Paper 205-B, p. 23-79.

Ross, C. S., and Shannon, E. V., 1926, Minerals of bentonite and related clays and their physical properties: Am. Ceram. Soc. Jour., v. 9, p. 77-96.

Roth, R. S., 1951, The structure of montmorillonite in relation to the occurrence and properties of certain bentonites: Unpublished thesis, Univ. of Illinois, p. 1-80.

Rubey, W. W., 1929, Origin of the siliceous Mowry shale of the Black Hills Region: U. S. Geol. Survey Prof. Paper 145 D, p. 153-170.

——————, 1930, Lithologic studies of the fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: U. S. Geol. Survey Prof. Paper 165, p. 1-54.

Russell, W. L., 1927, The origin of the sandstone dikes of the Black Hills Region: Am. Jour. Sci. 5th ser., v. 14, p. 402-408.

Wing, M. E., 1940, Bentonites of the Belle Fourche district, South Dakota: South Dakota Geol. Survey, Rept. Inv. 35, p. 1-29.

2 pieces in pocket