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# Petrology of the Sentinel Butte Formation (Paleocene), North Dakota

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# PETROLOGY OF THE SENTINEL BUTTE FORMATION (PALEOCENE), NORTH DAKOTA

by

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Bachelor of Science, University of North Dakota, 1974
Master of Science, University of Houston, 1978

A Dissertation

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for the degree of

Doctor of Philosophy

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This Dissertation submitted by Nels F. Forsman in partial fullfillment of the requirements for the degree of Doctor of Philosophy from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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This Dissertation meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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# ABSTRACT

Sedimentary materials of the Sentinel Butte Formation have been petrographically examined using optical and scanning electron microscope/microprobe techniques. The formation consists of fine-grained materials which generally are classified mineralogically as volcanic litharenites or feldspathic litharenites. Most rock units in the formation are siltstones and mudstones. Multiple source rock types, including volcanic, metamorphic, and sedimentary, are represented by mineralogic constituents, but volcanic rock fragments are most abundant. Petrographic distinctions between basal and uppermost sandstone units suggest that a change in sediment supply took place near the end of Sentinel Butte time. Authigenic cement development appears concentrated in more porous and permeable sandstone units. A general pattern of cement development is suggested; pore-lining montmorillonite precipitation preceded pore-filling zeolite development, which was followed by calcite or dolomite growth.

A widespread volcanic ash and bentonite unit in the formation indicates that volcanism accompanied Paleocene sedimentation and that volcanic glass can be preserved for longer periods of geologic time than commonly thought possible. The manner of preservation of the bentonite/ash unit makes it ideally suited for testing the usefulness of chemical-correlation procedures for bentonites developed in terrestrial settings. Petrographic comparison of the Sentinel Butte bentonite/ash with other claystone units may yet reveal the presence of other bentonites in Paleocene strata. Chemical correlation of newly discovered bentonites may lead to an improved understanding of the time-stratigraphic framework of the Fort Union Group.

Sodium montmorillonite is the most abundant clay mineral in the formation. Other clay minerals, including kaolinite and illite, are minor. Detrital and authigenic montmorillonite appears to be distinguishable on the basis of discriminant analysis of major element composition. Comparisons of lignitic samples suggest that lignite precursor material representing various stages of coalification is present in the formation. Similar characterization studies of other Fort Union Group rocks eventually may lead to the determination of petrofacies and sediment dispersal patterns.

# INTRODUCTION

## General Statement

Paleocene sedimentary materials in the Williston Basin were derived from source regions uplifted and eroded during the Late Cretaceous to Early Eocene Laramide orogeny. Because rocks of Laramide structural highs have been greatly removed by processes of erosion, we must examine the sediments shed from those highs to reconstruct certain aspects of the orogeny itself. Distally deposited sediments, such as those occurring in the Sentinel Butte Formation, do not lend themselves to convenient petrologic examination and interpretation due to both a fineness of grain sizes and a tendency toward dispersal and admixture of sediment from several source terranes. Nonetheless, study of distal deposits such as those of the Sentinel Butte can provide useful information for the eventual reconstruction of Early Tertiary geologic events.

## Purpose

This study is intended to improve our knowledge of the natural history of Sentinel Butte rocks through a specific examination of the materials comprising those rocks. Characterization of materials using optical, scanning electron microscope, and microprobe techniques is the primary purpose of this study. A major goal is to discover which descriptive procedures and techniques are most valuable for the eventual comparison of Early Tertiary sediments in the Western Interior. It is through such comparisons that sediment dispersal patterns, petrographic and geochemical "facies", and source terrane reconstructions might eventually be determined.

More specific questions which might be answered through the use of descriptive data are also considered in this study. These include:

1) What are the primary petrographic characteristics of Sentinel Butte rocks and sediments and what do these characteristics reveal about provenance?

2) What are the secondary (diagenetic) characteristics of Sentinel Butte rocks?

3) How significant was volcanic airfall activity in supplying material to the Sentinel Butte Formation?

4) How can a distinction be made between detrital and authigenic clay minerals in the Sentinel Butte Formation?

## Geologic Setting and General Geology

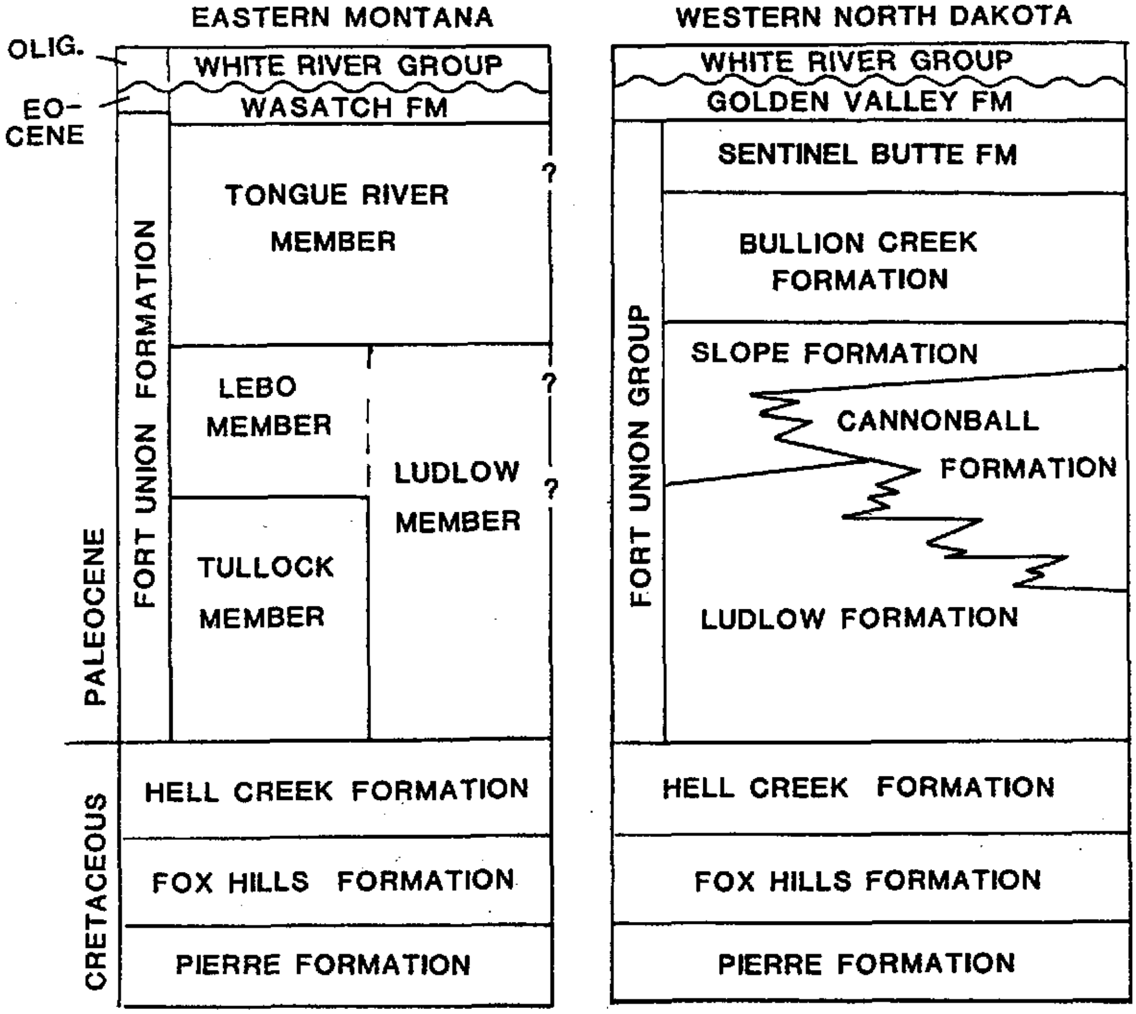
The Sentinel Butte Formation is exposed over much of the western third of North Dakota (Clayton et al., 1980). It is exposed at the surface along portions of stream valleys (e.g., the Knife River valley and Little Knife River valley), on buttes where mass wasting has removed a soil cover, and along the banks of Lake Sakakawea and westward along the Missouri River. The most abundant exposures are found within the broad expanse of badlands terrain on either side of the northward-flowing Little Missouri River. Exposures of lower portions of the formation are abundant but upper portions of the formation have been widely removed by erosion and can be observed only at relatively few localities.

The Sentinel Butte Formation occurs today within central portions of the Williston Basin; the stratigraphic position is shown in Figure

1. Its Late Paleocene age is assigned primarily from paleobotanical evidence (Brown, 1948). Precise correlation of Sentinel Butte rocks with formations in eastern Montana and northeastern Wyoming is problematic. Color and outcrop weathering characteristics are of use in recognizing the Sentinel Butte Formation where exposures are fairly continuous (Jacob, 1975), but these criteria alone become less useful where visual correlation is not possible. The Sentinel Butte Formation is informally recognized in eastern Montana near Sidney, and rocks equivalent to those of the Sentinel Butte Formation perhaps occur in the Powder River Basin of northeastern Wyoming (Ed Murphy, NDGS, personal communication, 1984). But other rocks, such as portions of the Tongue River in Montana, may be equivalent to the Sentinel Butte Formation in age, provenance, or both. A recognition of the temporal relations between Fort Union rock units can provide a framework within which to interpret sedimentologic data, decipher petrofacies patterns, and reconstruct the unroofing and erosion of Laramide structural highs.

Sentinel Butte sediments were deposited under low-energy alluvial conditions characterized by broad lignite-forming swamps, lakes, and high-sinuosity stream and associated floodplain systems. Royse (1970, 1972) interpreted the Sentinel Butte Formation to represent primarily fluvial channel, floodbasin, and backswamp environments. He suggested that there were two main pulses of Laramide tectonism leading to an influx of sand at the beginning and again near the end of Sentinel Butte time. He also suggested that the fluvial systems followed the path of the postulated retreating Cannonball Sea, but did not specify deltaic or other depositional models. Jacob (1972, 1973, 1976) interpreted the Sentinel Butte Formation to represent the landward portions of a delta

Figure 1. Generalized geologic column of surface rocks in western North Dakota and eastern Montana.



(S. Vuke, MBM, map in preparation)

(Clayton et al., 1977)

plain, but proximal relations to a possibly regressing Cannonball Sea have not been clearly documented. Other earlier studies generally agreed with the environmental conclusions of Royse or Jacob. Winczewski (1982) suggested that environmental patterns (near-channel and backswamp) can be recognized and related to structurally controlled diversions of a Powder River Basin drainage system. Environmental reconstruction of Fort Union rocks continues to be a challenging concern for geologists.

## Previous Work

Previous studies of petrologic aspects of Sentinel Butte rocks were conducted primarily using megascopic examination and polarized light microscopy. Most previous workers did not have access to a scanning electron microscope or microprobe system. It is the availability of such equipment that has led to much of the new information that is presented in this study. The petrographic observations of previous workers are summarized below.

Tisdale (1941) did not examine the Sentinel Butte Formation, but did conduct some of the earliest petrographic work on Fort Union strata in North Dakota. He provided descriptions of basal Fort Union light and heavy minerals and suggested multiple sources, perhaps multiple cycles, but probably dominantly metamorphic source terranes "not very far removed" from the depositional site. He cautioned that much more work would be required before provenance interpretations could be made with assurance.

Sigsby (1966) examined samples from one section in the south unit of Theodore Roosevelt National Park, taken from 2-1/2 feet intervals upward a distance of 44 feet from the top of the HT Butte lignite, which marks the boundary between Bullion Creek and Sentinel Butte strata. His petrographic examination of light minerals from sand size fractions showed quartz to be the dominant mineral, and plagioclase to be "surprisingly abundant". He found only minor potassic feldspar. He wrote that the freshness and angularity of most grains, particularly the feldspars, suggests a volcanic origin with either "limited or eolian transport". His examination of heavy minerals led him to agree with Tisdale (1941) that a metamorphic source was indicated.

Crawford (1967) examined the sand fraction of Sentinel Butte samples and found quartz, both potassic and plagioclase feldspar, and biotite to be unaltered. He also examined heavy mineral assemblages of ten sandstones and suggested that the type and character of grains in both the light and heavy mineral fractions are indicative of a relatively close metamorphic source terrane perhaps with associated granites. Crawford felt his evidence for such a determination of source terrane to be inconclusive, however, and suggested the need for more detailed work.

Royse (1967) evaluated the data of previous workers and concluded that the minor assemblage of metamorphic heavy minerals in Tongue River (now Bullion Creek in North Dakota) and Sentinel Butte samples is probably residual and should not be viewed as evidence in support of a primary metamorphic source for any portion of the Tongue River-Sentinel Butte sequence. He concluded that light mineral suites qualitatively suggest that Sentinel Butte sediments are less mature than Tongue River sediments.

Kulland (1975) examined 30 sand samples from lignite mine sites and determined that plagioclase is more abundant than potassic feldspar, and that rock fragments are dominantly sedimentary. He found that igneous rock fragments are nearly exclusively volcanic, and that metamorphic rock fragments are represented by subrounded grains of mica schist.

Jacob (1975) examined Tongue River and Sentinel Butte samples in an attempt to find petrographic distinctions between the two formations. He determined that all sandstone samples are litharenites and that many sandstones of the Sentinel Butte Formation are volcanic arenites (after Folk, 1974). He interpreted the heavy mineral assemblages as suggesting removal of sedimentary cover from metamorphic source terrane between Tongue River and Sentinel Butte time.

Steiner (1978) examined sandstones from both the Bullion Creek and Sentinel Butte Formations at 13 localities. He reported quartz and plagioclase to be the dominant minerals present in the Sentinel Butte Formation. He noted the fresh, normally unaltered character of plagioclase. Lithic varieties, in order of decreasing abundance, were reported to include chert, plutonic and metamorphic, sedimentary, and volcanic. He reported an apparent inverse relationship between quartz/feldspar ratios and sand grain size. He agreed with Royse (1967) that the Sentinel Butte Formation appears less mature mineralogically than the underlying Bullion Creek Formation.

Nesemeier (1981) examined several Sentinel Butte sandstones and found quartz to be the dominant constituent, with plagioclase much more common than potassic feldspar. He determined that chert is the dominant type of rock fragment and that other varieties make up less than two percent. He found carbonate cement in all samples and suggested that all carbonate grains present are probably cement rather than detrital carbonate components. Nesemeier examined 15 clay samples by x-ray diffraction and concluded that only four clay minerals were present, including in decreasing order of abundance, montmorillonite, mica, kaolinite, and chlorite.

Jacob (1975) concluded that differences in clay mineralogy between Tongue River and Sentinel Butte samples can be seen on an x-ray diffractogram at a glance. Brekke (1979) tested Jacob's suggestion by examining 35 clay samples from three measured sections. He found that the same types and relative amounts of clay minerals occur in both formations. Brekke found that sodium montmorillonite, mica/illite, chlorite, and minor kaolinite comprise the <2 µm clay fraction, with mica-illite and chlorite appearing to vary inversely with the amount of montmorillonite detected.

The question of the significance of volcanic airfall activity in supplying material to the Sentinel Butte Formation has led, in this study, to a special examination of a known bentonite unit in the formation. Previous workers have held various views regarding this claystone deposit and it is only recently that it has been shown to be a true bentonite.

Early workers noted that many Sentinel Butte claystones present a rough weathered surface apparently formed by the wetting and drying of swelling clay minerals. A particularly noticeable claystone in and near the North Unit of Theodore Roosevelt National Park was noticed to cap wide benches and to often locally drape many feet over the edge of the bench, partially covering the underlying strata (Fisher, 1953; Meldahl, 1956). Such characteristics suggested to early workers that this claystone and others might be bentonites, formed through the alteration of volcanic ash (Fisher, 1953; Hanson, 1955).

Subsequent workers have either accepted (Clark, 1966; Metzger, 1969) or questioned (Meldahl, 1956; Hickey, 1977) a volcanic origin for the prominent bench forming claystone variously referred to as the Big Blue bed, the blue bed, or simply the bentonite. Meldahl (1956) was apparently the first to look for petrographic evidence of a volcanic origin for this claystone. He searched for, but found no shards of volcanic glass in the samples he examined. This led him to suggest that the origin of the "bentonite" might be somehow related to that of lignite, which he suggested usually occurs in close proximity to the claystone. Based on Meldahl's observations, Hickey (1977) suggested that the Sentinel Butte bentonite may have formed without the involvement of volcanic debris through a reaction between cations and colloids trapped together in poorly drained swamps.

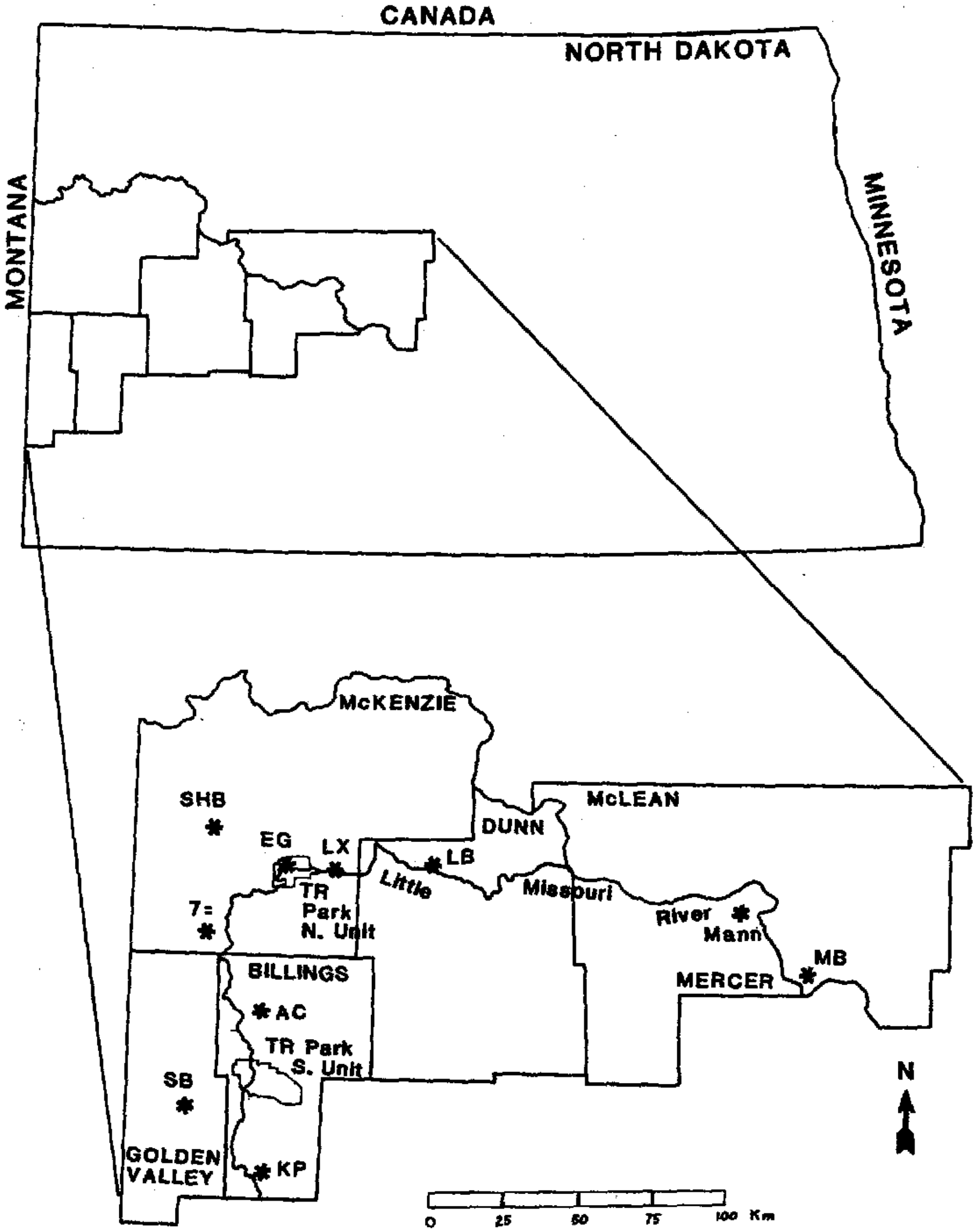
Clark (1966) reported the presence of glass shards in the prominent Sentinel Butte bentonite as well as throughout much of the Sentinel Butte sequence. However, his description of so-called glass shards and his comment regarding their abundance throughout the formation lead one to seriously question his identification of this material (see page ~~78~~ 102). Forsman and Karner (1975) were the first to document the presence of glass shards in the Sentinel Butte bentonite.

# Methods

## Field Sampling

A randomized sampling plan was implemented to eliminate bias in the selection of samples for this study. Sampling sites were chosen from a randomly generated list of township, range, and section numbers for western North Dakota. The first ten locations in which surface exposures of the Sentinel Butte Formation occur were selected for field sampling (Fig. 2). In the field, sampling sites were chosen as close to the center of geographic sections as practicable. A random number list with numbers between 5 and 15 was used in the field to determine the height of the first sample and subsequent vertical spacings between samples to be taken from measured sections. The choice of this footage bracket was based on an estimate of expected lithologic unit thicknesses and average section thickness. It was desired that approximately ten samples from each of ten sections comprise the core of this study. In so far as they could be determined, only single sedimentation units were sampled. Additional samples of many lignites, sandstones, and so-called marker beds, were chosen non-randomly and labeled accordingly. Altogether 192 samples, 81 random and 111 nonrandom, were collected for this study. Measured section descriptions were designed specifically to locate random samples and are provided in Appendix A. Information regarding field characteristics and locations of non-random samples is also provided in Appendix A.

Figure 2. Map showing locations of sections measured and sampled in this study. Section abbreviations explained in Appendix A.


CANADA
NORTH DAKOTA
MONTANA
MINNESOTA
McKENZIE
McLEAN
DUNN
SHB
EG
LX
LB
Little
Missouri
River
TR Park N. Unit
7=
Mann
MB
MERCER
BILLINGS
AC
TR Park S. Unit
SB
GOLDEN VALLEY
KP
N
0
25
50
75
100 Km

## Laboratory Treatment

Thin sections were prepared from all indurated samples, using epoxy impregnation in most cases. Oil was used in place of water in sandstone thin sections so that clays might be retained. Cover slips were not mounted so that thin sections could be examined by scanning electron microscopy (SEM) and electron microprobe analysis (EMA). Nearly all samples were easily disaggregated by simple soaking in water, enabling sand:silt:clay determinations to be made by pipette procedures. Sand (>63 µm), silt (10-63 µm), and <2 µm clay fractions were retained separately for each sample. The methods used in obtaining grain size data and separated size fractions are reported in Appendix B. Sand, silt, and clay percentage data for each sample are provided in Appendix C. Grain thin sections were prepared of sand-size grains from all samples found to have a >10 % sand content. Silt fractions were found to be too fine grained for useful optical microscope examinations. Both sand and silt grains were examined by SEM/EMA. Both untreated grains, brushed from their host rocks, and grains washed during the disaggregation and size fractionation process were observed by SEM. Undisturbed rock pieces were also examined by SEM but normally were found to provide less information than that gained from separated mineral grains.

## Analytical Procedures

Scanning electron microscope and electron microprobe examinations were carried out using a JEOL 35C microscope equipped with a KEVEX energy dispersive detector and a Tracor Northern TN-2000 x-ray analyzer. Quantitative data obtained by microprobe analysis were adjusted for electronic drift and processed using a Tracor Northern XML fitting program and the matrix correction program of Bence and Albee (1968).

Clay minerals were identified using standard x-ray diffraction (XRD) techniques using oriented clay mounts normally both air dried and subjected to ethylene glycol solvation. Heat treatment of x-ray samples was found to be unnecessary for Sentinel Butte clay mineral identifications. Examinations by XRD were carried out using a Philips-Norelco diffractometer with Cu-$K_\alpha$ radiation.

Whole rock major element composition of selected samples was determined by x-ray fluorescence (XRF), using pressed-powder pellets and a Rigaku S/MAX wavelength-dispersive system with CRISS fundamental alpha data-reduction programs. Trace element data were obtained by neutron activation analysis (NAA) contracted to the Nuclear Engineering Department of North Carolina State University (Weaver, 1978).

Point-count data from sand and silt fractions were obtained using combined optical and SEM/EMA techniques (see pages 22 and 34). Other, special techniques used in the examination of Sentinel Butte materials are reported in the relevant sections that follow.

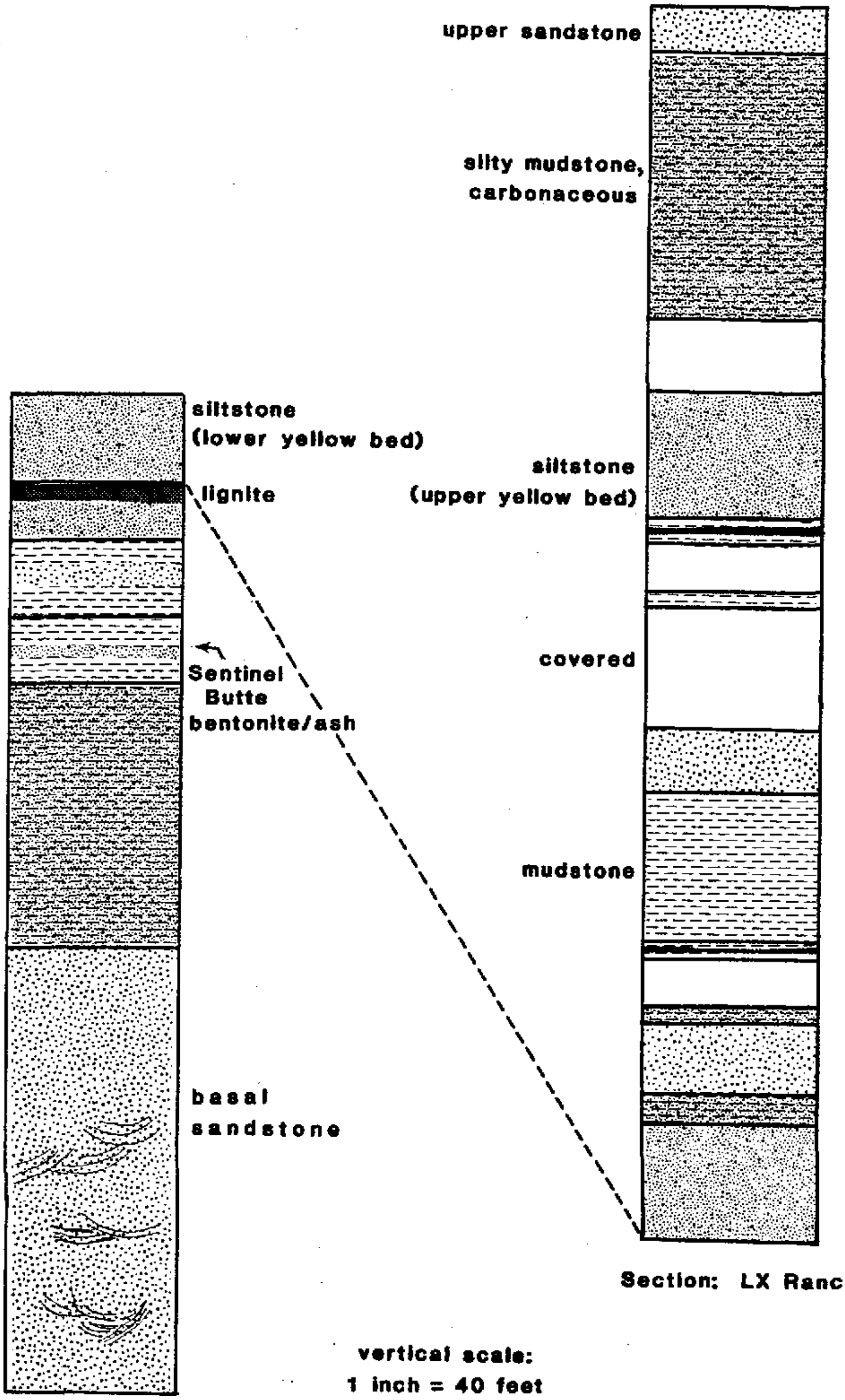
## ROCK TYPES

The Sentinel Butte Formation is composed predominantly of five rock types: sandstones, siltstones, mudstones, claystones, and lignites. Using standard sediment grain size classification schemes (Folk, 1974) and the sand:silt:clay percentage data given in Appendix C, the proportions of various rock types collected for the core of randomly selected samples are summarized in Table 1. Because of the random sampling, the rock type proportions shown in Table 1 are probably fairly representative of the formation as a whole. The values show the formation to be fine grained, with siltstones and mudstones most common. A generalized composite lithologic section, drawn using the data of Appendix A, is provided in Figure 3. Sentinel Butte rocks are commonly only slightly lithified. Relatively few Sentinel Butte rocks are well indurated, but some resistant sandstone bodies do occur. Because most Sentinel Butte materials have undergone and show effects of lithifying processes other than just simple compaction, use of the term "rocks" rather than "sediment" is suggested for most Sentinel Butte materials. Lithifying processes and effects are discussed further below, under "Authigenic Constituents" and "Diagenesis".

Table 1. Rock Types Collected from the Sentinel Butte Formation

| Sandstones | Siltstones | Mudstones | Claystones | Lignites |
|---|---|---|---|---|
| 9(11%) | 35(43%) | 24(30%) | 7(9%) | 6(7%) |

Figure 3. Generalized composite lithologic section of the Sentinel Butte Formation. Drawn using data of Appendix A.



Section: LX Ranch

vertical scale:
1 inch = 40 feet

Section: Edge of a glacier

Sentinel Butte carbonaceous rocks vary greatly in their resemblance to lignites. That is, a range of lignite physical qualities is seen between samples collected in this study. Some samples resemble non-coalified compressed plant remains. The possibility exists that a complete range of pre-lignitic to lignite samples is available in the Sentinel Butte Formation. A further discussion of this possibility follows on pages 117 through 122. Most lignites encountered are only a few centimeters to a meter thick. Most contacts of lignites with underlying sediments are gradational, with carbonaceous matter increasing upward. However, lignites directly overlying clean sand units were also encountered.

Several visually distinct units occur in the Sentinel Butte Formation and have been used by various workers as marker beds. These units are not present at all localities, and hence have only limited correlation value; however, they are very useful as reference horizons where they do occur. From the base upward, these beds include: 1) a basal sandstone, 2) the Sentinel Butte bentonite/ash (previously called the blue bed), 3) a lower yellow bed, 4) an upper yellow bed, and 5) an upper sandstone (Fig. 3). Brief descriptions of these units are given below.

The basal sandstone unit was recognized and mapped as an indicator of the Bullion Creek-Sentinel Butte contact by Royse (1967). The unit is characterized by its gray color, rilled weathering pattern, locally great thickness (up to 30 m), large-scale trough cross bedding and ripple bedding, ledge-like iron-stained or iron-cemented concretions, small concretionary nodules, and large spherical and log-shaped concretions. The unit is continuous over large areas at various localities, but mudstone deposits occur at this statigraphic level over perhaps equally large areas. It remains unclear what the actual geographic pattern of basal sand occurrence is and what type of depositional system it represents. The unit is deserving of individual study in that it probably represents renewed tectonism at the end of Bullion Creek time, a major change in fluvial drainage patterns, or both.

The Sentinel Butte bentonite/ash is discussed in detail on pages 82 through 97. It is probably an excellent true marker bed in a chronostratigraphic sense. It contains two distinctive bench-forming blue-gray to black clay units commonly easily visible from a large distance. The entire unit is normally 3.7 to 5.5 m thick.

The lower yellow bed is a distinctive, yellow, fine siltstone unit additionally characterized by ripple bedding, root pathways, and a near total absence of clay. The unit is often divided into a lower friable portion and a higher weakly lithified portion. Its uppermost portion (1/3 m) is often white instead of yellow. The lower yellow bed seems to have a broader geographic range than the easily recognizable Sentinel Butte bentonite/ash. It often occurs approximately 4.5 m above the bentonite/ash deposit, but appears further above that same isochronous layer at other locations.

The upper yellow bed appears similar in most respects to the lower yellow bed. It has been spared from removal by erosion at few localities and has not been extensively examined in this study.

The upper sandstone is a well-indurated, medium-grained, brown sandstone which is only locally exposed where uppermost Sentinel Butte strata have been preserved from erosion. The precise stratigraphic position of the upper sandstone is difficult to determine because it normally is the uppermost exposed unit where it occurs. Royse (1967) explained that, "Its proximity to the top of the Sentinel Butte section is assured north of Lost Bridge and near Grassy Butte where Eocene beds of the Golden Valley occur nearby." Royse briefly discussed the geologic significance of the upper sandstone and this report provides additional information that supports his evaluation.

The remainder of the formation consists largely of poorly sorted mudstone, siltstone, claystone, and carbonaceous units. Close inspection of mudstone units shows that they normally are bedded on a varying scale of millimeters to meters, with indistinct, small-scale size grading throughout. Iron-oxide staining along sub-horizontal planes adds further visual complexity to these units.

# PETROGRAPHY AND CLASSIFICATION

## Detrital Constituents

Petrographic examination by optical microscopy was carried out primarily using grain thin sections of sand grains. Standard whole-rock thin sections are often more informative, in that grain-to-grain relationships provide information regarding diagenesis. However, relatively few Sentinel Butte rocks are coarse grained enough to provide useful whole-rock thin sections. The basal sandstone, at some locations, consists largely of fine-sand-size grains, and the upper sandstone, where sampled, consists of medium-sand-size grains, but most sandstones consist primarily of very-fine-sand size grains. Additional examinations of both sand and silt grains were carried out by SEM/EMA.

As mentioned above, only 9 of the randomly collected samples are classifiable as sandstones if a criterion of >50 % sand-size grains is used (Folk, 1974). Because thin sections of silt-size grains are difficult to interpret, sand grain thin sections of all samples containing >10 % sand size grains were prepared and used for point counting. Samples classified as siltstones (<50 % sand and >2:1 silt:clay) were point counted using an SEM/EMA technique; grains sprinkled on tape were identified by chemical composition and counted as they crossed the center of the viewing screen during a unidirectional traverse across the mounting stub. Results of 200-grain point counts of detrital constituents of Sentinel Butte sands and silts are given in Table 2. Petrographic descriptions of individual constituents of Sentinel Butte samples are provided in the remainder of this section. The descriptions are summarized in Table 3.

Table 2. Results of 200-Grain Point Counts of Sentinel Butte Sands and Silts

| Sample | Q | K-Feld | Plag | Bio | Musc | C/D | VRF | MRF-S | MRF-PQ | PQ-UNK | SRF | PRF | URF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAND-SIZE GRAINS | | | | | | data in percent | | | | | | | |
| EG-1 | 29 | 5 | 20 | 1 | 1 | 1 | 20 | — | 1 | 6 | — | 1 | 15 |
| EG-17 | 18 | 3 | 18 | 0 | 2 | 12 | 14 | 1 | 0 | 5 | 1 | 2 | 24 |
| SB-12 | 29 | 4 | 9 | 1 | 0 | 13 | 14 | — | — | — | — | — | 30 |
| SB-17 | 13 | 4 | 1 | 0 | 2 | 38 | 5 | — | — | — | — | — | 37 |
| SB-18 | 36 | 1 | 1 | 1 | 1 | 0 | 12 | — | — | — | — | — | 48 |
| SB-21 | 24 | 8 | 7 | 9 | 2 | 21 | — | — | — | — | — | — | 29 |
| SB-25 | 36 | 3 | 16 | 0 | 0 | 5 | 5 | — | — | 1 | — | — | 34 |
| 7=1 | 26 | 4 | 7 | 2 | 0 | 15 | 6 | — | — | — | — | — | 40 |
| 7=G | 30 | 5 | 23 | 0 | 0 | 1 | 25 | — | — | — | — | 2 | 14 |
| LB-8 | 27 | 9 | 3 | 0 | 2 | 0 | 6 | 2 | — | — | — | — | 51 |
| SHB-3 | 30 | 8 | 12 | 0 | 0 | 10 | 13 | — | — | — | — | — | 27 |
| SHB-7 | 23 | 3 | 19 | 0 | 0 | 4 | 35 | — | — | — | — | — | 16 |
| LX-3 | 29 | 6 | 7 | 1 | 0 | 15 | 3 | — | — | — | — | — | 39 |
| LX-M | 10 | 1 | 7 | 0 | 0 | 57 | 4 | 3 | 3 | 4 | 1 | 2 | 8 |
| Mann-5 | 13 | 5 | 10 | 1 | 1 | 18 | 9 | 1 | 2 | — | — | — | 40 |
| Mann-7 | 20 | 6 | 13 | 0 | 0 | 11 | 11 | 2 | — | — | 1 | — | 36 |
| AC-6 | 21 | 4 | 7 | 1 | 0 | 23 | 5 | — | — | 3 | — | 1 | 35 |
| AC-9 | 42 | 7 | 3 | 0 | 0 | 11 | 2 | — | — | — | — | — | 35 |
| MB-8 | 27 | 7 | 0 | 0 | 1 | 35 | 4 | — | — | — | — | — | 26 |
| SQB-A | 33 | 6 | 7 | 0 | 1 | 5 | 5 | — | — | — | 1 | 2 | 40 |
| BR-A | 34 | 6 | 16 | 0 | 0 | 2 | 5 | 2 | — | 2 | — | 3 | 30 |
| SU-B | 43 | 7 | 4 | 0 | 2 | 4 | 10 | — | — | 2 | — | — | 28 |
| SILT-SIZE GRAINS | | | | | | | | | | | | | |
| 7=9 | 31 | 10 | 7 | 7 | 14 | 15 | — | — | — | — | — | — | 16 |
| LB-14 | 31 | 7 | 10 | 6 | 13 | 17 | — | — | — | — | — | — | 16 |
| SHB-1 | 41 | 7 | 3 | 0 | 6 | 0 | — | — | — | — | — | — | 43 |
| KP-4 | 29 | 6 | 12 | 10 | 10 | 14 | — | — | — | — | — | — | 19 |
| SHB-5 | 20 | 8 | 19 | 4 | 12 | 22 | — | — | — | — | — | — | 15 |
| MB-5 | 39 | 7 | 15 | 3 | 13 | 0 | — | — | — | — | — | — | 23 |
| MB-2 | 37 | 9 | 10 | 14 | 11 | 3 | — | — | — | — | — | — | 16 |
| LB-7 | 30 | 7 | 9 | 12 | 12 | 18 | — | — | — | — | — | — | 12 |
| LX-9 | 30 | 10 | 6 | 11 | 10 | 21 | — | — | — | — | — | — | 12 |
| LB-9 | 28 | 6 | 12 | 3 | 12 | 18 | — | — | — | — | — | — | 21 |
| LX-15 | 40 | 4 | 9 | 3 | 6 | 24 | — | — | — | — | — | — | 14 |
| SHB-3 | 30 | 12 | 6 | 6 | 6 | 14 | — | — | — | — | — | — | 26 |
| 7=7 | 24 | 4 | 12 | 17 | 19 | 8 | — | — | — | — | — | — | 16 |
| SHB-9 | 20 | 4 | 4 | 4 | 6 | 25 | — | — | — | — | — | — | 37 |
| Mann-1 | 16 | 2 | 5 | 12 | 21 | 19 | — | — | — | — | — | — | 25 |
| Mann-3 | 23 | 4 | 13 | 9 | 7 | 0 | — | — | — | — | — | — | 44 |
| KP-6 | 15 | 4 | 4 | 13 | 36 | 21 | — | — | — | — | — | — | 7 |

abbreviations: Q=quartz, K-feld=potassic feldspar, Plag=plagioclase, Bio=biotite, Musc=muscovite, MRF-S=schistose metamorphic rock fragments, MRF-PQ=polycrystalline quartz (metamorphic), PQ-UNK=polycrystalline quartz (unknown derivation), SRF=sedimentary rock fragments, PRF=plutonic rock fragments, URF=unknown rock fragments, —=not determined, RF=rock fragments

Sand

Table 3. Summary of Descriptive Characteristics of Constituents of Sentinel Butte Formation.

| Constituent | Occurrence, Characteristics |
|---|---|
| Quartz<br>10-43%<br>avg: 27% | Angular, normally with no abrasion-produced surface roughness. Some grains are second-cycle. |
| K-Feldspar<br>1-12%<br>avg: 6% | Angular, normally unaltered, but some show evidence of incongruent dissolution. |
| Plagioclase<br>0-23%<br>avg: 9% | Angular, normally unaltered, but some show evidence of incongruent dissolution. Most intermediate (andesine-oligoclase), some more sodic. Calcic varieties not detected. |
| Biotite<br>Muscovite<br>0-36%<br>avg: 5% | Minor in some samples. Formation, as a whole, is fairly mica-rich. Muscovite and biotite subequal, but only muscovite detected in the upper sandstone. Grains commonly larger than other detrital minerals in given sample. |
| Calcite<br>Dolomite<br>0-57%<br>avg: 14% | Most, if not all, is probably secondary. Commonly occurs as pore-filling cement, but locally has replaced detrital grains. Both calcite and dolomite occur in some samples. |
| Rock Fragments<br>7-60%<br>avg: 34% | Difficult to classify because of fine grain size. Volcanic types predominate. Metamorphic and sedimentary fragments also present. Some volcanic fragments resemble sedimentary fragments. Metamorphic types increase in upper sandstone. |
| Zeolites | Minor in formation as a whole, but locally abundant. Include members of heulandite group and analcime. Occur as pore-filling authigenic crystals postdating pore-lining montmorillonite development. |
| Montmorillonite | Common as authigenic pore-lining cement in nearly all sandstones and many siltstones. |
| Kaolinite | Occurs as booklets commonly altered from micas, feldspars, and rock fragments. Some may be detrital. |
| Opal, Cristobalite, Gypsum, Barite, Pyrite, Iron Oxides | Uncommon but locally present as authigenic species. |

## Rock Fragments

Rock fragments, because of fine grain size or alteration, were normally difficult to classify. Volcanic rock fragments greatly dominate the identifiable types of rock fragments present in each sample, but the number of unidentifiable rock fragments in some samples is so large as to make even comparative estimates of volcanic versus nonvolcanic rock fragments meaningless. Only rock fragments in the coarsest sandstones were classified with any degree of confidence. Most sand fractions examined were too fine grained for adequate rock fragment classifications to be determined. Many volcanic rock fragments are altered, making distinctions between them and possible mudstone fragments and some low rank metamorphic rock fragments questionable.

A specialized examination of recognizable volcanic rock fragments was conducted to determine the composition of both phenocrysts and groundmass as a step toward interpreting the type of volcanic terrane(s) contributing to Sentinel Butte materials. Rock fragments from both the basal sandstone and upper sandstone were compared to detect possible differences in the provenance of these two units. Grains in thin section to be analyzed by the SEM/EMA system were first located and given cartesian coordinates using a petrographic microscope and mechanical stage. A reference mark was placed on the thin section using dry transfer lettering and the coordinates were referred to this mark by simply counting mechanical stage click stops accordingly. It was then a straightforward matter to convert mechanical stage click stops to degrees of X,Y stage control rotation on the scanning electron microscope.

The results of microprobe analyses are provided in Appendix D. The composition of phenocrysts is summarized in Figure 4. The groundmass of individual rock fragments is commonly altered, making assessments of original chemical character difficult. Some apparently unaltered groundmasses revealed either intermediate (oligoclase-andesine) or more alkalic compositions. Albite is the dominant phenocryst in the examined volcanic rock fragments from the upper sandstone, while plagioclase phenocrysts from the examined basal sandstone rock fragments range in composition from Ab 39.5 to Ab 56.5 (labradorite to oligoclase). The more calcic data ~~is~~ are not consistent with intermediate to felsic volcanic source terrane(s). Although only a small number of phenocrysts were examined, it seems possible that source material available for eventual accumulation as the upper sandstone may have differed from that available for the basal sandstone.

Figure 5 gives examples of Sentinel Butte rock fragment appearances. Volcanic rock fragments vary greatly in appearance, but are commonly recognized by the presence of feldspar laths or subequant phenocrysts in a more felsitic or altered groundmass (Fig. 5a,b). Metamorphic rock fragments are fairly minor constituents except in the uppermost Sentinel Butte sandstone. Metamorphic rock fragments present are generally slaty, phyllitic, or schistose (Fig. 5f), but sheared, composite quartz grains also occur (Fig. 5e). Polycrystalline quartz grains of metamorphic derivation were identified using criteria outlined by Blatt (1967). All polycrystalline quartz grains not determined to be metamorphic were counted as polycrystalline quartz rock fragments of unknown derivation. Sedimentary rock fragments in the Sentinel Butte samples are extremely difficult to distinguish from those of volcanic origin. Many altered volcanic rock fragments resemble siltstone or

Figure 4. Ternary composition of feldspar phenocrysts in Sentinel Butte volcanic rock fragments. + = upper sandstone, o = basal sandstone.

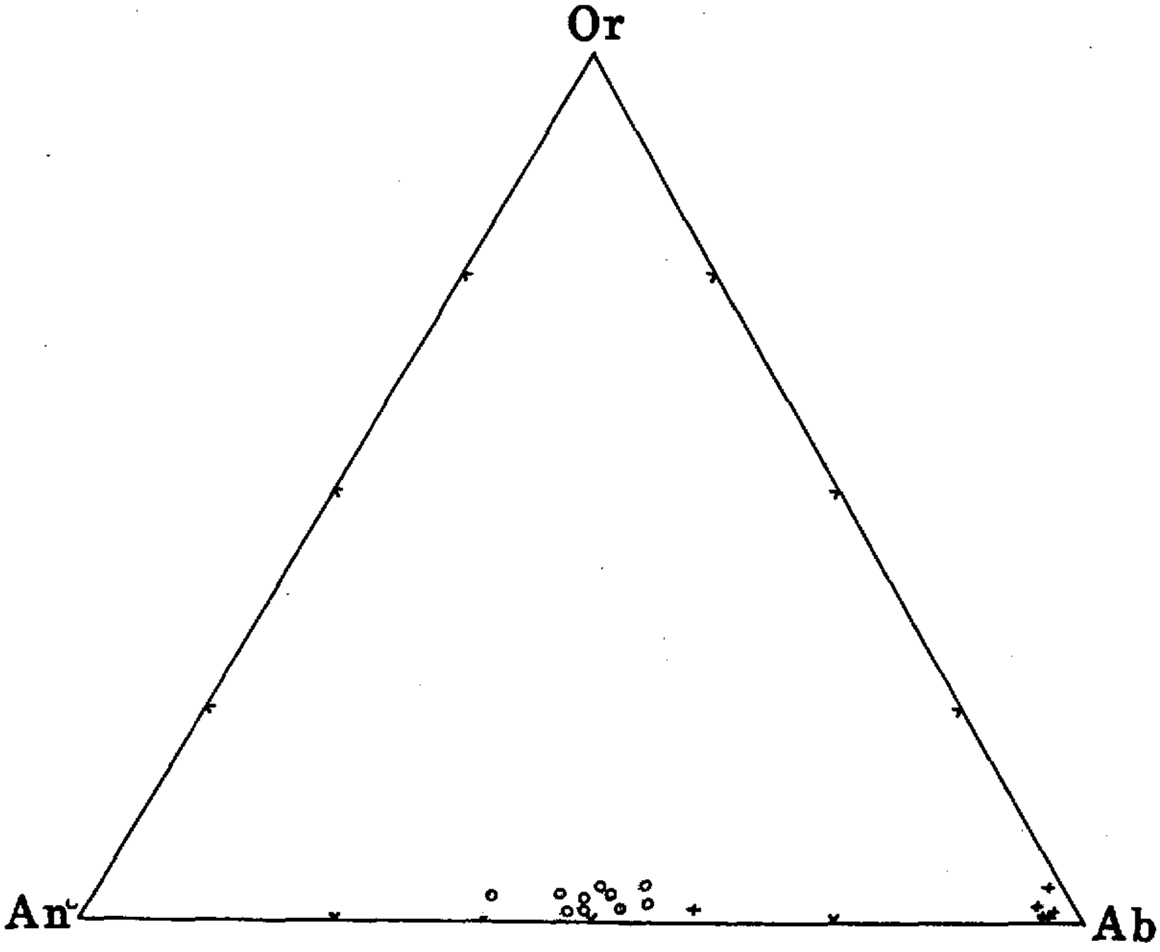
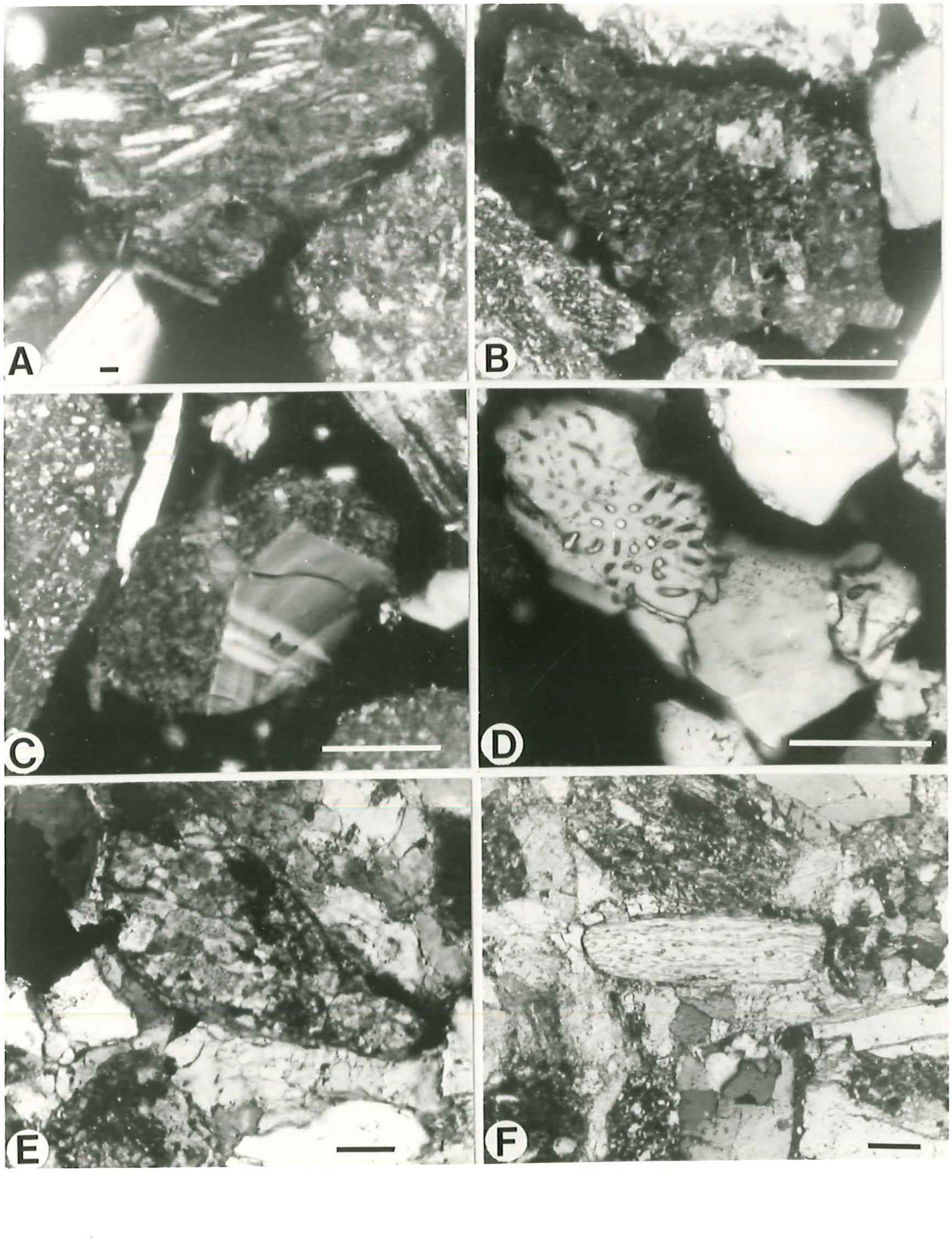

Or
An
Ab

Figure 5. Examples of rock fragments in Sentinel Butte sandstones: A, B, and C) volcanic rock fragments, A) plagioclase laths in a fine-grained groundmass, bar = 10 um, B) microlites of feldspar in an altered, fine-grained (glassy?) groundmass, bar = 100 um, C) large, zoned labradorite phenocryst in a fine-grained groundmass, bar = 100 um, D) plutonic rock fragment with myrmekitic texture, bar = 100 um, E) metamorphic polycrystalline quartz grain (note elongate grains and sutured grain contacts), bar = 100 um, F) schist fragment, bar = 100 um.


A
B
C
D
E
F

mudstone fragments and many fragments initially counted as chert were determined by microprobe analysis to be volcanic rock fragments with a felsitic texture.

### Quartz

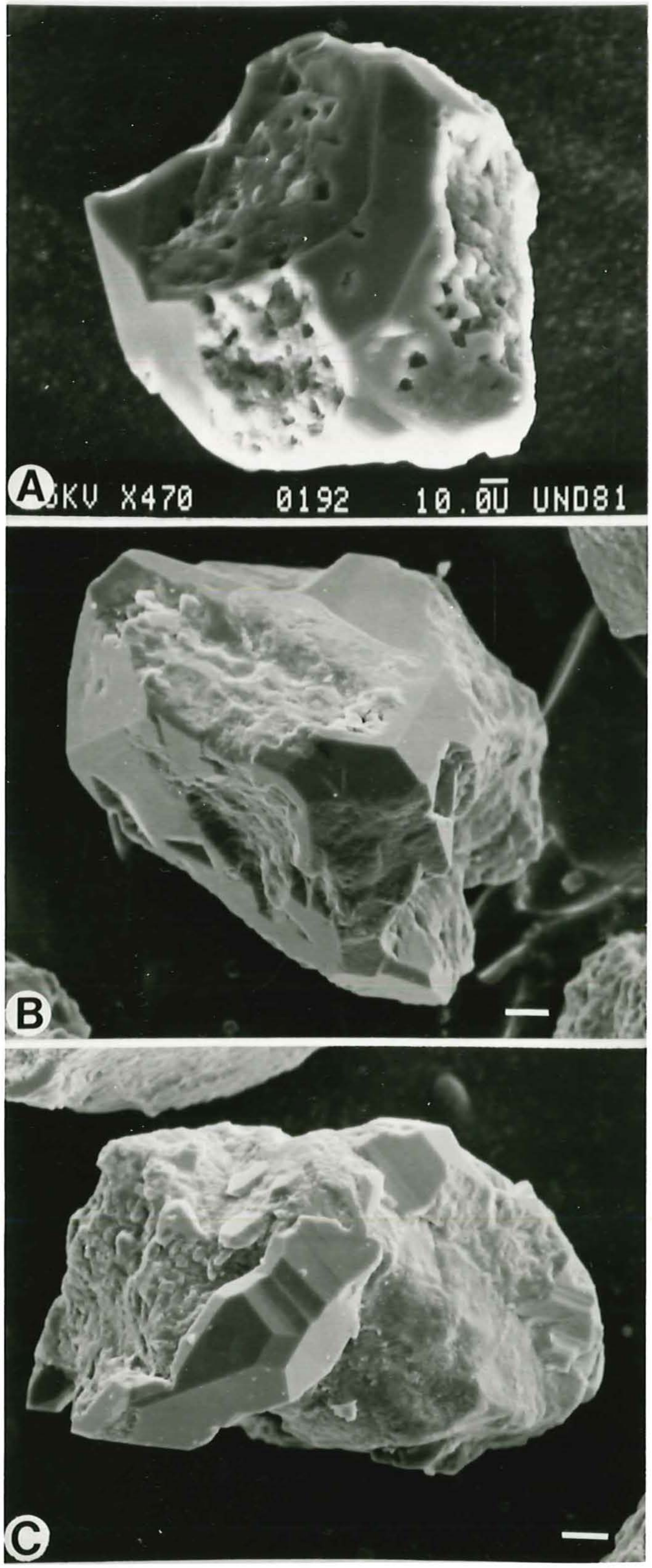
Quartz occurs in Sentinel Butte samples as angular grains, normally lacking surface abrasion features. Most quartz grains examined reveal no useful indications of source rock types. However, in one sample (Mann. 7), 7 quartz grains bear unmistakable quartz overgrowths, suggesting their derivation from a pre-existing sedimentary terrane (Fig. 6); evidence of quartz cementation following final deposition has not been detected in any Sentinel Butte samples. Only monocrystalline grains were counted as quartz.

### Feldspar

Potassic feldspar and plagioclase grains also appear angular and not significantly abraded by transport, although many samples contain slightly to deeply etched feldspar grains. Potassic feldspar and plagioclase seem to have been equally susceptible to chemical dissolution in many Sentinel Butte samples. Most plagioclase grains examined are intermediate in composition; grains approaching the composition of albite are minor, while calcic varieties are very rare in the samples examined. No clear relationship between feldspar compositions and chemical dissolution has been detected in any samples examined.

A microprobe comparison of feldspar grains in the basal and upper sandstone units was conducted. Chemical data is provided in Appendix E,

Figure 6. Second-cycle detrital quartz grains bearing quartz overgrowths, bars = 10 μm.


A
5KV X470 0192 10.0U UND81
B
C

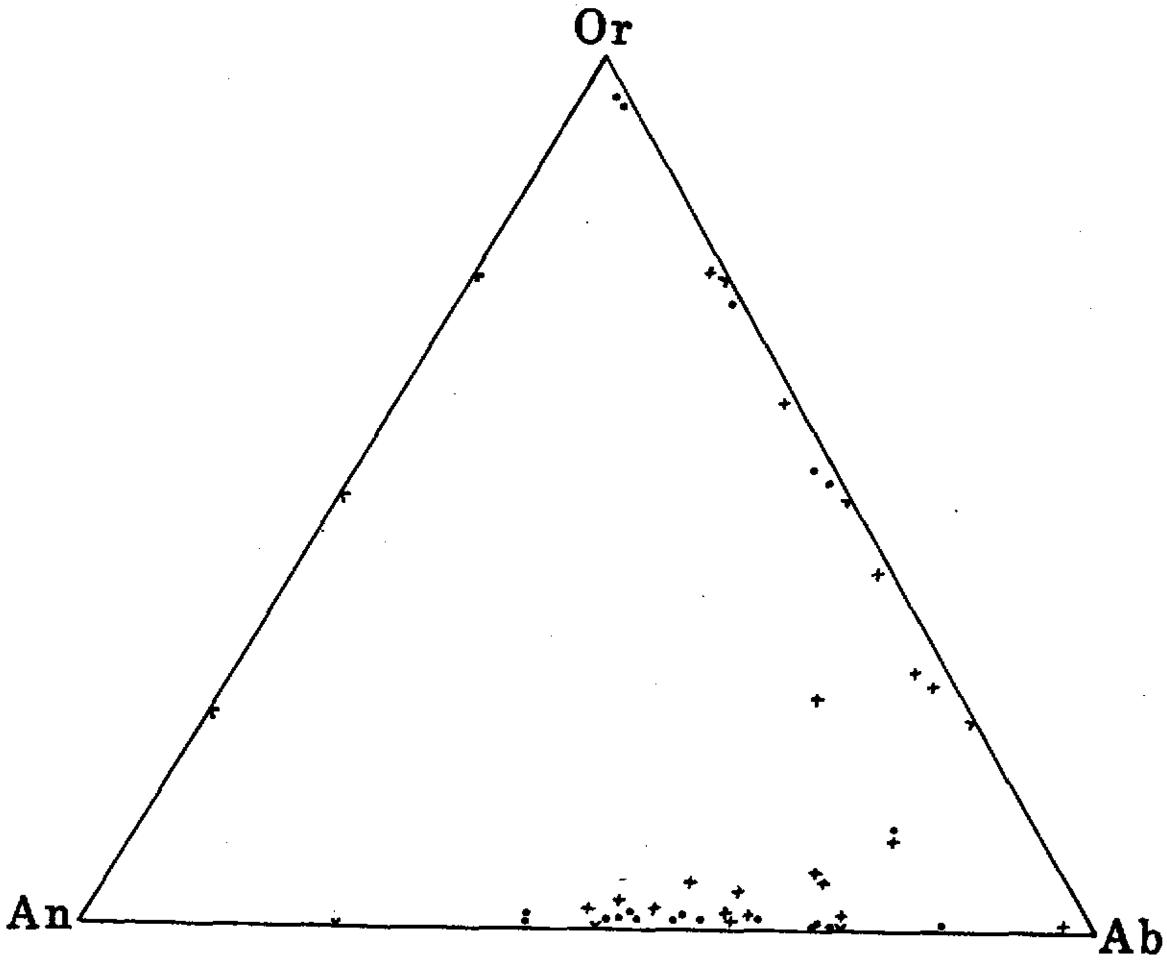
and results are summarized in Figure 7. No obvious difference in feldspar compositions of the two sandstone units is seen, but basal sandstone plagioclase compositions appear slightly more calcic than those of the upper sandstone. Whether this subtle difference, based on an examination of 20 grains from each unit, is meaningful awaits determination by a more thorough and specialized study of feldspars from these two units. A comparison of Figure 7 with Figure 4 suggests that many individual feldspar grains came from different source terranes than those represented by Sentinel Butte volcanic rock fragments. The intermediate alkali feldspar analyses are problematic in that they suggest volcanic phenocryst origin, but such grains were not found as phenocrysts in the rock fragments examined. It is possible that the spot analyses by microprobe were taken of intergrowths of two phases together, giving an average value; more potassic or sodic feldspar varieties would be suggestive of plutonic or metamorphic source terranes.

### Determination of Quartz and Feldspar

Optical microscopy determinations of quartz, potassic feldspar, and plagioclase were found to be in significant error when checked by SEM/EMA observations. As a result, percentage figures for these minerals, given in Table 1, were determined using SEM/EMA point counts; total quartz + K-feldspar + plagioclase values determined from the original, erroneous, optical point count data were subdivided according to the individual mineral proportions determined using the SEM/EMA point-counting technique described on page 22.

The primary factor making optical distinctions between quartz,

Figure 7. Ternary composition of feldspar grains from the Sentinel Butte upper sandstone (+), and basal sandstone (●).


Or
An
Ab

potassic feldspar, and plagioclase difficult is fine grain size. Cracks propagated across small quartz grains may appear quite straight and be mistaken as feldspar cleavages. In the case of fine grains, what appear to be untwinned potassium feldspar grains may very often be individual plagioclase twins now detached from a once larger grain. Common mineral characteristics found by many authors to be of use in distinguishing quartz and feldspars include: 1) differences in first order interference colors, 2) relief, 3) presence and orientation of inclusions, and 4) indications of cleavage, twinning, and alteration products. The degree to which each or all of these traits is of use in mineral identification can be expected to vary between sandstones and between petrographers. Further, in using interference figures to distinguish quartz from feldspars, one should always be aware that the presence of a visible melatope is required for the certain determination of uniaxial versus biaxial character. Specialized techniques of quartz and feldspar identifications should perhaps routinely be employed in sedimentary petrography, particularly in the case of fine-grained sediments. Either staining or microprobe techniques can be effective in this regard. Errors in mineral percentage values are, in effect, greatly compounded where such data are used to determine mineral ratios which are, in turn, applied to plots of regional mineral distribution patterns and interpretations of provenance.

### Calcite and Dolomite

It is not known what fraction, if any, of the individual calcite/dolomite figures in Table 2 represents detrital grains. Most of the carbonate in the Sentinel Butte formation appears to be secondary.

Evidence leading to that judgment is discussed in following sections.

### Micas

Muscovite and biotite grains are abundant in some Sentinel Butte samples and common to minor in others. Muscovite and biotite are approximately equally common in most samples. Many of the flake-shaped grains observed by SEM/EMA have the composition of chlorite, which may have formed pseudomorphically after biotite (see page 40).

### Heavy Minerals

The content of heavy minerals in Sentinel Butte sandstones and siltstones is very minor although this study has not provided any quantitative information. Apatite is the most common heavy mineral in the formation with epidote a distant second. Epidote grains are commonly chemically weathered, with deep, elongate dissolution features. The results of an attempt to estimate the heavy mineral contents of the basal and upper Sentinel Butte sandstones are summarized in Table 4. The upper sandstone seems to contain both a larger amount and variety of heavy minerals than the basal sandstone. That the commonly more stable heavy minerals, such as zircon and tourmaline, are so rarely encountered in Sentinel Butte samples is probably a result of provenance or attrition during transport, rather than a result of diagenetic removal following deposition.

TABLE 4. HEAVY MINERALS IN BASAL AND UPPER SENTINEL BUTTE SANDSTONES

| MINERAL | BASAL SAND | UPPER SAND |
|---|---|---|
| Almandine | - | A |
| Epidote | A | A |
| Kyanite | - | R |
| Cordierite | - | R |
| Andradite | - | C |
| Chloritoid | - | R |
| Clinozoisite | - | C |
| Grossular(?) | - | C |
| Sphene | A | - |
| Ilmenite | A | - |
| Apatite | C | - |

Note: (A) = abundant, (C) = common, (R) = rare, (-) = not detected

## Clay Minerals

Detrital clay in the Sentinel Butte Formation is restricted primarily to mudstones and claystones. The clay in most sandstones is authigenic, as discussed on page 44. A very simple clay mineral suite occurs in the Sentinel Butte Formation. X-ray diffraction data indicate the presence of montmorillonite, mica/illite, chlorite, and kaolinite. No mixed-layer clay phases were detected. Montmorillonite is by far the dominant clay mineral in the Sentinel Butte Formation. It appears in nearly all cases to be Na-montmorillonite, as suggested both by a swelling of the (001) spacing from 12.5 Å to 16.9 Å following ethylene glycol solvation, and by microprobe analysis (Appendix I). Chlorite, kaolinite, and mica/illite occur in the clay fractions of nearly all samples, but are almost always greatly subordinate, in amount present, to montmorillonite. The <2 µm clay mineralogy of each sample examined is reported in Appendix F.

Kaolinite is not as abundant as chlorite in the <2 μm fraction of Sentinel Butte samples. While chlorite was detected in 44 of the 46 samples examined, kaolinite was detected in only 36. Kaolinite and chlorite each have a basal (001) spacing of 7 Å, but are normally easily distinguished in Sentinel Butte samples where separate peaks are discernible at 3.53 Å and 3.56 Å, the (004) and (002) spacings of chlorite and kaolinite, respectively.

It is possible that the clay mineral suite of the Sentinel Butte Formation is even simpler than that reported above. It is very difficult to distinguish illite from muscovite using XRD. It is possible that a peak present at 10 Å in the samples examined usually represents a mica, either muscovite, biotite, or both, rather than illite. Chlorite, muscovite, and biotite flakes occur together in many Sentinel Butte sand and silt fractions as determined by SEM/EMA observations of grains loosely sprinkled onto tape. Much, if not all, of the chlorite present appears to be a pseudomorphic alteration product of biotite; microprobe analyses of mica grains reveal a range of compositions from biotite to chlorite. In oil immersion mounts, mica flakes, other than muscovite, reveal a range of interference colors from brown to green, further suggesting that some biotite has undergone varying degrees of alteration to chlorite. Brekke (1979) reported that mica group minerals and chlorite have similar XRD intensities and are directly proportional in Sentinel Butte samples. In this study, chlorite peaks have not been detected in the absence of mica group peaks. Perhaps all the chlorite present in the Sentinel Butte Formation is a pseudomorphic alteration product of mica.

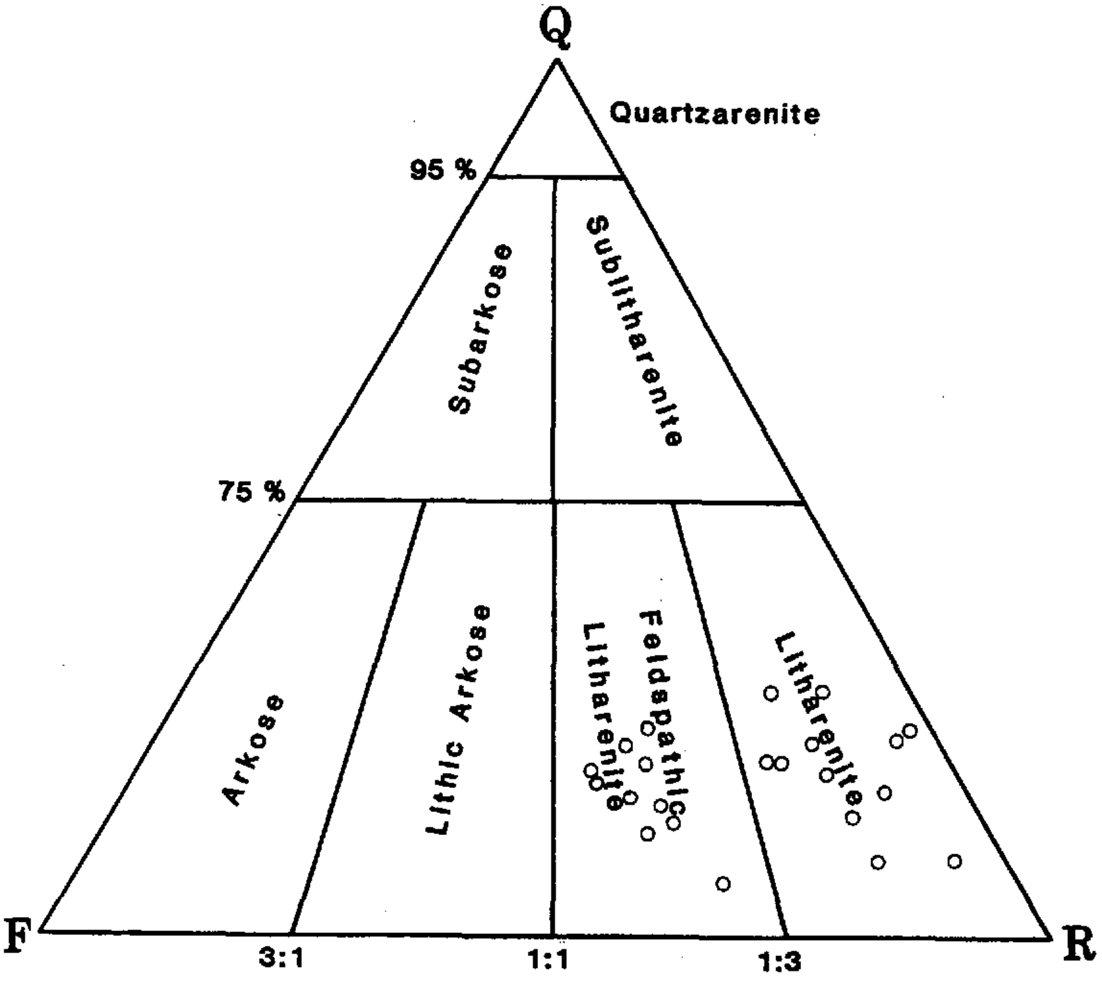
## Classification

Disregarding authigenic constituents, Sentinel Butte sandstones are classified generally as volcanic arenites or feldspathic volcanic arenites (after Folk, 1974) (Fig. 8). Volcanic rock fragments are abundant in most samples and feldspar content ranges from 2 to 28 % (avg. 14 %). Most siltstone samples examined are also lithic arenites or feldspathic lithic arenites. Primary matrix appears minor among the 13 samples classified as sandstones because of a >50 % sand content. The matrix of some sandstones is difficult to distinguish from rock fragments that have been wedged or squeezed between other detrital grains. And in some samples, secondary calcite has displaced and partially replaced grains making matrix versus framework distinctions even more difficult. But in most samples, matrix is largely absent, and many pores are left open except for pore-lining authigenic clay. The minor matrix that is present is silt. It is probable that very little of the total clay present in any of the sandstone samples examined is detrital. Evidence that much, if not most, of the the clay present in the sandstones is authigenic is discussed below, under "Montmorillonite" and "Diagenesis". It appears that detrital clays were largely winnowed from stream channel environments and deposited on floodplains, leaving behind clean sand deposits.

## Authigenic Constituents

The Sentinel Butte Formation contains far more authigenic material than previously has been recognized. Most authigenic minerals occur

Figure 8. Classification of Sentinel Butte sandstones (samples with >10 % sand-size grains). Q = quartz, F = feldspar, R = rock fragments.


Q
Quartzarenite
95 %
Subarkose
Sublitharenite
75 %
Arkose
Lithic Arkose
Feldspathic Litharenite
Litharenite
F
R
3:1
1:1
1:3

only in relatively small amounts, and in only some of the samples gathered. Others are abundant throughout the formation, while still others occur only locally but abundantly enough to cement their host sediments.

### Montmorillonite

The most abundant and widespread authigenic mineral in the Sentinel Butte Formation is Na-montmorillonite. It occurs as a chemically precipitated pore-lining cement in nearly all sandstones and in some siltstones. It forms such thin coatings on detrital grains of some sandstones that it normally is noticeable in thin sections only in the way it accentuates, by slightly darkening, the edges of those detrital grains. In fact, it probably would not have been noticed in those sandstones were it not first detected by SEM. It is very conspicuous in thin sections of some sandstones, forming thick, birefringent grain coatings which sometimes fill small pores.

Authigenic montmorillonite only weakly cements Sentinel Butte sediments, but does provide a cohesiveness such that hand-specimen-size rocks can be thin-sectioned if further cemented by an impregnating substance. Weakly cemented Sentinel Butte rocks become completely disaggregated by soaking in water for a few hours, as a result of swelling and sloughing of montmorillonite from detrital grain surfaces. Individual framework grains can be scraped or brushed from sandstone hand specimens and mounted for SEM viewing. Authigenic montmorillonite coats nearly all detrital grains regardless of host grain mineralogy. The morphology of authigenic montmorillonite is quite distinctive. Clay particle edges that are oriented nearly perpendicular to host grain surfaces interconnect to form a crenulated pattern (Fig. 9). It is clear that pore-lining montmorillonite in Sentinel Butte rocks formed by precipitation from solution. The montmorillonite is easily rinsed away in water, exposing smooth, unaltered detrital grain surfaces. Some montmorillonite resists rinsing away in water and appears to lie upon irregular, perhaps partially dissolved, grain surfaces. Such montmorillonite may have formed by alteration of the host grain surface rather than by the precipitation process that has led to most of the montmorillonite found in Sentinel Butte sandstones. A description of authigenic montmorillonite interpreted as forming by reordering of host grain surface structure is given on pages 105 through 107. Regardless of specific mode of origin, authigenic Sentinel Butte montmorillonite produces sharp, symmetrical XRD peaks and a rational series of secondary basal reflections up to (006), reflecting a well-ordered structure.

### Kaolinite

Stacked kaolinite platelets are seen in some grain thin sections (Fig. 10). Many appear to have originated by recrystallization or replacement of detrital grains as shown by microprobe analysis of various portions of kaolinite grains. Micas, feldspars, and volcanic rock fragments have acted as precursors for the kaolinite in these instances. It remains unknown whether the alteration to kaolinite occurred prior to or following final deposition. The kaolinite seems rounded in some cases, and it is possible, given the non-abraded character of most Sentinel Butte sand grains, that such kaolinite might have survived transport over some unknown distance from eroded upstream

Figure 9. Morphology of authigenic montmorillonite as observed by SEM. Bar = 100 μm.

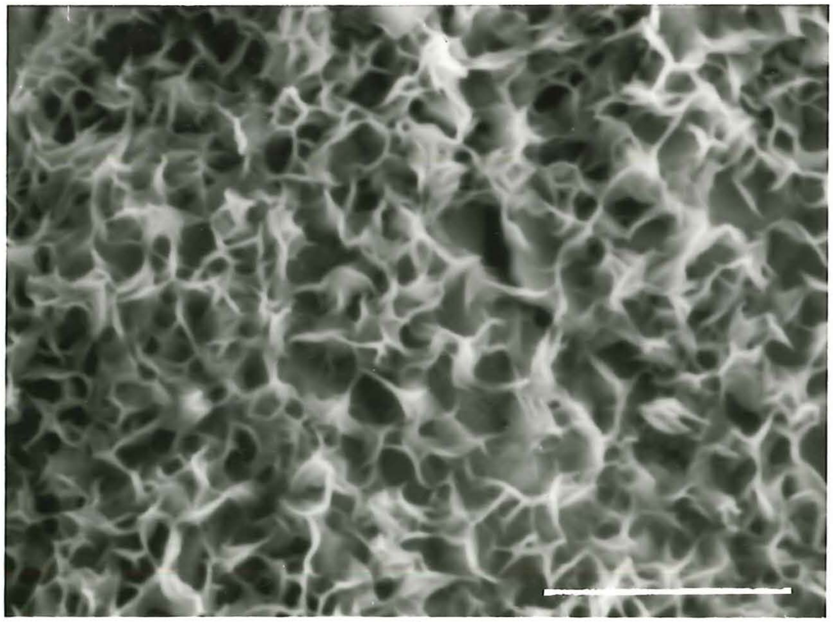


Figure 10. Kaolinite grain as seen in thin-section (center of photo). Bar = 10 µm.

floodplain deposits.

### Carbonates (calcite, dolomite, and rhodochrosite)

Calcite and dolomite both occur as authigenic minerals in many of the samples examined. Both occur as pore-filling cements and definitely postdate the development of authigenic montmorillonite. Calcite occurs both as irregular masses or aggregates and as subhedral crystals which sometimes rim other, possibly detrital, carbonate grains. Calcite also occurs as large anhedral interlocking crystals that completely fill pores by both displacement and replacement of detrital grains. Dolomite is present both as irregular aggregates and euhedral rhombohedra, but only the latter are known to be authigenic. Several characteristics are useful in distinguishing the authigenic carbonates in thin sections. These include:

1) size of carbonate grains noticeably different than other, detrital, grains;
2) radiating calcite subhedra around a host grain;
3) irregular grain outlines (in grain thin sections) due to previous attachment to detrital grains;
4) aggregates cemented by carbonate;
5) obvious occurrence as pore-filling cement.

Figures 11 and 12 provide examples of Sentinel Butte authigenic calcite and dolomite appearances. It is more difficult to recognize detrital carbonate grains. Evidence of modification of surface texture as a result of transport abrasion is rare among detrital grains of the Sentinel Butte Formation, so roundness has not proven to be a useful criterion in recognizing detrital calcite or dolomite. The large

Figure 11. Examples of characteristics of authigenic carbonates in Sentinel Butte samples: A) calcite subhedra radiating outward from surface of calcite host, B) calcite grain with irregular outline due to previous attachment to detrital pore walls, C) calcite-bound aggregate, D and E) pore-filling and displacive calcite cementation (note calcite filling cracks in grains), F) replacement of detrital grains by calcite (lower right) and dolomite(?) (center) (rhomb-shaped crystals are probably dolomite). Bars = 100 µm.

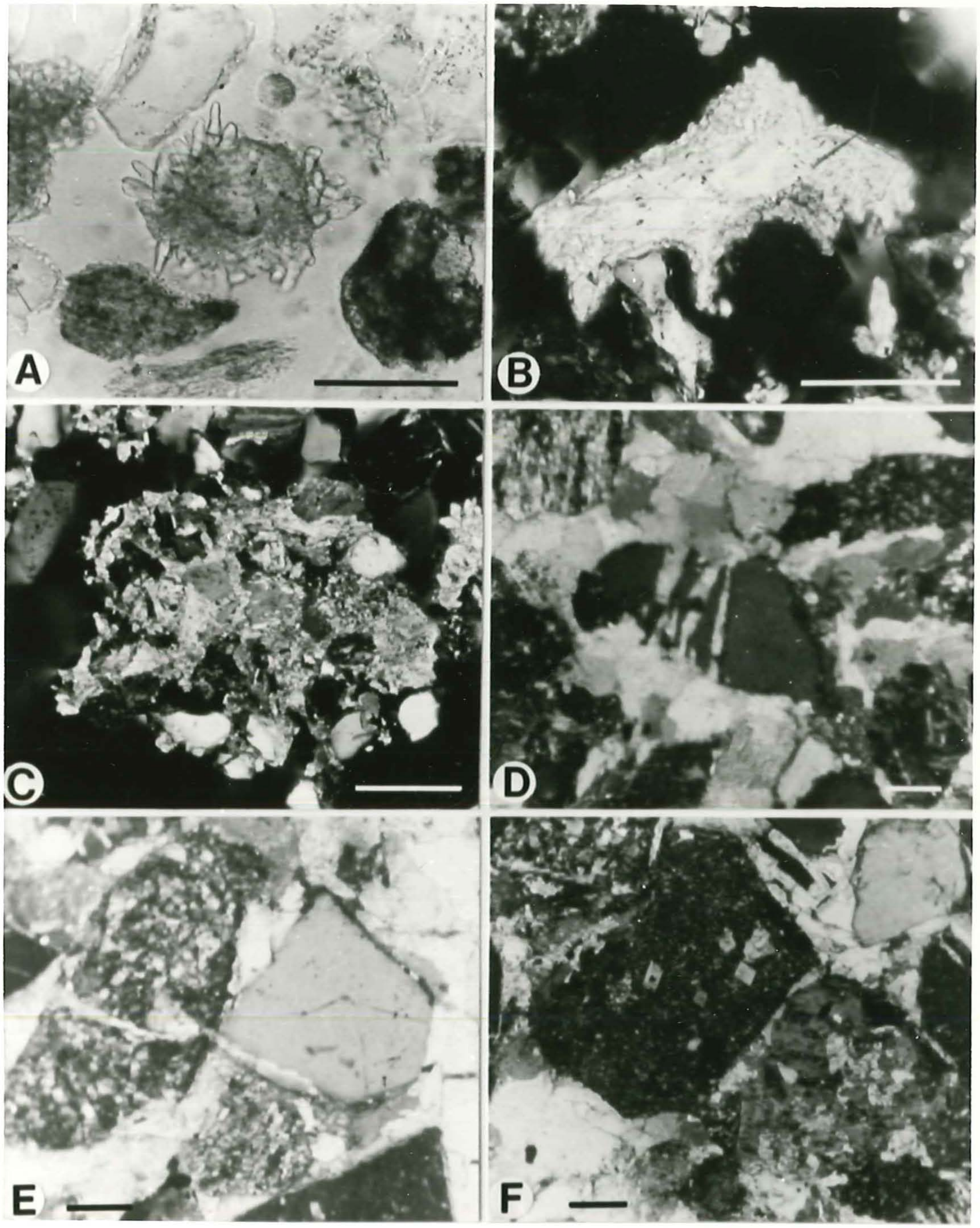
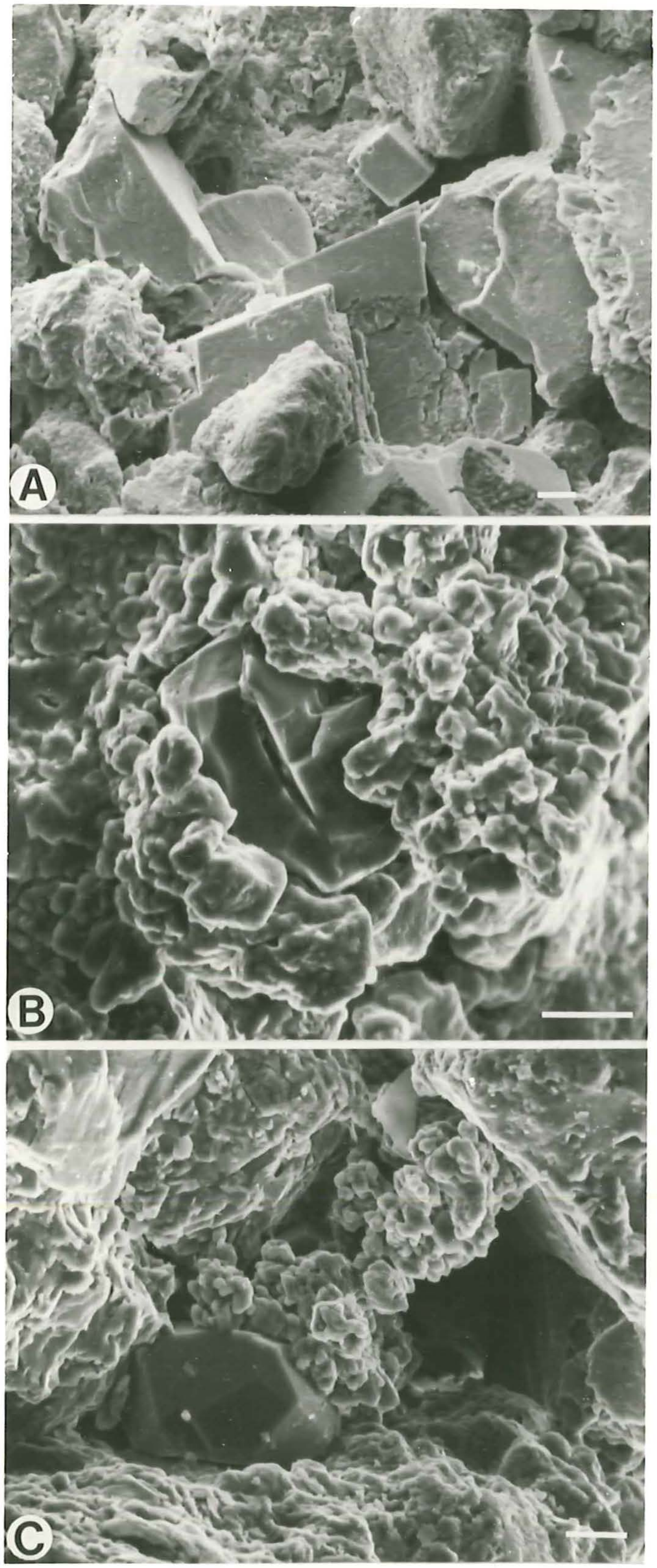

A
B
C
D
E
F

Figure 12. Authigenic carbonate as observed by SEM: A) dolomite rhombohedra as pore-filling cement, B) irregular pore-filling calcite cement (quartz grain in center), C) irregular pore-filling calcite (bridging pore). Bars = 10 µm.


A
B
C

variations in carbonate content in Sentinel Butte samples (Table 2) supports the possibility that most carbonate presently in the Sentinel Butte Formation is authigenic.

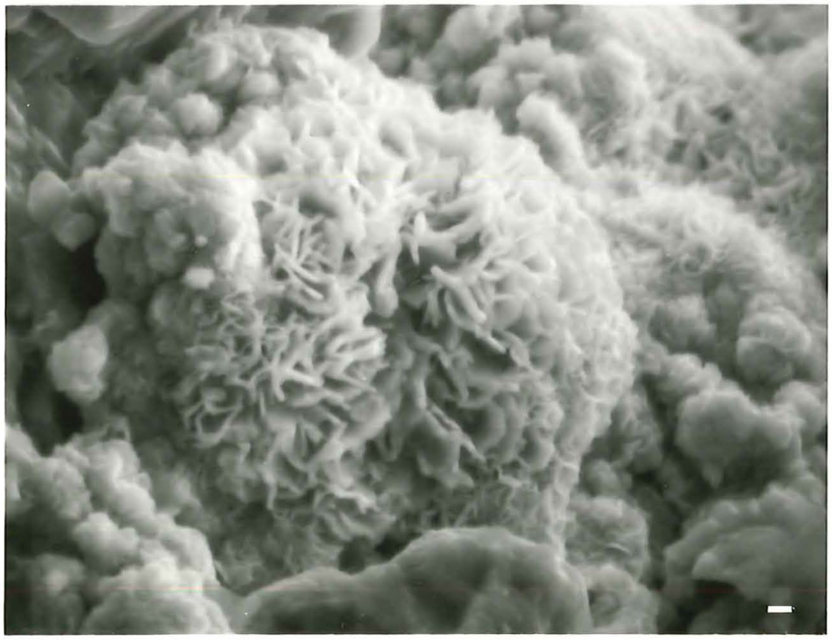
Rhodochrosite ($MnCO_3$) was detected in one Sentinel Butte sample as a local pore-filling material. It has a bladed habit as seen in Figure 13. Small gray-white pods or lenses of calcareous material are common but not abundant in the Sentinel Butte Formation. They are small (several centimeters to 2 m long) and normally occur together with others along the same bed. These masses have been interpreted as freshwater limestones (Royse, 1967). Optical and XRD examination of one such sample (LX-C) showed it to consist of normal detrital sand grains dispersed in a matrix of microcrystalline and locally recrystallized sparry calcite.

### Zeolites

After montmorillonite, calcite, and dolomite, zeolites are the next most common authigenic minerals found in the collected samples. They are abundant enough in some samples to be easily located in thin section, but must be searched for in most samples. In other samples they were not found in thin sections, but were detected among the grains sprinkled on tape for SEM viewing. (Each SEM mount holds a few hundred to a few thousand grains depending on whether sand or silt grains are mounted.) In still other samples, zeolites were found only as cement in sand-size aggregates that survived the disaggregation procedure.

Most of the zeolites occur as pore-filling subhedral to euhedral crystals and crystal clusters. Crystals range in size from <10 µm to 200 µm in maximum dimension. Authigenic zeolite growth post-dated pore-

Figure 13. SEM photograph of authigenic rhodochrosite. Bar = 1 µm.



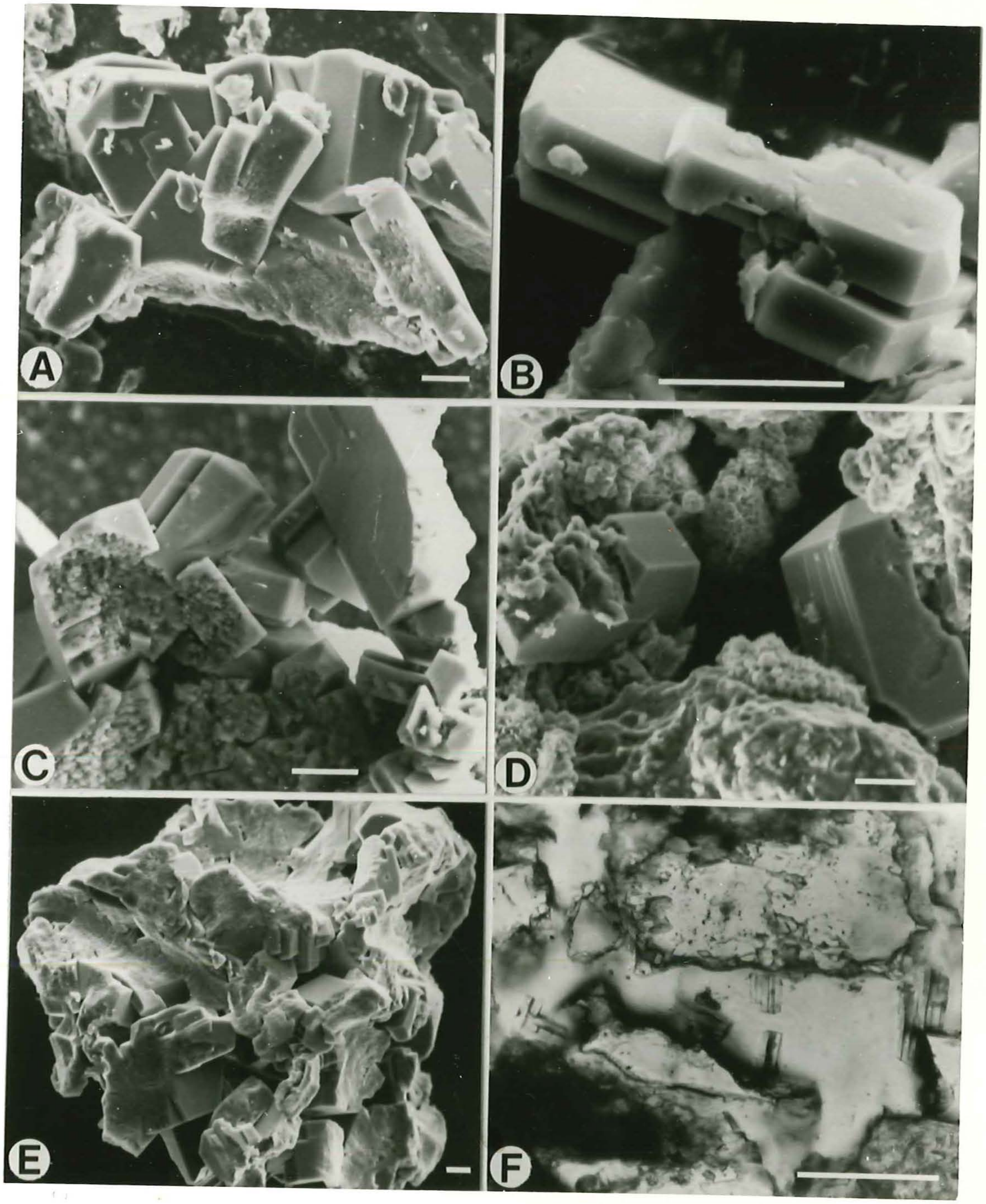
lining montmorillonite development, as evidenced by the superposition of uncoated zeolites upon the pore-lining montmorillonite that coats detrital grains in unwashed samples. The pore-filling character of the zeolites indicates that they formed as chemical precipitates from pore fluids.

### Heulandite Group

Many of the zeolite crystals examined are thought to be of the heulandite structural group (heulandite, clinoptilolite, stilbite, epistilbite), on the basis of crystal morphology and composition. This determination is based on comparisons with literature examples. Crystals thought to be of the heulandite group are not present in great enough numbers or large enough crystals in any sample to be effectively studied using XRD. Photographs of typical crystals are shown in Figure 14. Chemical data obtained by microprobe analysis of these crystals and others are presented in Appendix G.

Among individual heulandite group minerals there is considerable variation in Si:Al ratio and cation proportions (Deer et al., 1963). There is also considerable variation in possible crystal morphologies (Hay, 1966). It is somewhat difficult to identify confidently some zeolite minerals where XRD data is unavailable. The minerals chosen as best fitting the analyses of Appendix G and the photographs of Figure 14 are based on comparisons with published examples in Deer et al. (1963), Hay (1966), Mumpton and Ormsby (1976), and Barrows (1980). The name clinoptilolite is used instead of heulandite where Na and K exceed Ca. Clinoptilolite is reported to be the most abundant zeolite in sedimentary rocks (Mumpton, 1978). The mineral of analyses no. 6 and 7

Figure 14. Sentinel Butte Formation zeolites: A, B, C, and E) scanning electron micrographs of clinoptilolite crystals and crystal clusters. Note, in A, C, and E, roughened surfaces where the zeolites were once attached to detrital framework grains; note indentations produced by electron beam at lower right portion of crystal in B, and leftmost crystal in A; D) mordenite(?) crystals, F) thin section view of clinoptilolite crystals projecting into open pore space (plane light). All specimens from sample EG-1. Bars = 10 µm, except in F, where bar = 100 µm.


A
B
C
D
E
F

of Appendix G is labeled mordenite because of the lack of potassium. In other rocks, mordenite normally occurs as long hairlike fibers, but stubby crystals have been reported (Hay, 1966).

## Analcime

Analcime has been found in four samples collected for this study. In two of these samples (SS-1 and SB-12), analcime was found by examining sandy aggregates to see what held them together. In a third sample (SB-1), analcime was detected in thin section as the dominant cement of a fairly well indurated sandstone. This sandstone may be the lateral equivalent of an analcime-bearing layer sampled on Sentinel Butte by Furman (1970). In a fourth sample (SB-15), analcime was found concentrated in multiple thin layers within a coal seam cleat. The sample obtained from this horizon was thought to be a sandy lignite until examined in the laboratory, where it was determined to be a rock in which sand-size analcime crystals occur in intimate association with organic material.

Analcime in the above samples is easily recognized by its trapezohedral habit and Na-rich composition (Fig. 15 and 16, and Appendix G). A high enough concentration of analcime was available in each of the above four samples to also allow its recognition by standard powder XRD techniques. Photographs of the various analcime occurrences are provided in Figures 15 and 16. Analcime cementing the indurated sandstone (SB-1) occurs as somewhat colloform aggregates of many small (5 to 30 µm) crystals (Fig. 15a,d). These aggregates project toward pore centers and are cored by what appears in thin section as an irregularly lamellar, somewhat stacked arrangement of low-order

Figure 15. Analcime as pore-filling cement in sample SB-1. Each spheroidal mass is an aggregate of many small crystals. Trapezohedral crystal terminations are visible along outer surfaces of the spheroids (D), while interior views (A,B,C) reveal birefringent lamellar structures. Bars = 100 µm.

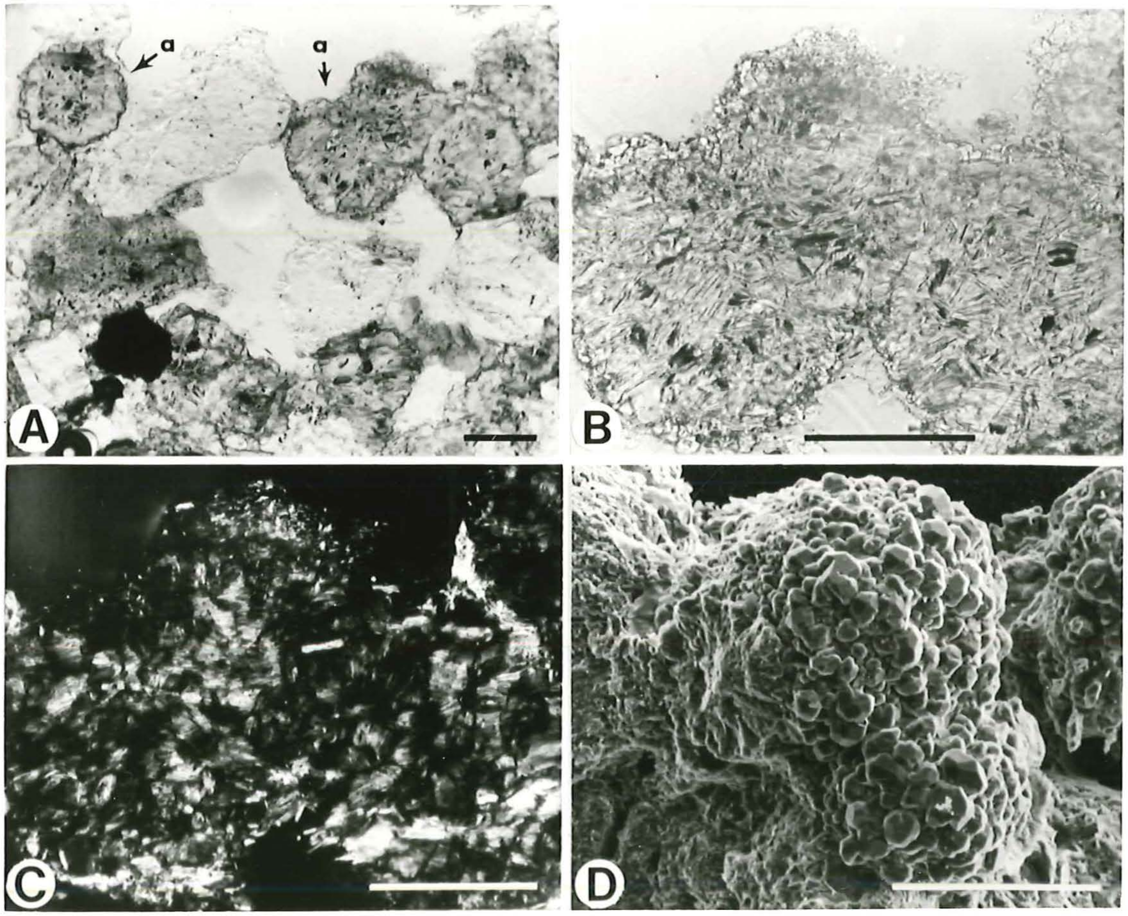
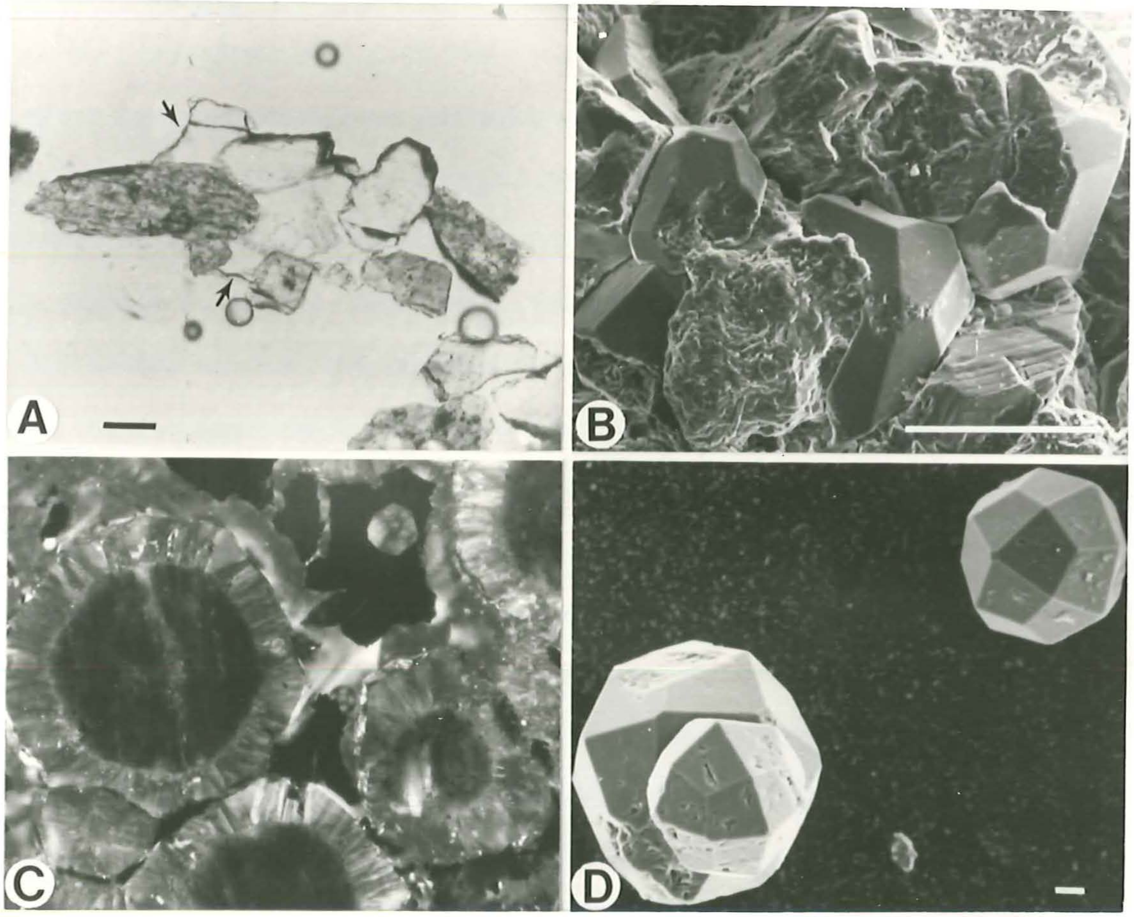

a
a
A
B
C
D

Figure 16. Appearance of analcime in sample SB-12 (A,B) and sample SB-15 (C,D): a) thin section view (plane light) of analcime cement (arrows) binding a sand fraction aggregate, bar = 100 µm, B) SEM view of similar-occurring analcime, bar = 100 µm, C) thin section view (crossed polars) of analcime trapezohedra. Note dark cores and lamellar twinning(?), D) SEM view of analcime trapezohedra, bar = 10 µm.


A
B
C
D

birefringent grains (Fig. 15b,c). Microprobe analysis suggests that these cores have the composition of analcime, even though literature examples of this type of occurrence have not been seen. The birefringent grains resemble sericite, except for their stacked arrangement. Furman (1970) reported authigenic sericite incorporated within analcime spherulites in the samples he examined. Analcime in the coal seam sample (SB-15) occurs as near-perfect trapezohedra, up to 200 µm in size (Fig. 16d). In thin section, these trapezohedra have first order gray birefringence and what appears to be lamellar twinning on (110) (Figure 16c). The core of each trapezohedron is an opaque reddish brown spherical zone that might represent entrapped organic or clay precursor material. Microprobe analysis did not reveal a chemical difference between the cores and surrounding portions of the analcime crystals. Analcime in the remaining two samples occurs as subhedral crystals bearing trapezohedral faces. These pore-filling grains are firmly anchored to detrital grains, forming a very effective local cement (Fig. 16b).

### Barite

Barite occurs as small marble-like nodules and as both large and microscopic prismatic masses. The nodules and some 1/2-m-diameter fractured stump-like masses locally occur on the surface of the Sentinel Butte bentonite (discussed in following sections). Microscopic prism-like masses are present among organic-rich portions of the analcime-bearing coal seam horizon mentioned above, and large prism-like masses have been seen in the field, within a carbonaceous mudstone horizon. Little is known about the geochemical environments involved in the formation of barite cement in non-marine sandstones (Pettijohn et al., 1973, p. 432). Specialized study of the restricted occurrences of barite in the Sentinel Butte Formation may provide some new data in this area.

### Pyrite

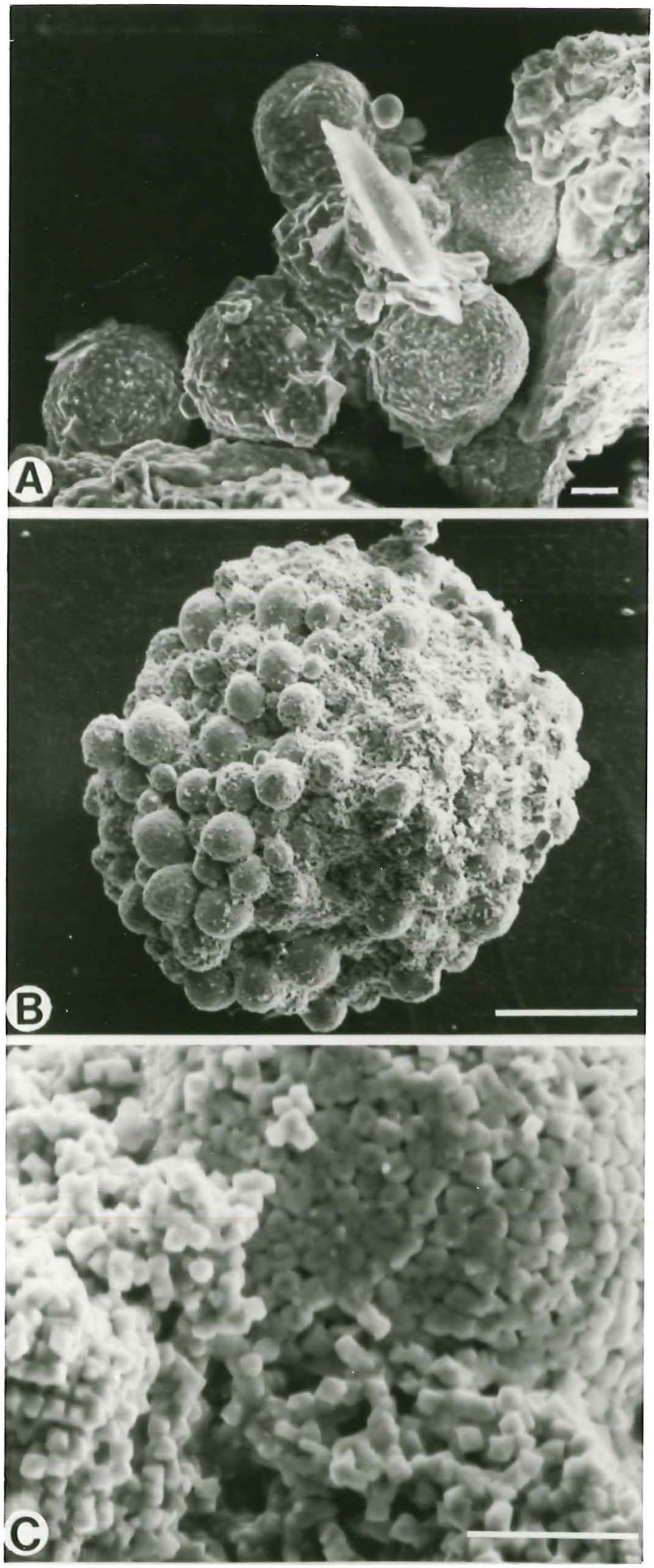
Pyrite was detected in three samples of clastic material collected in this study. Other workers have found pyrite to be associated with Sentinel Butte lignites (Karner et al., 1979; Moran et al., 1978). Pyrite does not appear to be common throughout the Sentinel Butte Formation and may indeed have an origin closely related to the availability of organic material. Two of the three samples in which pyrite was found are from beds immediately above lignites. The third sample bearing pyrite is from an alternating sand and silt interval in which the silty portions contain plant fragments. The pyrite occurs as individual cubes, clusters of cubes, interpenetrating cubes, framboids (raspberry-like spherical aggregates), and globular clusters of framboids (Fig. 17).

### Silica Minerals

Authigenic quartz is primarily restricted to occurrences within the structure of petrified wood in the Sentinel Butte Formation, where it occurs in both microcrystalline and megacrystalline form.

Opal and cristobalite have been found in three Sentinel Butte samples, (EG-A, Blue Bed 4, and BB-13), all of which were collected from beds immediately above the Sentinel Butte bentonite. Opal occurs as individual spheres together with coalesced or aggregated spheres (Fig.

Figure 17. Appearance of pyrite in Sentinel Butte samples: A) pyrite framboids and interpenetrating cubes (from sample SB-25), bar = 10 µm, B) a cluster of pyrite Framboids, bar = 100 µm, C) close-up of (B) showing individual cubes (from sample AC-1), bar = 10 µm.


A
B
C

18). Some authigenic montmorillonite occurs locally among less clearly resolved spheres of opal, strongly suggesting a genetic relation between the opal and montmorillonite. Pollard and Weaver (1973) suggested that opal spheres form where much free silica exists relatively free from Al, Mg, Fe, etc. Where the latter cations are available, they may combine with silica to form an impure amorphous opal or, apparently, authigenic clay.

Cristobalite occurs as neighboring spheroids which thickly line pore spaces. Each spheroid is an aggregate of many flat individual plates or blades with an edge-to-face arrangement (Fig. 19). Cross-sectional views show these spheroids to be solidly intergrown or coalesced, forming authigenic pore walls with bladed spheroids remaining only on the open pore side. Where once attached to detrital grains, the pore-lining cristobalite walls are found to have a composition and a morphology similar to that of authigenic montmorillonite, suggesting either the presence of an earlier pore-lining clay or an intimate genetic relation between montmorillonite and the early silica phase (probably opal) now present as cristobalite.

### Gypsum

Gypsum occurs as an apparently late authigenic mineral locally throughout much of the Sentinel Butte Formation. It was found in only two samples collected for this study. It normally occurs as selenite crystals and masses a few centimeters in maximum dimension, which probably are still forming today under near-surface evaporation conditions. It acts as a cement locally, on a very small scale, as shown in Figure 20, where it has strongly displaced detrital grains but bound

Figure 18. Opal spheres lining pore in sample BB-13. Bar = 10 µm.

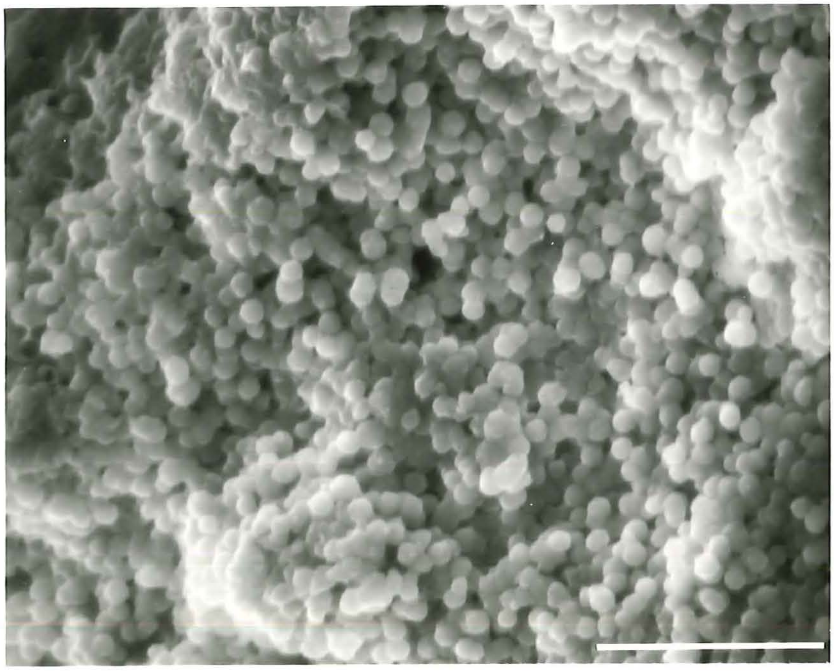


Figure 19. Cristobalite "spheroids" lining pores in sample Bent-4. Note the cross sectional view of the new cristobalite pore walls and the underside view of these walls (upper left) where detrital grains have been removed. Note also that montmorillonite is locally present along exposed undersides of cristobalite walls. Bar = 10 µm.

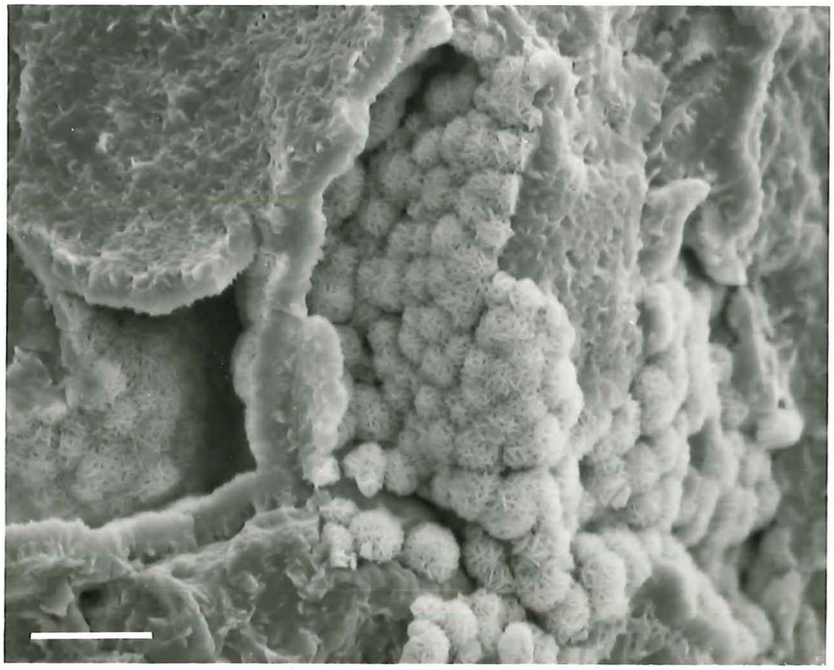
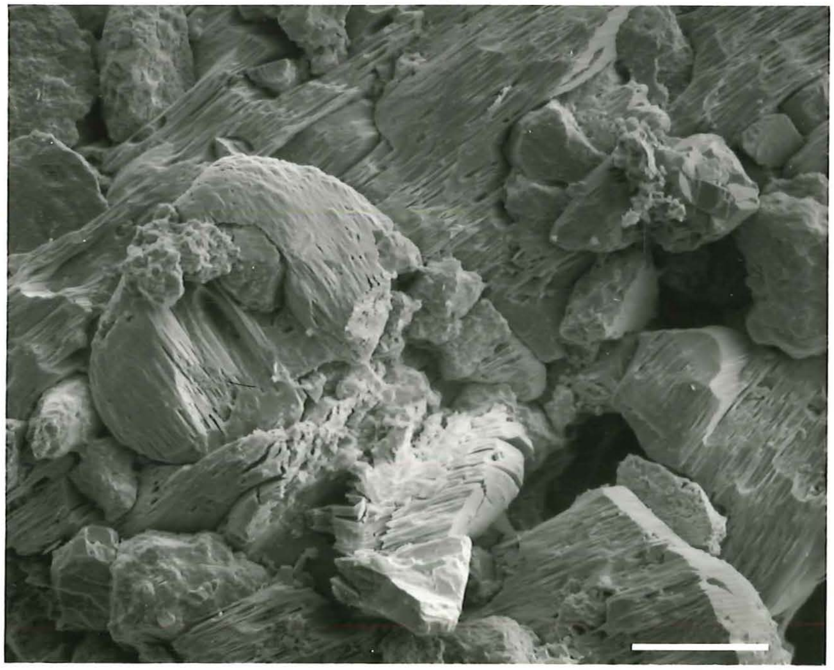


Figure 20. Gypsum cement binding an aggregate in sample MB-8. Bar = 100 µm.



them into one aggregate.

## Iron Oxides

Intrastratal dissolution of detrital grains observed in thin section has often led to an iron oxide precipitate which covers a local area far larger than the weathered grain. This points to the importance of intrastratal dissolution as a mechanism for the production of ferruginous cements. Development of iron oxide has produced thin, well-indurated bedding horizons in Sentinel Butte sandstones. Iron oxidation has also produced banding or staining of many Sentinel Butte bedding surfaces. Royse (1970) suggested that Sentinel Butte iron fixation "probably resulted from redox reaction involving anoxic decomposition of organic matter".

## BULK ROCK CHEMICAL ANALYSES

Major element chemistry data were obtained for a small number of samples in this initial study of the general composition of Sentinel Butte sandstones and siltstones, and as a preliminary test of the usefulness of major element composition in distinguishing sandstone units. Five samples of the widespread sand that occurs at the base of the Sentinel Butte Formation were analyzed and compared with one sample of the uppermost Sentinel Butte sand and two samples of intermediate sands. Six silt samples from what is commonly referred to as the lower yellow bed and one silt sample from the upper yellow bed were also analyzed and compared.

Most samples were analyzed both before and after removal of authigenic montmorillonite and carbonate. Calcite and dolomite were removed by treating samples with warm dilute HCl, and <2 µm clays were removed by decantation. Each treated sample was then repeatedly centrifuged, decanted, and rinsed to remove ions suspended by the acid treatment. Results of all analyses are provided in Table 5.

The data show little difference in major element composition between the eight sand samples. The fact that calcium is the only element that shows much variation between samples prior to acid treatment lends support to the interpretation that most Sentinel Butte carbonate grains (or at least those in the presumably equivalent basal sand samples) are authigenic. The similarity between samples is particularly evident where authigenic (as well as detrital) clays, calcite, and dolomite have been removed.

The two acid-treated yellow bed silt samples also do not appear different from the sand samples except for higher potassium and lower

Table 5. X-ray Fluorescence Analyses of Sentinel Butte Sandstones and Siltstones

Part I --SANDSTONES

| sample: | 1a | 1b | 1c | 2a | 2b | 2c | 3a | 3b | 3c | 4a | 4b | 4c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 62.55 | 74.45 | 78.30 | 63.65 | 69.15 | 75.81 | 64.84 | 70.54 | 74.73 | 63.09 | 70.10 | 75.24 |
| $Al_2O_3$ | 16.27 | 12.10 | 12.71 | 14.35 | 12.82 | 14.05 | 14.82 | 13.50 | 14.30 | 14.93 | 10.95 | 11.75 |
| FeO* | 3.14 | 1.55 | 1.61 | 3.48 | 1.63 | 1.79 | 3.32 | 2.29 | 2.43 | 2.93 | 1.61 | 1.72 |
| MgO | 2.08 | 0.76 | 0.80 | 2.08 | 0.77 | 0.85 | 2.23 | 0.99 | 1.05 | 2.82 | 1.66 | 1.78 |
| CaO | 1.67 | 1.00 | 1.05 | 3.15 | 1.73 | 1.90 | 3.47 | 1.77 | 1.87 | 5.72 | 2.80 | 3.01 |
| $Na_2O$ | 1.92 | 2.17 | 2.28 | 1.99 | 2.17 | 2.38 | 2.50 | 2.32 | 2.46 | 1.71 | 1.59 | 1.71 |
| $K_2O$ | 1.91 | 2.64 | 2.75 | 2.15 | 2.50 | 2.74 | 2.08 | 2.42 | 2.56 | 2.11 | 2.32 | 2.49 |
| $TiO_2$ | 0.69 | 0.44 | 0.46 | 0.51 | 0.39 | 0.43 | 0.78 | 0.50 | 0.53 | 0.62 | 0.43 | 0.46 |
| $P_2O_5$ | 0.16 | 0.02 | 0.02 | 0.14 | 0.03 | 0.03 | 0.18 | 0.03 | 0.04 | 0.15 | 0.11 | 0.12 |
| MnO | 0.03 | 0.02 | 0.02 | 0.07 | 0.02 | 0.02 | 0.05 | 0.03 | 0.03 | 2.93 | 1.61 | 1.72 |
| Total | 90.42 | 95.15 | 100.00 | 91.57 | 91.21 | 100.00 | 94.27 | 94.39 | 100.00 | 96.91 | 93.18 | 100.00 |

|  | 5a | 5b | 5c | 6a | 6b | 6c | 7a | 7b | 7c | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 70.09 | 69.65 | 72.93 | 64.14 | 69.64 | 76.41 | 59.70 | 70.85 | 73.98 | 75.70 |
| $Al_2O_3$ | 14.28 | 14.76 | 15.45 | 14.73 | 12.92 | 14.17 | 11.34 | 14.22 | 14.85 | 11.49 |
| FeO* | 2.84 | 2.99 | 3.13 | 3.28 | 1.41 | 1.55 | 3.08 | 3.67 | 3.83 | 1.73 |
| MgO | 2.02 | 1.53 | 1.60 | 2.50 | 0.95 | 1.04 | 1.24 | 1.35 | 1.40 | 1.09 |
| CaO | 2.95 | 1.29 | 1.36 | 5.26 | 1.41 | 1.55 | 11.39 | 0.95 | 0.99 | 0.57 |
| $Na_2O$ | 2.08 | 1.85 | 1.94 | 2.20 | 1.99 | 2.18 | 1.35 | 1.65 | 1.72 | 1.19 |
| $K_2O$ | 2.24 | 2.72 | 2.84 | 1.82 | 2.33 | 2.56 | 1.84 | 2.39 | 2.49 | 2.73 |
| $TiO_2$ | 0.56 | 0.66 | 0.69 | 0.54 | 0.45 | 0.50 | 0.54 | 0.66 | 0.68 | 0.54 |
| $P_2O_5$ | 0.14 | 0.03 | 0.03 | 0.13 | 0.02 | 0.02 | 0.12 | 0.03 | 0.03 | 0.08 |
| MnO | 0.03 | 0.03 | 0.03 | 0.04 | 0.02 | 0.02 | 0.06 | 0.03 | 0.03 | 0.01 |
| Total | 97.23 | 95.51 | 100.00 | 94.64 | 91.14 | 100.00 | 90.66 | 95.80 | 100.00 | 95.13 |

Part II --SILTSTONES

|  | 9a | 9b | 9c | 10a | 10b | 10c | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.28 | 76.09 | 75.32 | 58.82 | 72.59 | 77.71 | 58.41 | 62.15 | 54.99 | 52.84 | 60.82 |
| $Al_2O_3$ | 12.76 | 14.66 | 14.51 | 9.33 | 11.71 | 12.53 | 10.11 | 12.81 | 9.87 | 8.75 | 13.29 |
| FeO* | 3.50 | 2.94 | 2.91 | 2.59 | 2.59 | 2.77 | 2.62 | 4.09 | 2.31 | 8.75 | 13.29 |
| MgO | 3.92 | 1.77 | 1.75 | 3.30 | 1.42 | 1.52 | 3.48 | 3.91 | 3.52 | 4.26 | 3.57 |
| CaO | 6.23 | 0.18 | 0.18 | 10.11 | 0.20 | 0.21 | 9.06 | 7.60 | 11.51 | 14.37 | 7.70 |
| $Na_2O$ | 0.94 | 1.00 | 0.99 | 0.92 | 1.12 | 1.20 | 0.89 | 1.15 | 1.04 | 0.70 | 0.64 |
| $K_2O$ | 3.21 | 3.73 | 3.69 | 2.46 | 3.14 | 3.36 | 2.63 | 3.21 | 2.34 | 2.09 | 3.04 |
| $TiO_2$ | 0.56 | 0.63 | 0.62 | 0.54 | 0.60 | 0.64 | 0.53 | 0.56 | 0.56 | 0.57 | 0.59 |
| $P_2O_5$ | 0.12 | 0.02 | 0.02 | 0.15 | 0.04 | 0.04 | 0.12 | 0.11 | 0.12 | 0.14 | 0.14 |
| MnO | 0.04 | 0.01 | 0.01 | 0.05 | 0.01 | 0.02 | 0.05 | 0.09 | 0.05 | 0.05 | 0.08 |
| Total | 97.56 | 101.03 | 100.00 | 88.27 | 93.42 | 100.00 | 87.90 | 95.68 | 86.31 | 85.94 | 94.07 |

*Total iron as FeO.

Column a: Pre-treatment element data in weight %, unnormalized.

Column b: Post-treatment (clays and carbonates removed) data, unnormalized.

Column c: Post-treatment data, normalized to 100 %.

Note: Analytical uncertainty due in part to presence of carbon and oxygen in carbonates and to stuctural $H_2O$. Analytical precision 1 %, accuracy within 5% (analyst: Robert Stevenson, UND Natural Materials Analytical Laboratory).

Samples: 1) sandstone BR-A, 2) sandstone EG-1, 3) sandstone 7-G, 4) sandstone SQB-A, 5) sandstone SB-25, 6) sandstone EG-17, 7) sandstone SB-18, 8) sandstone LX-M, 9) siltstone LYB-1, 10) siltstone LYB-2, 11) siltstone Edge-3, 12) siltstone Long X-D, 13) siltstone LB-C, 14) siltstone SHB-9, 15) siltstone LX-L, See Appendix A for sample locations.

calcium contents. Untreated yellow bed samples are different from the examined sand samples in calcium and magnesium content, reflecting the higher carbonate mineral content of the yellow beds.

# BENTONITE

Much of the literature concerning Paleocene rock units in western North Dakota refers to the presence of bentonitic beds. As historically developed in scientific usage, the term "bentonite" refers to a rock composed of clays that originated through the alteration of a glassy igneous rock, usually a volcanic tuff or ash (for a review of the development or phylogeny of the term bentonite, see Knight (1898), Hewitt (1917), Wherry (1917), Ross and Shannon (1926), and Schultz (1963)). The choice, by most previous workers, of the term bentonite for many clay layers in Fort Union Group rocks results from the physical weathering characteristics of those clay layers that suggest the presence of swelling clays, rather than from any independent evidence that some Fort Union claystones were volcanically derived. However the author did succeed, in an earlier study, in providing evidence for the volcanic origin of one Sentinel Butte clay layer (Forsman and Karner, 1975). As mentioned above, one of the specific questions within this investigation is how significant volcanic airfall activity was in supplying material to the Sentinel Butte Formation. A strong effort was made, during the course of field work for this study, to sample all clay layers that looked bentonitic. A detailed examination of the single known Sentinel Butte bentonite was conducted, providing examples of what field characteristics to look for in a search for other true bentonites. A large content of swelling clays determines the field expression of the known Sentinel Butte bentonite. These clays are blue-gray when dry and nearly black when wet. When dry, the bentonite surface is covered to a depth of several centimeters with pebble-size clay aggregates, the typical popcorn-weathering effect characteristic of many bentonites.

The bentonite commonly caps prominent benches and locally drapes underlying sediments. Other clay-rich layers with well-developed popcorn surfaces were sampled for later laboratory examinations which might determine whether or not they have volcanic origins. Laboratory efforts involved a careful characterization of the known Sentinel Butte bentonite and comparisons with a known bentonite in the Hell Creek Formation in southwestern North Dakota, followed by a search for similar characteristics in other Sentinel Butte claystones.

## The Sentinel Butte Bentonite/Ash

The Sentinel Butte bentonite/ash is a deposit that has been referred to as the blue bed by previous workers. It had long been suspected of being a bentonite, but was not verified as such until volcanic glass was found to be associated with the clay (Forsman and Karner, 1975). The deposit is known to occur over a large area within and north of the North Unit of Theodore Roosevelt National Park, in McKenzie County, North Dakota (Fig. 21). It can be traced visually as a nearly continuous deposit for many miles within the park, where it commonly caps prominent benches. North of the park, toward the town of Arnegard, it is found in shallow gullies and on small, resistant plateaus. Future mapping will probably extend the known range of this deposit, particularly toward the west. Upon close examination the deposit is found to consist of three distinct layers: a lower, 1.5 to 3.7-m-thick bentonite; a middle, 0.6 to 1.5-m-thick gray-white silt; and an upper, 0.6 to 1.5-m-thick bentonite. The upper and lower bentonites commonly form separate popcorn-covered benches, with the sandwiched silt layer between (Fig. 22). Although Royse (1967) described this deposit

Figure 21. Presently known range of the Sentinel Butte bentonite/ash deposit. This range can be extended by further mapping.

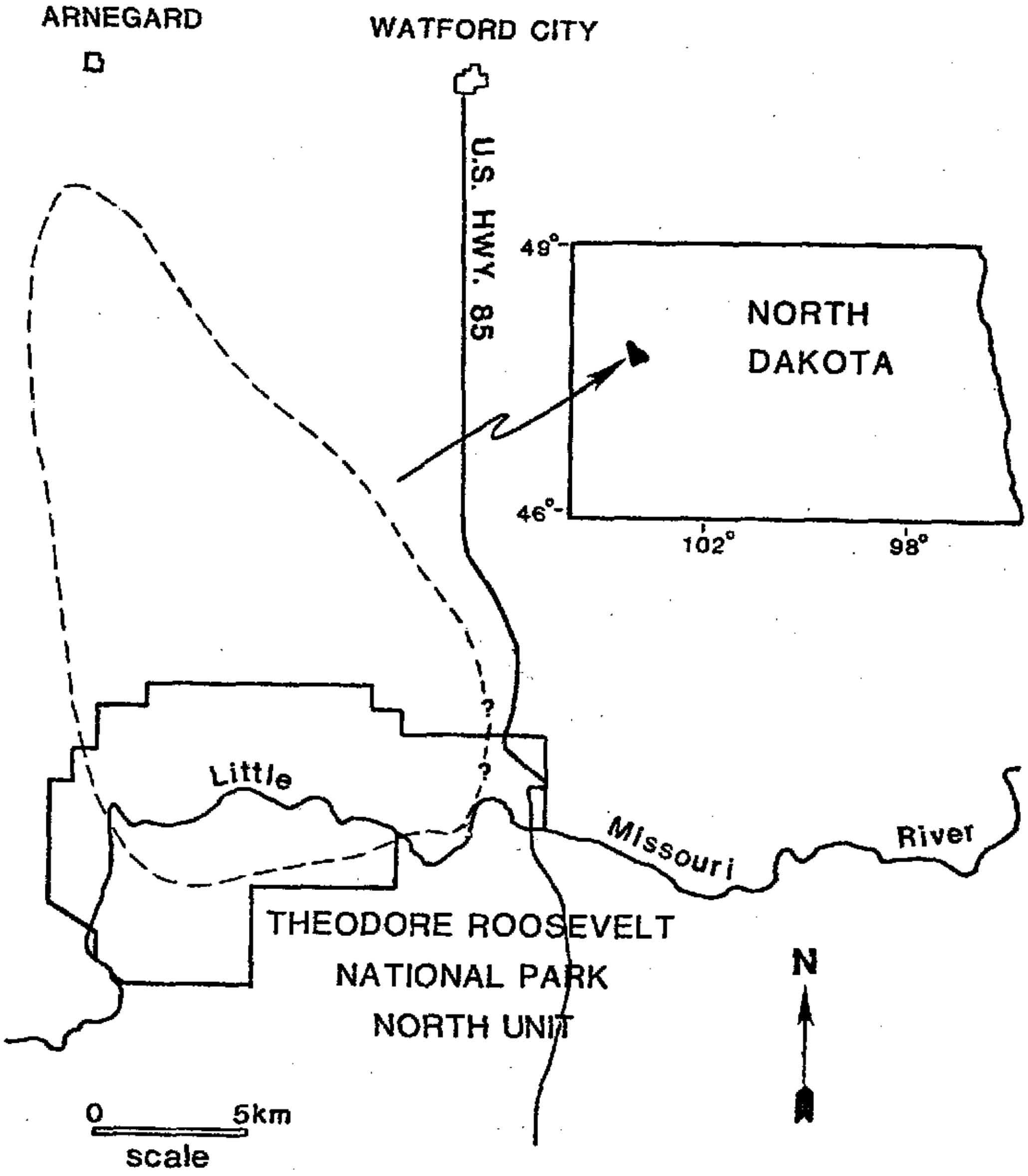
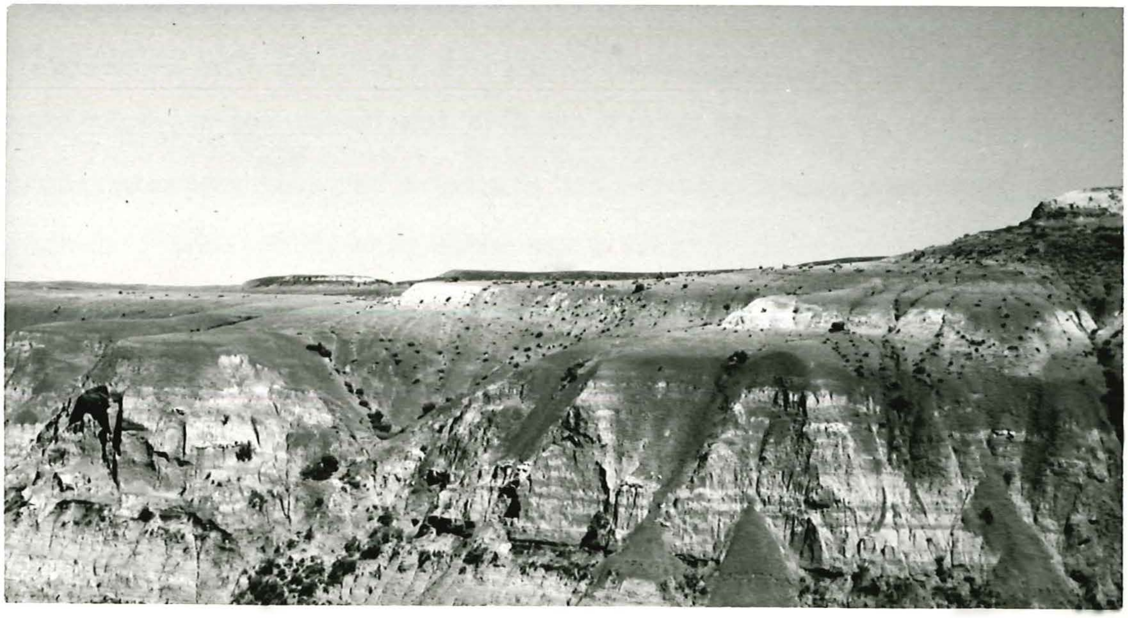
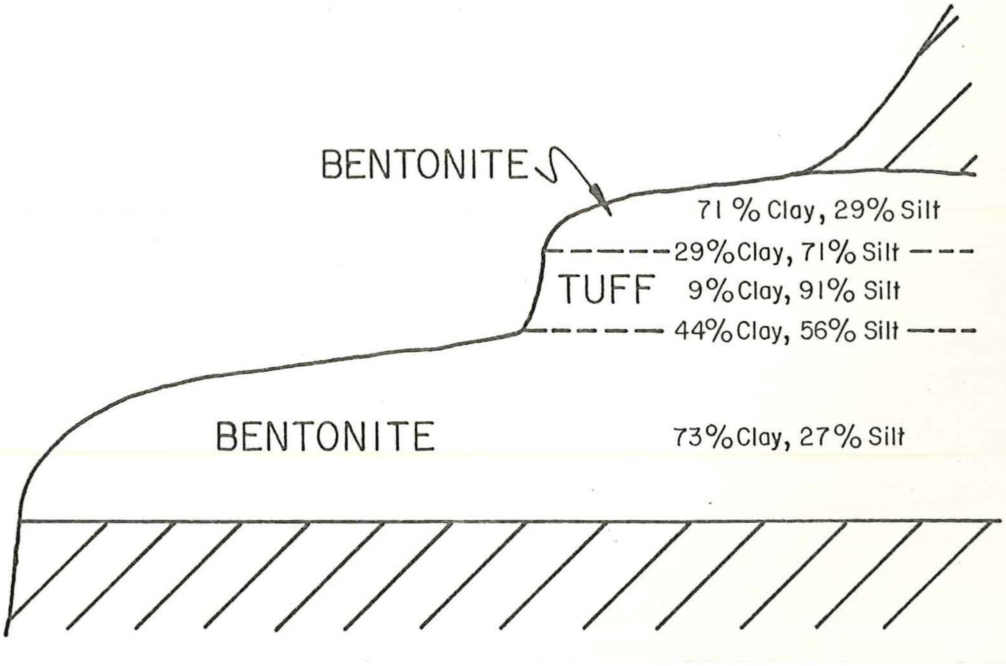

ARNEGARD
WATFORD CITY
U.S. HWY. 85
49°
46°
102°
98°
NORTH
DAKOTA
?
?
Little
Missouri
River
THEODORE ROOSEVELT
NATIONAL PARK
NORTH UNIT
N
0
5km
scale

Figure 22. Field expression and grain size characteristics of the Sentinel Butte bentonite/ash. Dashed lines represent thin (few centimeters) contact zones between ash and sandwiching bentonites.




BENTONITE
71 % Clay, 29% Silt
29%Clay, 71% Silt
TUFF
9%Clay, 91% Silt
44%Clay, 56% Silt
BENTONITE
73%Clay, 27% Silt

as having a "tri-partite" character, and Metzger (1967) wrote of "alternating blue and light gray layers", apparently no close examination of the sandwiched silt was conducted prior to this study. At all locations thus far examined, the silt is finely laminated. It is noticeably less gritty than other silts (easily determined by chewing a small sample). Microscopic examination shows it to be composed dominantly of silt-size pumice fragments and minute glass shards, verifying that it is a volcanic ash. A silica-enriched zone commonly occurs immediately below this three-layer deposit, in at least one case leading to the preservation of a water-rippled surface on a mudstone.

Petrographic, textural, and geochemical examinations have been carried out for all three layers of this deposit. Grain size data for each of the three layers and the thin (few centimeters) gradational contact zones between layers at one locality were obtained by standard pipette procedures. These data are provided in Appendix H and are summarized in Figure 22. The vertical change in clay:silt ratio between the ash and its sandwiching bentonites is suggestive of a genetic relation between the bentonites and the ash; i.e., it might be better to regard the thin contacts between layers as transition zones rather than gradational contacts. The upper and lower bentonites may be derived from an originally thicker single ash accumulation.

The silt fractions consist of 11 %, 75 %, and 4.5 % glass fragments in the lower bentonite, ash, and upper bentonite, respectively. Other components of the silt fractions include the minerals biotite, muscovite, dolomite, quartz, chlorite, plagioclase, calcite, apatite, cordierite, sphene, and zircon, in approximate order of abundance.

Most pumice fragments or vesicular glass grains in this deposit range from 30 to 60 μm in size, with glass shards commonly as small as a few microns. The majority of glass occurs as very fine silt-size grains. A variety of vesicle morphologies occur within, and control the shape of, the larger grains. Ovoid to ellipsoidal vesicles occur in irregularly shaped roughly equant grains, and wavy string-like vesicles to straight pipe vesicles occur in more elongate grains (Fig. 23a,b). The glass is isotropic and colorless, with birefringence usually absent except for a thin discontinuous rim, or patchy birefringence, seen on relatively very few grains. This birefringence is the result of alteration of glass grains to montmorillonite (Fig. 23e,f). Strain birefringence, commonly reported for hydrated glass (Ross and Smith, 1955), is not present in these grains even though the presence of "water"-filled enclosed vesicles indicates these grains are superhydrated (Steen-McIntyre, 1975). (An example of a superhydrated glass grain from the Marmarth Ash (discussed in the following section) is provided in Figure 23c,d). Using SEM, the glass grains, except where partially altered to montmorillonite, appear fresh and very angular, and show no evidence of transport abrasion.

Major element composition of glass grains from the three layers of this deposit was determined by microprobe analysis of individual grains mounted on tape. The glass is rhyolitic in composition (Table 6). No obvious difference in the major element composition of glass grains was detected between the three layers of this deposit, again suggesting an origin from a single thick ash accumulation.

The <2 μm clay fraction of all three layers consists of virtually pure montmorillonite; XRD patterns of glycolated samples provide sharp, symmetrical reflections of (001) and an integral series of secondary

Figure 23. Sentinel Butte bentonite/ash glass grains: A) glass grain with numerous ovoid vesicles, B) glass grain with elongate stringy to tubular vesicles, C,D) superhydrated glass grain with enclosed "water"-filled vesicles (arrows in C). Note slightly higher relief than open, Caedex-filled vesicles. Direction of Becke line movement shown by arrows in (D) -- away from glass grain into higher index mounting medium, and away from "water"-filled vesicles into higher index glass grain, E) glass grain with authigenic montmorillonite in elongate vesicles, F ~~D~~) close-up of authigenic montmorillonite on a glass grain. Note distinctive crenulated pattern. Bars = 10 µm, except in D, where bar = 100 µm. and F (bar = 1 µm)

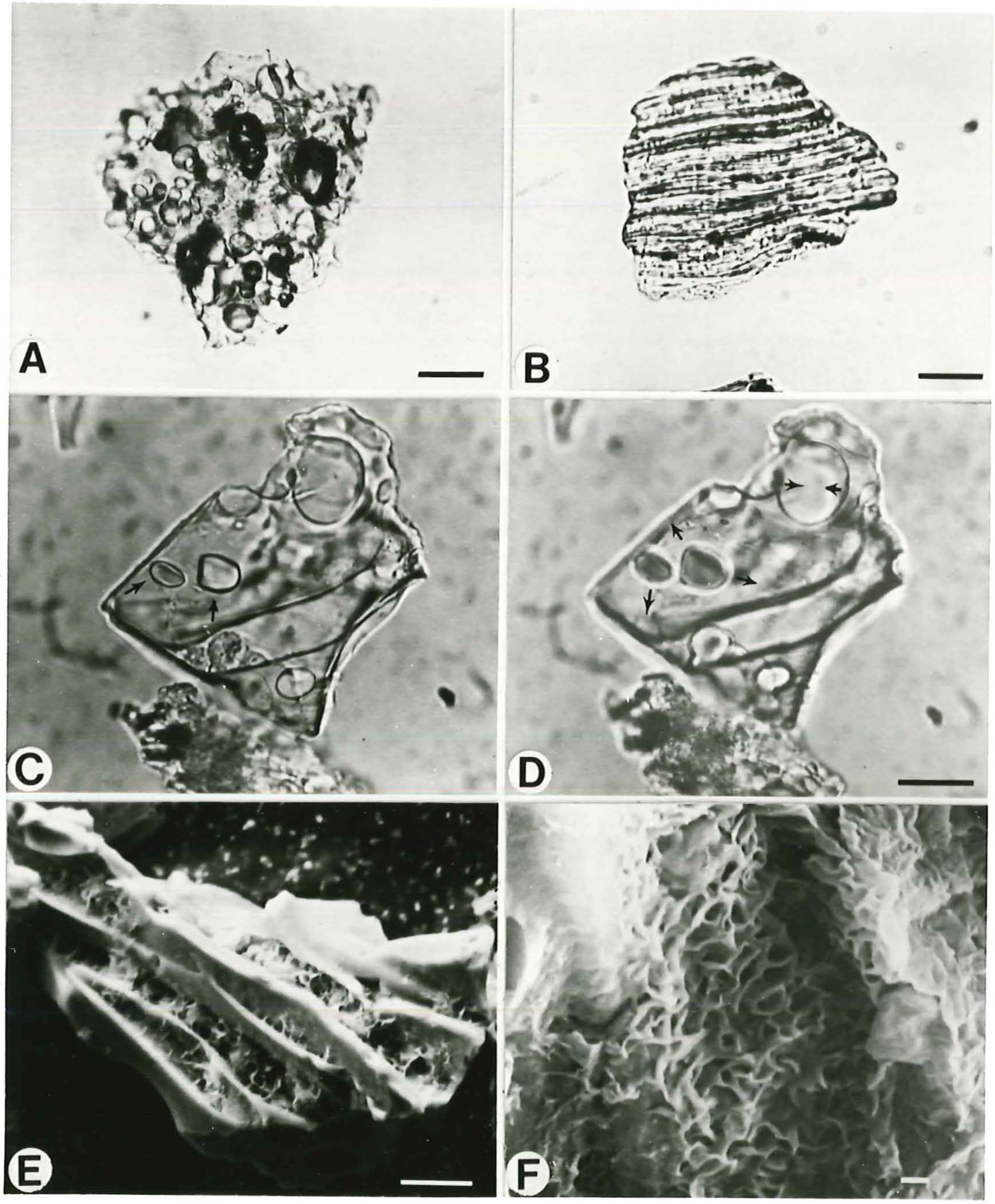

A
B
C
D
E
F

Table 6. Microprobe Analyses of Sentinel Butte Bentonite/Ash Glass Grains

| Layer: | Lower Bentonite | Tuff | Upper Bentonite | Average Rhyolite |
|---|---|---|---|---|
| | (12 analyses) | (16 analyses) | (8 analyses) | |
| $SiO_2$ | 78.80(±1.52) | 78.41(±0.89) | 78.84(±1.05) | 74.00(±3.51) |
| $Al_2O_3$ | 13.98(±1.05) | 14.50(±0.68) | 14.03(±0.57) | 13.53(±1.77) |
| FeO* | 1.36(±0.30) | 1.34(±0.25) | 1.11(±0.11) | 2.63(±1.27) |
| MgO | 0.26(±0.24) | 0.17(±0.17) | 0.23(±0.12) | 0.41(±0.48) |
| CaO | 1.28(±0.23) | 1.11(±0.14) | 1.16(±0.12) | 1.16(±0.96) |
| $Na_2O$ | 1.73(±0.42) | 2.16(±0.59) | 2.14(±0.61) | 3.62(±1.29) |
| $K_2O$ | 2.22(±0.23) | 2.13(±0.25) | 2.32(±0.22) | 4.38(±1.69) |
| $TiO_2$ | 0.12(±0.10) | 0.17(±0.18) | 0.13(±0.13) | 0.27(±0.25) |

Note: Calculated $H_2O$-free and normalized to 100 %. Values in weight percent. Standard deviation in parentheses.

*Total iron as FeO.

From LeMaitre (1976), average of 667 whole-rock samples.

basal reflections from (002) to (006). Very minor chlorite and mica basal reflections are also present in the diffraction patterns. The results of chemical analysis of the authigenic montmorillonite in this deposit are discussed on pages 105 through 116.

Most silt fraction mineral grains are <30 µm in size, making their examination by optical microscopy difficult. Minerals present were identified using SEM/EMA examinations. It is difficult to determine which minerals are phenocrysts of the original ash. The assemblage of minerals present suggests detrital admixture has occurred as well as possible authigenic mineral growth. Muscovite is not a likely phenocryst in rhyolitic eruptions, and the presence of both biotite and muscovite also seems unlikely. A range of compositions from biotite to chlorite exists among many of the sheet silicates present, suggesting a pseudomorphic alteration of biotite to chlorite. Chlorite may be entirely secondary in origin. Some but not necessarily all of the quartz in this deposit is detrital. Some quartz grains seen show evidence of the high temperature $\beta$ quartz form (Fig. 24c). Cordierite has been found in non-bentonitic Sentinel Butte rocks, and is a rare mineral in rhyolitic eruptions. It perhaps is not a phenocryst in this deposit. Plagioclase occurs in this deposit as apparently unaltered, euhedral, 20 to 30 µm, tabular, elongated, and (less commonly) equant rhomb-shaped crystals (Fig. 24a). Many grains are broken and a few reveal incipient fractures. One grain was found partially enclosed in glass (Fig. 24b). Similar plagioclase crystals have not been found in other Sentinel Butte samples. The range of compositions determined for plagioclase grains from the three layers of this deposit are shown in Figure 25. The range of compositions observed (An 25 to An 84) appears

Figure 24. Phenocrysts(?) of Sentinel Butte bentonite/ash; A) plagioclase crystal, bar = 10 µm, B) broken, tabular plagioclase crystal partly enclosed in glass, bar = 10 µm, C) quartz crystal possibly of $\beta$-form, bar = 1 µm.

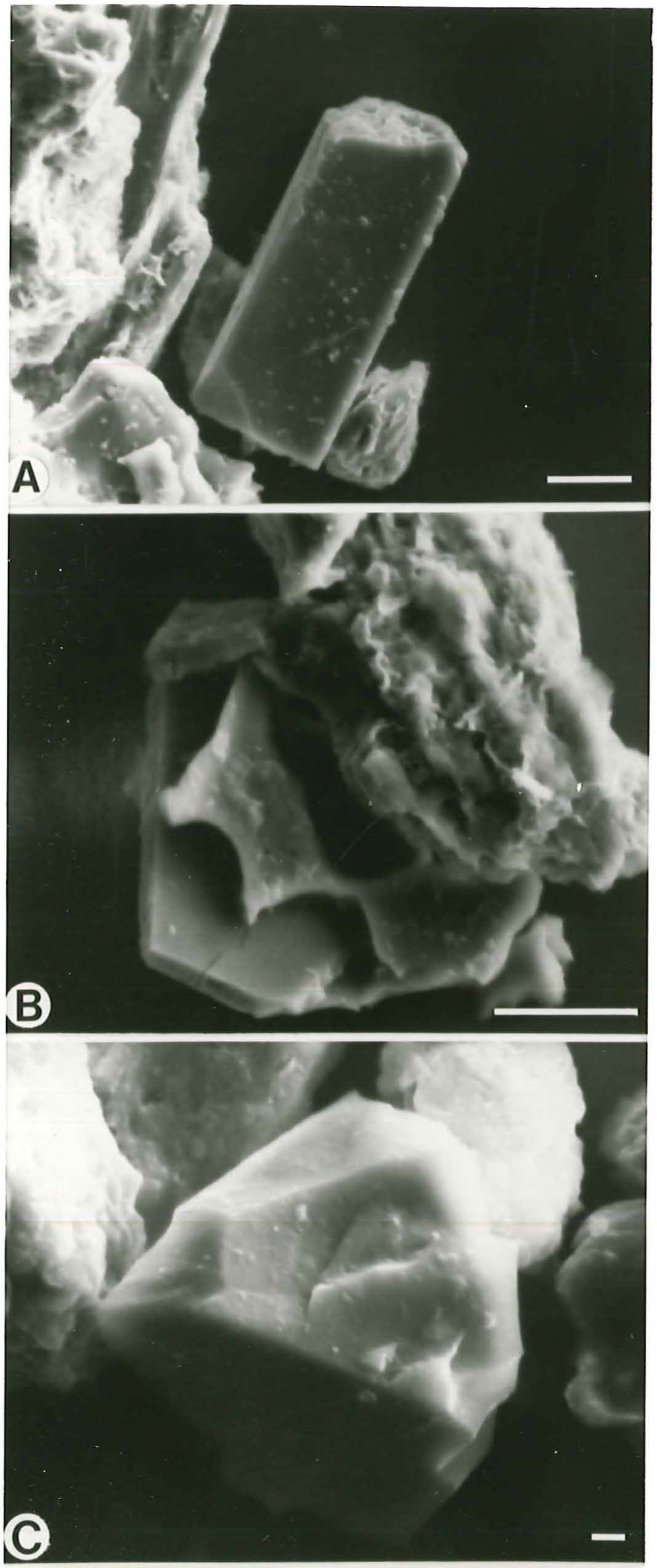
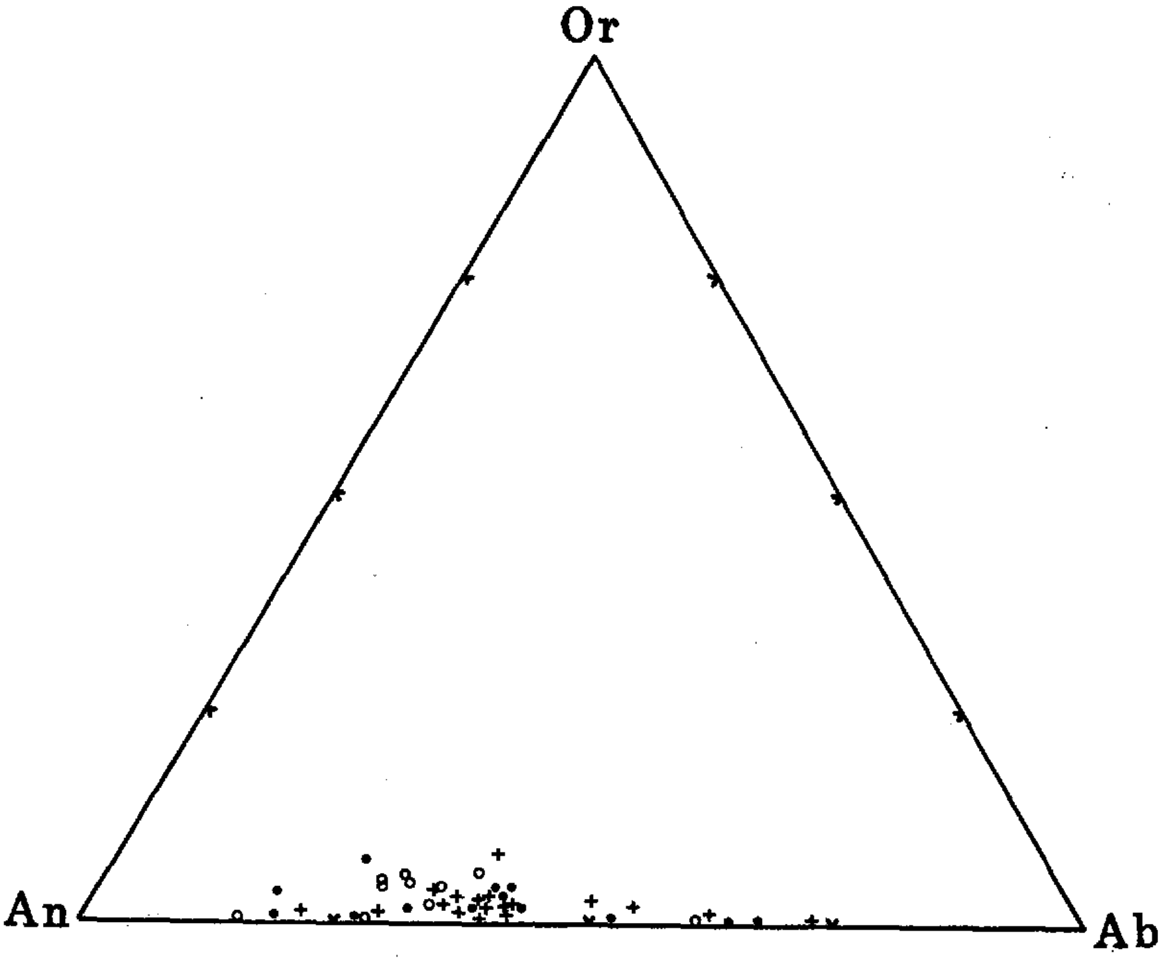

A
B
C

Figure 25. Ternary diagram showing range in composition of possible plagioclase phenocrysts from the Sentinel Butte bentonite/ash. + = ash layer, o = lower bentonite, ● = upper bentonite.


Or
An
Ab

quite broad for these grains to all be phenocrysts from a single deposit. However, because only grain surfaces and not grain cores were analyzed by microprobe, chemical zoning within crystals may account for the observed compositional variability.

Calcite and dolomite in this deposit clearly are either detrital or authigenic; these minerals do not occur as phenocrysts in rhyolites. Although sphene and zircon are likely rhyolite phenocrysts, they also occur in minor amounts in much of the Sentinel Butte sedimentary section. Slender, euhedral apatite crystals that occur in this deposit are also likely rhyolite phenocrysts, but such crystals are also fairly common in the Sentinel Butte Formation.

It is recommended that usage of the informal name "blue bed" be abandoned, and that the informal names "Sentinel Butte ash", "Sentinel Butte bentonite", and "Sentinel Butte bentonite/ash" be adopted in all references to the corresponding portions of this deposit. Many Fort Union clay layers are blue-gray when dry. It is probably in large part the emphasis on color in the name "blue bed" that has led to the probable misidentification, by earlier workers, of different blue clay layers as the single "blue bed" marker unit (see e.g., Brekke, 1979; Nesemeier, 1981). More appropriate field, petrographic, and chemical criteria are continuing to be developed to aid in the recognition and distinction of this deposit.

## The Marmarth Bentonite/Ash

An additional occurrence of ash/bentonite has been examined in an effort to further determine the characteristics of bentonites. Although this deposit does not occur in the Sentinel Butte Formation, its examination and comparison with the Sentinel Butte bentonite/ash might benefit the search for other bentonites by revealing what characteristics certain bentonites might be expected to have in common. The deposit is well-exposed in badlands terrain in Sections 4 and 5, T. 133 N., R. 105 W., Slope County, North Dakota, approximately seven km northeast of the town of Marmarth. Frye (1969) reported this deposit to be in the ~~Fox Hills~~ Tullock ([illegible]) Formation, but the most recent stratigraphic evaluation of rocks in the region shows it to occur a few meters below the top of the Upper Cretaceous Hell Creek Formation (E. Murphy, ND Geol. Survey, personal communication). It is locally similar in field expression to the Sentinel Butte bentonite/ash, consisting of an ash sandwiched between two bench-forming, popcorn-weathered bentonites. The original ash was at least locally water-laid and reworked as evidenced by ripple cross-lamination throughout a 4.6-m-thick section (Fig. 26). The Marmarth deposit differs from the Sentinel Butte deposit in the nature of the contacts between the ash and enclosing bentonites. A thin non-volcanic sandy parting occurs between the ash and the underlying bentonite in the Marmarth deposit, suggesting either two original ash accumulations or at least an interruption to an otherwise continuous ash-accumulation event. The sandy zone becomes less sandy and more clayey downward, over a 1/3 m distance, grading into the lower bentonite. The contact between the ash and the upper bentonite is gradational (perhaps transitional) over only a few centimeters thickness, but bifurcating root pathways are seen locally, extending into the upper portion of the ash from the overlying bentonite; the origin of the upper bentonite may have involved pedogenic processes. The upper bentonite seems sand-free for a thickness of only 45 to 60 cm,

Figure 26. Exposure of Marmarth bentonite/ash. The white ash layer is 4.6 m thick at this location. Note bentonite above and below ash.

above which it becomes increasingly sandy until a lignitic interval is reached.

A sample of ash from the middle of the 4.6-m-thick section mentioned above was determined by pipette analysis and optical microscopy to consist of 86 % glass grains, 9 % "phenocrysts", and 5 % clay. X-ray diffraction analysis of the <2 µm clay fraction revealed it to consist of virtually pure montmorillonite. The clay is authigenic, and formed through the alteration of glass grains. The glass grains of this deposit are coarser than those of the Sentinel Butte bentonite/ash with ~90 % distributed between the medium silt and fine sand size ranges (Appendix H). Vesicle morphologies and grain shape relations are similar to those described for Sentinel Butte bentonite/ash glass grains. The glass grains are superhydrated (Fig. 23c,d), but not devitrified, except along those margins that have altered to clay.

A sample from the middle third of the lower bentonite consists of 77 % clay, 22 % silt, and 1 % sand. An optical microscope point count of a grain mount of the silt fraction of this bentonite showed it to consist of about 20 % glass grains.

## Bentonite Petrographic Characteristics

As a result of the examination of the Sentinel Butte and Marmarth bentonites, other clay layers suspected to be bentonites were evaluated on the basis of overall clay mineralogy, clay chemistry, and the presence or absence of volcanic glass. There is no reason that some glass grains must survive alteration to clay in bentonites, but glass grains are preserved in the very well developed bentonite layers of both the Marmarth and Sentinel Butte deposits, suggesting that at least some glass perhaps normally does survive. By definition, bentonites do not have to be composed of the clay mineral montmorillonite. However, the Marmarth and Sentinel Butte bentonites are composed of montmorillonite, so it is reasonable to expect that other ashes deposited in the same geologic setting, and subjected to roughly the same geochemical environments, also alter to montmorillonite (if they alter at all). Because of the high silica content of the rhyolitic glass grains, the secondary clay also has a high silica content. The overall major element chemical composition of clay derived from glass grains appears to be a very useful criterion in identifying potential bentonites in the region of this study. This possibility is discussed further in the section which follows. Table 7 summarizes the descriptive laboratory characteristics of the known bentonites and of all the samples collected as possible bentonites (Appendix A). Consistent laboratory procedures were utilized for each sample to insure that similar size fractions were compared. The characteristics of the known bentonite samples include a very high total <2 μm clay percentage, a nearly monomineralic <2 μm clay composition, a high-silica clay chemical composition, and the presence of preserved glass grains in silt fractions. As mentioned above, clay from the bentonite samples also produces sharp, symmetrical XRD peaks characteristic of well ordered structures.

Contrary to the report of Clark (1966), that, "Microscopic studies reveal the presence of glass shards throughout much of the Sentinel Butte member", glass other than that associated with the Sentinel Butte bentonite/ash was not found in any samples examined. In view of Clark's description of glass shards: "These shards range from acicular fibrous

Table 7. Characteristics of Bentonites (b) and Potential Bentonite Samples

| SAMPLE | GLASS PRESENT (?) | % CLAY | <2μm CLAY MINERALS | CLAY % Si |
|---|---|---|---|---|
| EG-11 (b) | yes | 80 | M*,7Å(tr) | 66.1 |
| EG-13 (b) | yes | 78 | M*,7Å(tr) | 63.2 |
| BB-3 (b) | yes | 73 | M*,7Å(tr) | 67.4 |
| BB-9 (b) | yes | 71 | M*,7Å(tr) | 68.7 |
| Marmarth (b) | yes | 86 | M* | 68.6 |
| BENT-1 (b) | yes | 66 | M*,7Å(tr) | 66.8 |
| BENT-3 (b) | yes | 84 | M*,7Å(tr) | 68.4 |
| LX-A | NO | 86 | M,MICA | 63.4 |
| LX-E | NO | 70 | M(m),C,K | 63.8 |
| LX-J | NO | 97 | M(m),C,K | 65.9 |
| LX-"C" | NO | 70 | M*,C,MICA(tr) | 64.1 |
| sbk-10 | NO | 66 | M,C,K,MICA | 60.6 |
| LX-11 | NO | 67 | M,C | 60.0 |
| BB-5 | NO | 88 | M*,C,MICA | 69.5 |
| BB-7 | NO | 41 | M,C,MICA | 68.9 |
| BB-17 | NO | 54 | M*,C(tr) | 64.0 |
| BADLANDS 3 | NO | 86 | M,C,MICA | 56.5 |
| SB-C | NO | 81 | M,C,MICA | 57.3 |
| SHB-1 | NO | 70 | M,7Å,MICA | 59.8 |
| SHB-6 | NO | 83 | M,C,MICA | 63.4 |
| KP-B | NO | 99 | M,C,MICA | 59.9 |
| 7= 15 | NO | 61 | M,7Å,MICA | 59.9 |
| LX-K | NO | 100 | M(m),C,K | 58.3 |

* (well-ordered, giving sharp, symmetrical peaks and a rational series of basal reflections)

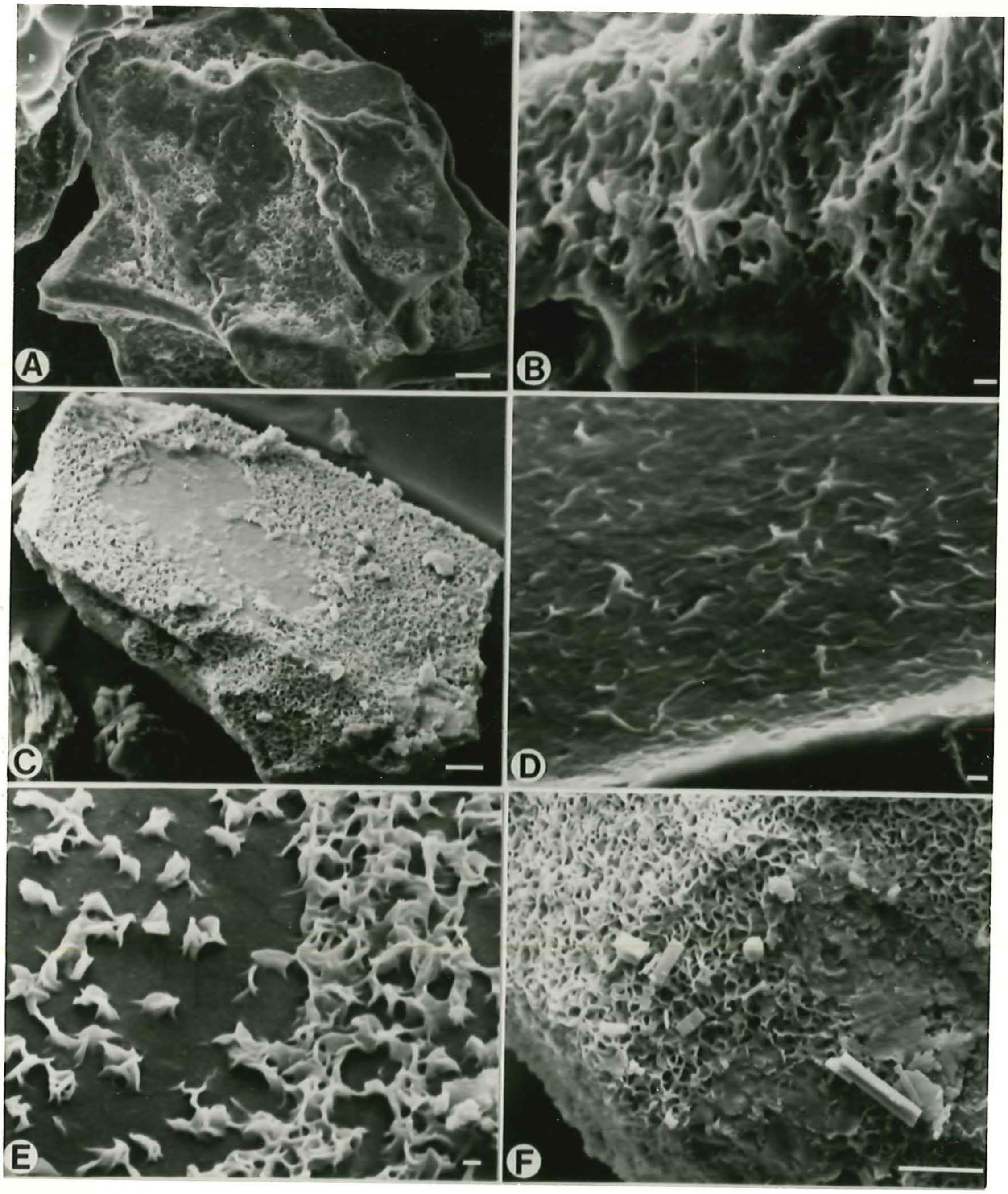
abbreviations: (b) = known bentonite, M = montmorillonite, C = chlorite, K = kaolinite, m = minor, (tr) = trace shapes to splinters, are .25 to 100 µm long, and colorless, greenish, brown and black.", it seems likely that he actually saw plant fragments. Plant fragments are abundant throughout much of the Sentinel Butte Formation, and are present in sand fractions as variably colored grains, having undergone varying degrees of carbonification or coalification, and fit well the shape and size characteristics given by Clark for so-called glass shards.

# CLAY MINERAL ORIGINS AND CHEMICAL COMPARISONS

It is clear that the pore-lining montmorillonite in Sentinel Butte sandstones formed by chemical precipitation from pore fluids. The clay lines pores and only fills them where it has extensively developed. It coats all detrital grains regardless of their composition. The clay is easily dislodged by washing, leaving smooth detrital grain surfaces showing no evidence of alteration to clay. The clay attached to volcanic glass grains did not precipitate from pore fluids, but formed _in situ_ as an alteration product of the glass itself. Crystallization of glass grain surfaces to clay was accompanied by addition of some ions from pore solution. But the clay does not seem to have formed through any large-scale dissolution/re-precipitation process. This judgment is based on visual evidence gathered from examination of clay/host-grain relationships (Fig. 27). In contrast to the visual evidence that authigenic montmorillonite in Sentinel Butte sandstones is lying upon host detrital grains (Fig. 27c,e,f), the clay associated with glass grains appears to be a part of the glass grain surface. Crenulated montmorillonite appears to derive from the glass surface itself (Fig. 27a,b,d). Furthermore, the glass-derived clay, unlike the pore-lining clay, is not dislodged from the host grain surface during the disaggregation or wet-sieving process.

A comparison of the major element chemical composition of Sentinel Butte montmorillonites has been conducted in an effort to determine whether glass-derived montmorillonites are chemically distinct from those of other origins. A slurry of the <2 µm clay fraction of each sample examined was allowed to dry on a clean glass slide which was then carbon coated for microprobe analysis. This technique does not produce

Figure 27. Authigenic clay/host-grain relationships in Sentinel Butte samples; A) authigenic montmorillonite derived from glass grain surface, bar = 10 µm, B,D) close-ups of crenulated montmorillonite derived _in situ_ from glass grain surfaces, bars = 1 µm, C) montmorillonite formed by precipitation onto detrital quartz grain, bar = 10 µm, E) close-up of precipitated authigenic montmorillonite, note smooth, unaltered surface of host grain, bar = 1 µm, F) precipitated authigenic montmorillonite superposed by clinoptilolite crystals, bar = 10 µm.


A
B
C
D
E
F

a smooth, flat surface best for microprobe analysis, but is adequate for the simple comparison of sample compositions. Analyses of each sample were calculated using the matrix correction program of Bence and Albee (1968). Twenty four samples were analyzed, including six known detrital montmorillonites (from claystones), four precipitated authigenic montmorillonites (from sandstones), ten glass-derived montmorillonites (from bentonites and ashes), and four samples of unknown origin. Sample names and major element chemical data are provided in Appendix I. A second oriented clay mount, identical to that used for microprobe analysis, was prepared for each sample for XRD analysis. Results indicate that all samples are nearly pure montmorillonite, with a minor amount of chlorite and mica occurring in a few samples, particularly those of detrital origin. The small amount of additional clay minerals is not thought to have affected adversely the intended comparison of montmorillonite composition in the samples examined. Averaged major element values of samples from each of the four genetic groups examined are presented in Table 8. There are apparent chemical differences between some groups, particularly in the values of silicon and potassium.

Table 8. Averaged Chemical Composition of Compared Clay Groups

| Clay Groups: | glass-derived | detrital | precipitate | unknown |
|---|---|---|---|---|
| $SiO_2$ | 67.25 | 57.45 | 58.73 | 61.74 |
| $Al_2O_3$ | 18.79 | 18.97 | 21.07 | 22.06 |
| FeO | 4.33 | 5.90 | 5.54 | 5.92 |
| MgO | 3.30 | 2.62 | 2.41 | 2.25 |
| CaO | 1.48 | 2.22 | 1.14 | 0.77 |
| $Na_2O$ | 3.43 | 7.33 | 8.30 | 2.44 |
| $K_2O$ | 0.47 | 2.21 | 0.39 | 2.75 |

The chemical data for all samples were subjected to both cluster and discriminant analysis in an effort to determine whether groupings of chemically similar samples correspond to groupings based on known origins, and to determine if clays of known origin are sufficiently distinct to suggest that clay samples of unknown origin may be allocated to one of the known groups using statistical techniques. Results of the cluster analysis and the discriminant analysis are summarized in Figures 28, 29, and 30. Discriminant scores are provided in Appendix J. Only the glass-derived clays form a distinct group in cluster analysis. The remaining clays do not cluster into groups corresponding to their origins. This suggests that glass-derived clays may be effectively distinguished from other clays by chemical composition, but that clays of other origins may be less effectively distinguished from one another by major element composition. Discriminant analysis revealed that the clay samples of unknown origin are closest in composition to the grouping of detrital clays. However, plotting discriminant scores of the four individual unknowns on the line with glass-derived clay values reveals one of the unknowns (LX-"C") to plot near the glass-derived clay scores (Fig. 29). This potential bentonite sample is discussed further below. In general, using major element variables, glass-derived clays appear distinct from Sentinel Butte clays of other origins. Silicon values account for most of the major element chemistry difference between glass-derived clays and both detrital and authigenic precipitated clays (Table 9).

Figure 28. Cluster dendrogram of chemical analyses of Sentinel Butte claystones. Four claystone groups are compared: D = detrital, P = precipitated, G = glass-derived, U = unknown origin.

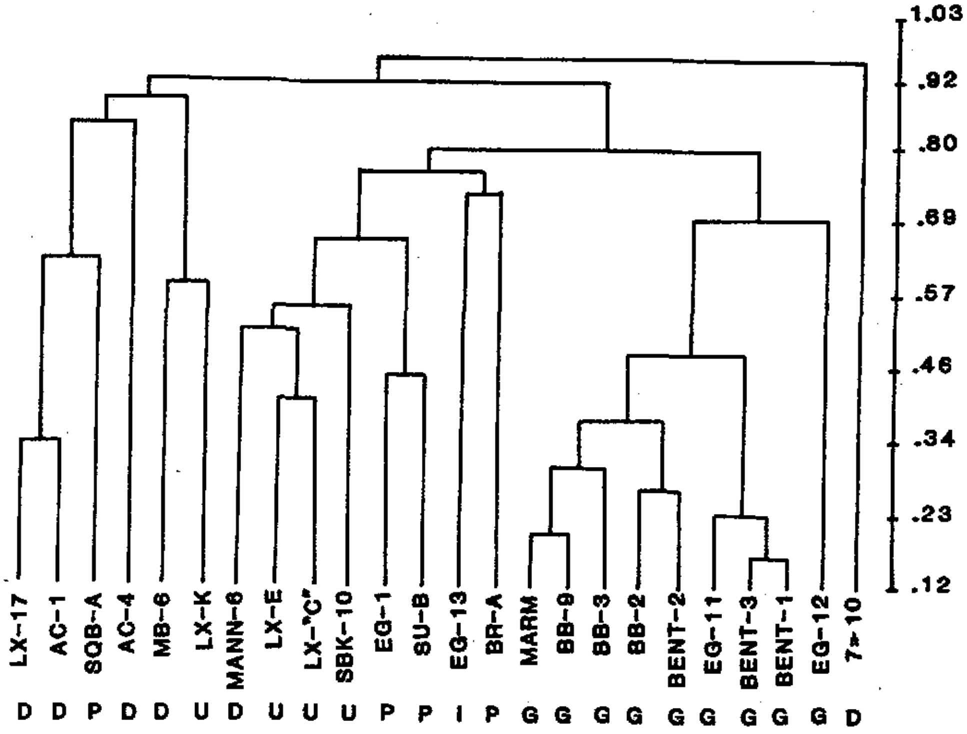
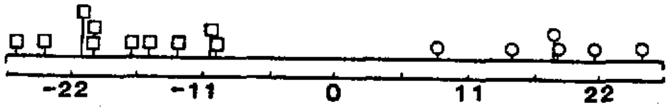
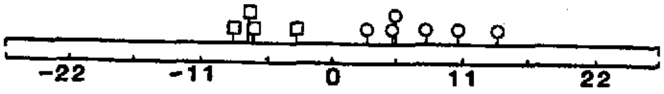

1.03
.92
.80
.69
.57
.46
.34
.23
.12
LX-17
AC-1
SQB-A
AC-4
MB-6
LX-K
MANN-6
LX-E
LX-"C"
SBK-10
EG-1
SU-B
EG-13
BR-A
MARM
BB-9
BB-3
BB-2
BENT-2
EG-11
BENT-3
BENT-1
EG-12
7=10
D D P D D U D U U U P P I P G G G G G G G G G D

Figure 29. Projection of samples from Appendix J onto discriminant function lines. D = Mahalonobis' distance, C.L. = confidence limit.



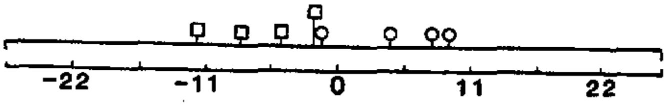
○ = Detrital □ = Glass-Derived

$D^2$ = 34.08 C.L. = 98 %



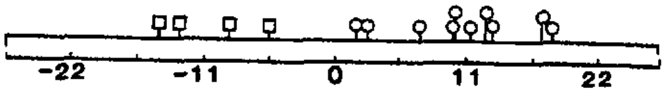
○ = Detrital □ = Precipitated

$D^2$ = 14.09 C.L. = 50 %



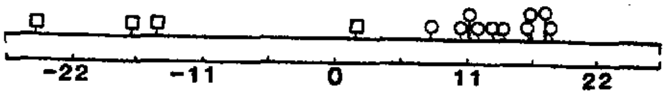
□ = Unknown ○ = Detrital

$D^2$ = 12.91 C.L. = 50 %



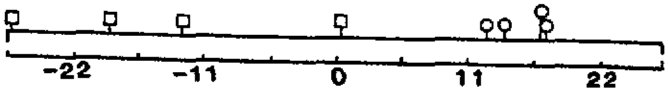
□ = Precipitated ○ = Glass-Derived

$D^2$ = 20.17 C.L. = 75 %



□ = Unknown ○ = Glass-Derived

$D^2$ = 26.30 C.L. = 95 %



□ = Unknown ○ = Precipitated

$D^2$ = 28.88

Table 9. Percent Contribution of Elements Toward Discriminant Distances

| | % contribution | | | | | |
|---|---|---|---|---|---|---|
| group: | D/GD | D/P | D/U | GD/P | GD/U | P/U |
| $SiO_2$ | 61 | 2 | 46 | 82 | 15 | 13 |
| $Al_2O_3$ | -1 | 13 | 31 | -19 | -15 | 2 |
| FeO | 12 | 1 | -1 | 13 | 5 | -2 |
| MgO | 14 | -1 | -2 | 30 | 25 | -1 |
| CaO | -1 | -3 | 12 | 0 | 4 | 2 |
| $Na_2O$ | -3 | 0 | -4 | -8 | 1 | -3 |
| $K_2O$ | 19 | 89 | 16 | 1 | 66 | 88 |

abbreviations: D = detrital, P = precipitated, U = unknown, GD = glass-derived

Although not clearly distinguished as groups by cluster analysis, the detrital and precipitated authigenic montmorillonite samples were treated as separate groups in the discriminant analysis because of their differing origins. A meaningful, at the 50 % confidence level, discriminant function distance was obtained between these two groups. Calculation of the percent contribution from each variable (each chemical element) to the discriminant function reveals that potassium content contributes most to the chemical distinction between detrital and precipitated authigenic Sentinel Butte clays (Table 9).

The results of the chemical comparison of Sentinel Butte montmorillonites can be summarized as follows. Based on the examination of ten glass-derived, four pore-lining (precipitated), six detrital, and four other (of unknown-origin), <2 µm clay samples, clays from Sentinel Butte bentonites (and ashes) appear chemically distinct from other Sentinel Butte clays. Authigenic precipitated and detrital clay groups appear distinct from one another, particularly in potassium content; higher potassium values were detected in detrital clays. Silicon content alone may, in some cases, serve to distinguish Sentinel Butte bentonites from other claystones.

Following the determination that known bentonites are discriminated from other Sentinel Butte claystones by major element composition, each of the samples listed in Table 7 were evaluated, on the basis of the discriminant function between detrital and glass-derived clays, as to whether they should be allocated to the group of known bentonites. Figure 30 shows that four of the potential bentonite unknowns plot on the glass-derived authigenic or bentonite side of the discriminant line. Three of the samples (BB-5, BB-17, and LX-"C") are from stratigraphic positions just above the Sentinel Butte bentonite/ash deposit. These samples may have been silica enriched as a result of their proximity to the known bentonite. The remaining sample (SHB-1) may represent the Sentinel Butte bentonite from a location where the tri partite character is absent.

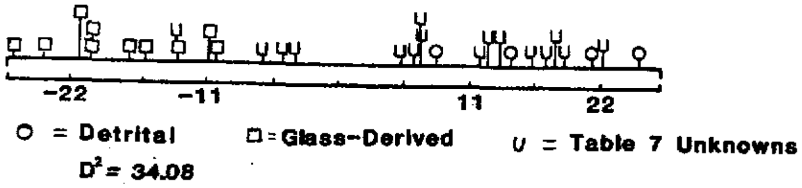


Figure 30. Projection of samples from Table 7 onto the discriminant function line between known detrital and known glass-derived authigenic clays.

A determination of clay mineral origin by alteration of ash requires further supportive evidence than that afforded by clay mineralogy and major element composition alone. Glass grains are common in the known bentonites examined, but glass grains have not been identified in the four samples that do, nonetheless, group with glass-derived clays in discriminant analysis. Further study of clay samples pre-selected by XRD and discriminant analysis may yet provide more conclusive answers regarding clay mineral origins. Particularly, the study of trace element composition and structural ordering of pre-selected clay samples may be of value in the search for bentonites or authigenic clays in general.

# LIGNITE

Lignite is an important rock type in the Sentinel Butte Formation, as an indicator of depositional environments, as a potentially useful tool for interpretations of sedimentation and subsidence rates, and as an energy source and source of energy-related materials for a technological society. Laboratory examinations of lignites require specialized techniques that are dependent on the type of information sought. In this study, geochemical data from lignitic samples have been compared with visual rankings of those samples in an effort to obtain information concerning the histories of Sentinel Butte lignites.

Sentinel Butte organic-rich samples can be visually ranked in an order from least lignitic to most lignitic. In so doing, the samples may actually be arranged in a pre-lignitic to lignitic to lignite order; that is, some samples might be lignite precursor material with the visual ordering of the samples then representing an increasing degree of coalification between samples. Such an hypothesis is difficult to test without employing specialized and detailed studies of the materials comprising each sample. Preliminary characterization of the samples has been conducted, and the data examined for the presence of any chemical trends corresponding to sample ranks that might add credence to the lignite-precursor hypothesis.

Standard proximate, ultimate,and heating value analyses were obtained for all 20 lignitic samples at the University of North Dakota Energy Research Center (UNDERC). Proximate analysis determines the percentage of volatile matter, fixed carbon, moisture, and ash. Ultimate analysis determines carbon, hydrogen, sulfur, nitrogen, ash, and the oxygen content by difference. As-determined values can be recalculated to as-received, dry, and dry-and-ash-free bases (ASTM, 1980). Heating value analysis determines calorific value expressed in British Thermal Units (BTU) per pound of coal. The results of these various analyses are provided in Appendix K.

One of the ways of expressing compositional relationships between coals and coal precursors or products is through the use of a graph of atomic H/C versus atomic O/C (Pitt and Millward, 1979). On such a graph nearly all coals lie within a narrow curved band, representing, as coalification and coal rank increase, a tendency first toward decreasing values of O/C and then toward decreasing values of H/C (Fig. 31). Lines representing various chemical reactions involved in the development of coals, such as decarboxylation, dehydration, and demethanation, are commonly drawn on such diagrams. These lines can be used to infer reaction pathways between two substances plotted on the same graph. The plotting of H/C and O/C values for each of the organic-rich Sentinel Butte samples reveals most samples to have O/C values consistent with lignites, but to be low in hydrogen. No compositional trends corresponding to the subjective visual ranking of the samples are evident in Figure 31.

An attempt was made to rank visually the samples in a possibly more objective way by using color designations. With the assistance of three volunteers, independent gray-scale values were assigned to each sample. An average color value was then obtained for each sample.

The results of tests of correlation between rank and all determined chemical variables, are provided in Appendix L. The visual ranking and carbon content of each sample are presented in Table 10. The original visually determined rank of each sample correlates well with both as

Figure 31. Twenty Sentinel Butte lignitic samples plotted on a graph of atomic H/C versus atomic O/C. Positions of samples are indicated by numbers that represent a visually determined rank of lignitic character from 1 for least lignitic to 11 for most lignitic. (A) represents wood, (B) cellulose, (C) lignin, (D) peat, (E) lignite, (F) low-rank coal, (G) medium-rank coal, (H) high-rank coal, (I) semi-anthracite, (J) anthracite. (Modified from Pitt and Millward, 1979, after van Krevelen, 1950).

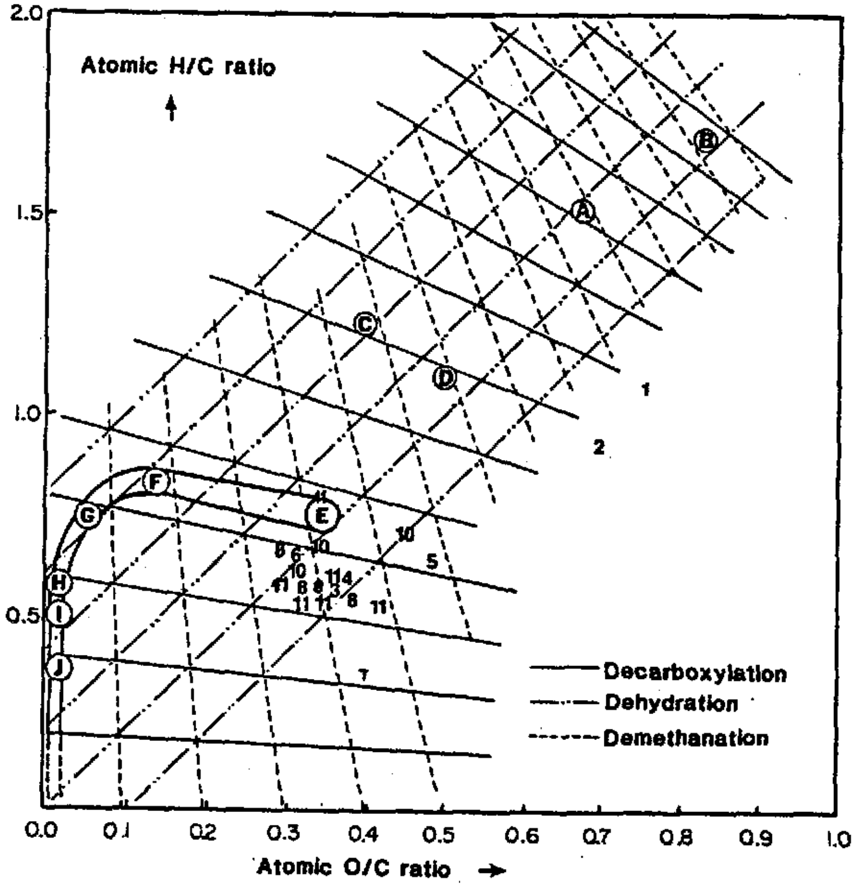

2.0
Atomic H/C ratio
1.5
1.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Atomic O/C ratio
A
B
C
D
E
F
G
H
I
J
1
2
10
5
11
8
6
10
10
11
8
8
11
4
3
11
11
8
11
7
Decarboxylation
Dehydration
Demethanation

Table 10. Visual Ranks and Carbon Content of Sentinel Butte Lignitic Samples

| Sample | Visual Rank | Gray-Scale Rank | Carbon %* |
|---|---|---|---|
| LB-2 | 8 | 1.6 | 38.64 |
| MB-7 | 7 | 1.6 | 23.15 |
| SBK-3 | 11 | 1.6 | 39.19 |
| KP-7 | 5 | 1.3 | 15.65 |
| Mann-2 | 8 | 2.2 | 51.48 |
| 7=C | 10 | 1.9 | 51.24 |
| AC-8 | 8 | 1.3 | 39.42 |
| LX-F | 8 | 1.3 | 48.78 |
| EG-8 | 11 | 1.3 | 51.49 |
| AC-2 | 10 | 1.6 | 44.40 |
| 7=B | 11 | 2.2 | 52.46 |
| SB-9 | 11 | 1.6 | 30.38 |
| SB-16 | 1 | --- | 7.35 |
| LX-21 | 6 | 1.3 | 34.51 |
| SB-19 | 3 | 1.6 | 27.53 |
| EG-3 | 4 | 1.3 | 44.85 |
| AC-B | 10 | 1.9 | 42.77 |
| LX-B | 11 | 2.2 | 50.37 |
| SBK-9 | 11 | 1.6 | 51.75 |
| EG-16 | 2 | --- | 5.26 |

*as-determined values listed.

determined and moisture-and-ash-free carbon content (correlation coefficients of .767 and .731, respectively). Gray-scale color values do not reveal a strong correlation with any determined chemical variables.

If carbon content can be regarded as an indication of degree of coalification, the correlation between carbon content and visual appearance of Sentinel Butte lignitic samples suggests that lignite precursor material in various degrees of coalification presently exists in that formation. Further specialized study of such samples may provide new information regarding coal petrogenesis.

# DISCUSSION

## Introductory Statement

This study has attempted to characterize Sentinel Butte sediments and to determine which types of petrographic examination are most useful for determination of provenance and reconstruction of Early Tertiary geologic history. Materials shed from a source terrane are modified in several ways in the course of becoming a sedimentary rock. During transportation, differential abrasion and attrition of minerals and rock fragments of different mechanical durabilities acts to regulate the final primary mineralogy and mineral/grain size relations of a sedimentary deposit. Sorting of minerals into different deposits or into different grain size classes of the same deposit occurs in response to the interaction of a moving fluid with grains of different size, density, and shape. During, and even after lithification, minerals may be lost partially or completely or added to a deposit by the effects of dissolution, alteration, and precipitation.

Understanding the history and particularly the provenance of some sedimentary rocks is a difficult task. Significant, especially for distal sedimentary deposits, are the effects of mixing and dilution of minerals during transport, which commonly all but eliminate the chances of deciphering provenance. In such cases, an understanding of provenance is normally gained only through an integrated effort involving detailed studies within the fields of both sedimentology and stratigraphy. Such is the case with rocks of the Sentinel Butte Formation and other units comprising the Fort Union Group in and near the Williston Basin region of the Western Interior. An understanding of the provenance of these rocks and, more significantly, an understanding of the nature and timing of Laramide activities leading to the development of these rocks, is a long-term objective that can only be gained through an integration of many studies.

## Detrital Constituents

Rock fragments and feldspar grains comprise a large portion of Sentinel Butte sediments. The sandstones examined can be classified as either litharenites or feldspathic litharenites. The sand fractions of most Sentinel Butte samples examined are very fine grained, causing great difficulty in identifying individual rock fragment types. It is unfortunate that more detailed rock fragment information is not a product of this study, as rock fragments are commonly invaluable as indicators of specific source terranes or source terrane types. Most Sentinel Butte rock fragments are volcanic. It is true that, in point counting, the majority of rock fragments ~~were~~ was unclassifiable. But of the four basic rock fragment types, plutonic, volcanic, metamorphic, and sedimentary, most recognizable Sentinel Butte rock fragments are volcanic. In that glassy volcanic rock fragments are likely to be the most labile constituents of sandstones, and that grain alteration, in part, hindered rock fragment identifications in Sentinel Butte samples, it is probable that the majority of unclassified Sentinel Butte rock fragments ~~are~~ is volcanic. Few sedimentary rock fragments were clearly identified in the samples examined. Many volcanic rock fragments resemble siltstone fragments, but are shown by microprobe analyses to have highly feldspathic compositions. Many grains initially identified as chert were determined to be fine-grained volcanic rock fragments when examined by SEM/EMA. Although some sedimentary rock fragments in the form of chert are present, a detailed, specialized study of rock fragments would be required to provide quantitative data. Metamorphic rock fragments are fairly minor in most Sentinel Butte samples but are abundant in the upper sandstone. They are easily recognized especially where schistose or sheared polycrystalline quartz textures are present.

From the rock fragment data gathered in this study, it appears that Sentinel Butte sediments were derived from intermediate to felsic volcanic, sedimentary, metamorphic, and perhaps plutonic terranes, but apparently primarily from volcanic terranes. The presence of quartz overgrowths on detrital grains in one sample suggests a previous erosional cycle for at least some of the grains derived from sedimentary terranes. The presence of volcanic rock fragments in Sentinel Butte samples does not reveal whether sediments were derived from older volcanic terranes or from contemporaneous volcanic activity. However, the presence of bentonite and volcanic ash in the Sentinel Butte Formation indicates that volcanic activity did take place during Sentinel Butte time. Moreover, the dominance of volcanic rock fragments in Sentinel Butte samples is strongly suggestive of the relative amount of volcanic terrane exposed in the source area(s) of Sentinel Butte sediments. Differential attrition of rock fragments as a result of differences in weathering at source areas and differences in physical and chemical durabilities of various rock fragment types are important considerations in studies of provenance. The effects of differential attrition on Sentinel Butte materials might become more evident and more easily interpretable if data can eventually be integrated among studies of both distal and proximal Fort Union Group sediments.

Quartz and feldspar content varies between the samples examined (Table 2). Polycrystalline quartz varieties are only a minor component of most samples examined, and normally reveal no clear indications of source. Quantitative determinations of feldspar types have been presented above for one sample each of the basal and upper sandstones. Alkali and plagioclase feldspar varieties are approximately subequal in Sentinel Butte samples considered as a whole, and intermediate plagioclase varieties dominate over sodic varieties with only minor calcic plagioclase present. Average feldspar content of the samples examined, presuming all carbonate grains are authigenic, and counting only detrital components, is 17 %. Even assuming all carbonate grains to be detrital leads to an average feldspar value of 14 %. Such values seem high in comparison to other estimates of feldspar percentages in continental interior deposits (Pettijohn et al., 1973, p. 36). This may be an artifact of insufficient published data on feldspar occurrences in Laramide and post-Laramide continental interior deposits, but might also be a result of the preservation of feldspar grains in fine sand and silt size classes due to reduced mechanical abrasion and breakage of such small grains in fluvial environments; it has been common practice in many petrographic studies of sedimentary rocks to investigate only sand size grains. Chemical dissolution of feldspar grains has occurred in many portions of the Sentinel Butte Formation, but probably has not had a great effect on the overall abundance of feldspar in the formation.

Except for an increase in metamorphic rock fragment content in the uppermost Sentinel Butte sand, and an apparent difference in heavy mineral amounts and types present (Table 4), and a slight difference in feldspar compositions in the basal and upper Sentinel Butte sandstones

(Fig. 7), there appear to be no major differences in any other determined mineralogic variables within the rest of the formation (Table 11 and Fig. 32).

The reader is urged to consider the data used in preparing Figure 32 before drawing any conclusions regarding real or suggested mineralogic differences between measured section locations. The drawing is provided only as a visual aid to the data presented in Tables 2 and 11. Conclusions regarding dispersal trends or patterns were not made for several reasons: 1) A single sample of a sandstone from a section site is not necessarily representative of that sandstone; 2) The total thickness of exposed section and the number of sandstones available for sampling at a given section site varies between section locations; 3) Temporal relations between the sands at different section sites generally are not known. Future studies designed to compare materials from different section sites must consider these factors.

Lateral differences in mineral proportions are not normally expected in distal sedimentary deposits where the effects of mixing are most pronounced. Such differences may occur where multiple drainage systems bring sediments from different source terranes. The paleodrainage pattern for the Early Tertiary in the region of this study is not well understood. Royse (1970), based on a comparison of cross-bed measurements between the Tongue River (now Bullion Creek) and Sentinel Butte Formations, suggested a variable paleoslope with shifting river courses and changing or multiple areas of sediment supply for Sentinel Butte time. Winczewski (1982) suggested that Sentinel Butte sediments were derived from diversions of the Powder River Basin fluvial system around the north end of the Cedar Creek anticline. It may well be that

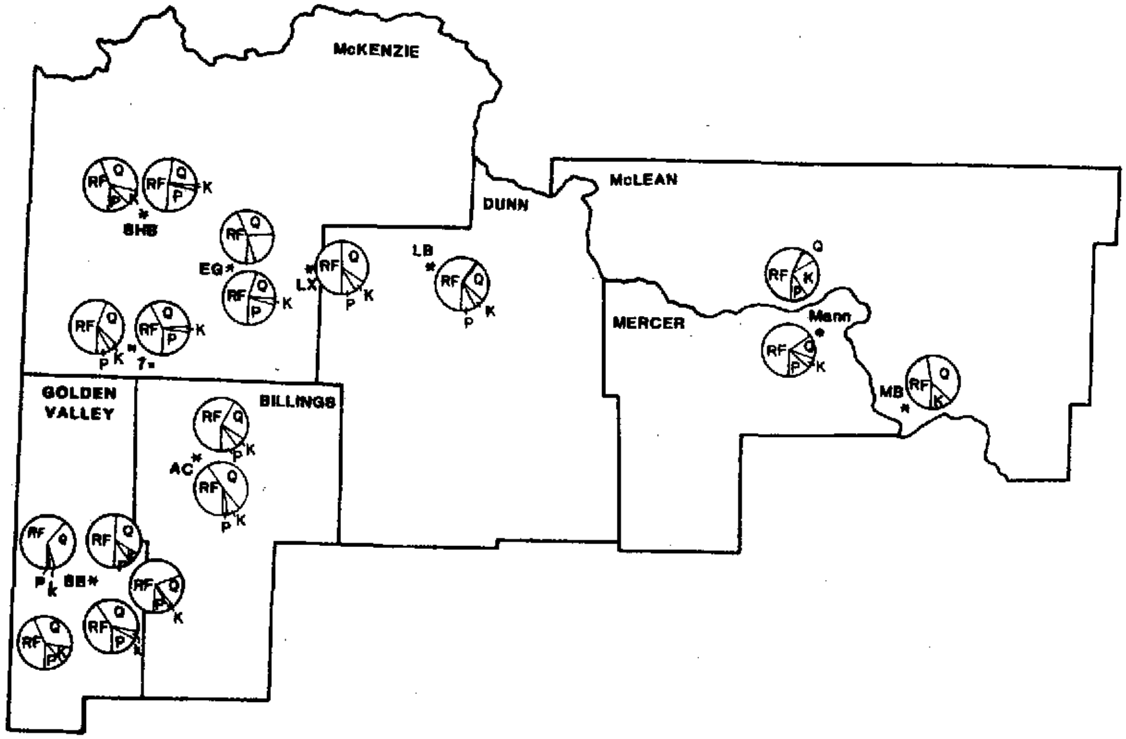
Table 11. Ratio Values Between some Mineralogic Variables of Sentinel Butte Sandstones*

| Sample | RF% | S | RF:S | Q:K+P | K:P | RF:K+P | RF:K | RF:P |
|---|---|---|---|---|---|---|---|---|
| EG-1 | 43 | 54 | 0.8 | 1.2 | 0.2 | 1.7 | 8.6 | 2.1 |
| EG-17 | 47 | 39 | 1.2 | 0.9 | 0.2 | 2.2 | 15.7 | 2.6 |
| SB-12 | 44 | 42 | 1.0 | 2.2 | 0.4 | 3.4 | 11.0 | 4.9 |
| SB-17 | 42 | 18 | 2.3 | 2.6 | 4.0 | 8.4 | 10.5 | 42.0 |
| SB-18 | 60 | 38 | 1.6 | 0.5 | 1.0 | 30.0 | 60.0 | 60.0 |
| SB-21 | 29 | 39 | 0.7 | 1.6 | 1.1 | 1.9 | 3.6 | 4.1 |
| SB-25 | 40 | 55 | 0.7 | 2.0 | 0.2 | 2.1 | 13.3 | 2.5 |
| 7=1 | 46 | 36 | 1.2 | 2.3 | 0.6 | 4.1 | 11.2 | 6.4 |
| 7=G | 41 | 58 | 0.7 | 1.1 | 0.2 | 1.5 | 8.2 | 1.8 |
| LB-8 | 59 | 39 | 1.5 | 2.2 | 3.0 | 4.9 | 6.5 | 19.7 |
| SHB-3 | 40 | 50 | 0.8 | 1.5 | 0.7 | 2.0 | 5.0 | 3.3 |
| SHB-7 | 51 | 45 | 1.1 | 1.0 | 0.2 | 2.3 | 17.0 | 2.7 |
| LX-3 | 42 | 42 | 1.0 | 2.2 | 0.9 | 3.2 | 7.0 | 6.0 |
| LX-M | 25 | 18 | 1.4 | 1.2 | 0.1 | 3.1 | 25.0 | 3.6 |
| Mann-5 | 52 | 28 | 1.9 | 0.9 | 0.5 | 3.5 | 10.4 | 5.2 |
| Mann-7 | 50 | 39 | 1.3 | 1.1 | 0.5 | 2.6 | 8.3 | 3.8 |
| AC-6 | 44 | 32 | 1.4 | 1.9 | 0.6 | 4.0 | 11.0 | 6.3 |
| AC-9 | 37 | 52 | 0.7 | 4.2 | 2.3 | 3.7 | 5.3 | 12.3 |
| MB-8 | 30 | 34 | 0.9 | 3.9 | --- | 4.3 | 4.3 | --- |
| SQB-A | 48 | 46 | 1.0 | 2.8 | 0.9 | 3.7 | 8.0 | 6.9 |
| BR-A | 42 | 56 | 0.7 | 1.5 | 0.4 | 1.9 | 7.0 | 2.6 |
| SU-B | 40 | 54 | 0.7 | 3.9 | 1.7 | 3.6 | 5.7 | 10.0 |

*samples with greater than 10 % sand-size grains

abbreviations: RF=rock fragments, S=(Q+K+P)%, Q=quartz, K=potassic feldspar, P=plagioclase

Figure 32. Relative proportions of rock fragments (RF), quartz (Q), K-feldspar (K), and plagioclase (P), in Sentinel Butte sandstones from various measured section locations.


McKENZIE
DUNN
McLEAN
MERCER
GOLDEN VALLEY
BILLINGS
SHB
EG
LX
LB
Mann
MB
AC
SB
7-
RF
Q
P
K

a clear understanding of paleo-drainage patterns and directions of source terranes will come only after more regional rock characterization studies lead to a determination of petrographic facies and sediment dispersal patterns.

Vertical differences in mineralogic variables are more likely in distal sediments due to progressive changes in tectonism, unroofing, and erosion in source areas. However, it is impossible to interpret vertical differences unless relative ages of samples are known. Previous workers have relied heavily on marker beds to determine their relative position from outcrop to outcrop in the Sentinel Butte Formation. These marker beds, the basal sand, the Sentinel Butte bentonite/ash, the lower yellow bed, the upper yellow bed, and the upper sand, are of limited use over a large sampling area such as that of this study. In this study, the Sentinel Butte bentonite/ash is present at only one, and the lower yellow bed has been confidently identified at only three, of the ten randomly chosen measured section sites. The upper yellow bed and upper sand occur only where upper Sentinel Butte sediments have not been lost to erosion. Because of the scarcity of marker beds at the widely spaced section sites of this study, determinations of the relative ages of samples from different sites normally could not be made.

Although only one sample of the upper sand has been collected and examined, its high content of metamorphic rock fragments suggests a provenance different from that of older Sentinel Butte sediments. The upper sand is also coarser grained than sandstones lower in the Sentinel Butte section. Royse (1970) observed that the upper sand, "is cleaner and coarser than any sediment previously introduced into the basin and appears to represent a significant rejuvenation to the west." Whether mineralogic characteristics of the upper sandstone reflect an abrupt provenance change during upper Sentinel Butte time or a gradual change from lower to upper Sentinel Butte time is not apparent from the results of this study. But the sudden appearance of such a sandstone at the top of the Sentinel Butte sequence strongly suggests a significant event of some kind near the end of Sentinel Butte time.

## Diagenesis

An assessment of post-depositional modifications of a sedimentary unit is important in studies directed toward an understanding of provenance. A determination of diagenetic effects must be made in order for geologists to see through those effects to the original character of the sediment. Diagenesis in the Sentinel Butte Formation has led to an assemblage of authigenic mineral phases and to the dissolution or alteration of certain detrital phases. Secondary carbonate minerals and montmorillonite are abundant in the formation, while kaolinite, zeolites, barite, pyrite, quartz, opal, cristobalite, gypsum, and iron oxides occur less commonly and more locally. A general pattern of cement development seems to occur in Sentinel Butte sandstones. Pore-lining montmorillonite precedes zeolite development where both minerals occur together. Calcite or dolomite are the final cementing agents in Sentinel Butte sandstones, and where they have not developed, much open pore space remains.

The addition of new minerals to a sediment is commonly easier to detect than the loss or alteration of detrital minerals by dissolution or replacement processes. Although the effects of partial dissolution of feldspar and epidote grains, alteration of volcanic rock fragments, local intrastratal dissolution, and kaolinite replacement of detrital grains are evident, the loss of detrital constituents in the Sentinel Butte Formation as a whole does not appear to have been very significant. Although there is an abundance of unstable and altered volcanic rock fragments in the Sentinel Butte Formation, it should not yet be assumed that it is their alteration that has provided the necessary dissolved reactants for the development of pore-lining montmorillonite. Authigenic clay is a prominent constituent of many quartz sandstones that lack any trace of possible precursor detrital grains (Wilson and Pittman, 1977).

It is difficult to make specific deductions about the chemical conditions attending development of the pore-lining cements in Sentinel Butte sandstones. Because of the pore-lining and pore-filling character of authigenic montmorillonite, calcite, dolomite, and zeolites, it is clear that they formed as precipitates from solutions. Pore fluid chemistry initially favored montmorillonite precipitation. Montmorillonite is a widespread pore-lining cement in nearly all initially porous and permeable Sentinel Butte sandstones; channel-filling sandstones normally contain abundant pore-lining montmorillonite cement. Authigenic montmorillonite also occurs in many Sentinel Butte siltstones, especially those that appear to lack appreciable detrital clay (detrital and authigenic montmorillonite is distinguished on the basis of morphology and evidence of pore-lining character). Original porosity and permeability of sediments probably has greatly affected the present distribution of authigenic pore-lining clay in the Sentinel Butte Formation.

It is difficult to distinguish detrital and authigenic carbonate materials, but both direct and indirect evidence (discussed on pages 50 through 55 and on page 78) suggests that most Sentinel Butte carbonate is authigenic. Authigenic pore-filling calcite and dolomite are abundant in Sentinel Butte sandstones, but this study has not determined the extent of authigenic carbonate development in finer-grained samples. Carbonate cementation has occurred to varying degrees in the samples examined; some samples contain only minor carbonate cement, and only one sample (LX-M) is well-cemented by carbonate.

Zeolites are apparently minor in the formation as a whole, but do occur as pore-filling grains scattered throughout sandstone samples. The zeolites definitely postdate the origin of pore-lining montmorillonite and probably formed as precipitates from pore solutions in most samples.

Most literature discussions of zeolite genesis propose that zeolites form by the reaction of pore water with pre-existing solid materials. Although exact mechanisms are still not understood, dissolution-reprecipitation reactions are commonly favored by most authors (Mumpton, 1973).

Convenient precursor materials are present at many zeolite localities reported in the literature. Most zeolites detected in this study occur as pore-filling crystals or crystal aggregates, and reveal no clear indications of having formed by the alteration of some solid precursor material. Instead, most Sentinel Butte zeolites probably formed as precipitates from pore solutions only locally chemically suited for zeolite precipitation, perhaps without the involvement of progenitor solid reactants. The abundant analcime in samples SB-1 and

SB-15 may have formed through the reaction of solid materials with a more pervasive pore-solution chemical situation; this is a subject for future study.

Although the necessary chemical constituents for montmorillonite, calcite, dolomite, and zeolite formation are clearly available among the detrital components of the volcanic-rock-fragment-rich Sentinel Butte Formation, further collection and evaluation of data are needed to provide a clearer understanding of the chemistry of authigenic cement development. A comparison of the major and trace element composition of detrital and authigenic clays together with reliable analyses of present-day subsurface water in various portions of the formation may prove valuable. It is an easy matter to extract and concentrate authigenic montmorillonite from many Sentinel Butte sandstones; careful dating of this clay might clarify particular precipitation processes. A careful petrographic and geochemical comparison of channel sandstones and more silty or muddy materials from channel-marginal facies might also prove valuable for the recognition and interpretation of authigenic cement development.

## Chemical Analysis of Sedimentary Rocks

Bulk rock chemical analyses of sedimentary rocks are not as easily interpreted as those of igneous and metamorphic rocks, largely because sedimentary rocks normally have undergone complex mixing, dilution, and diagenetic processes. Sedimentary rocks are best distinguished and classified using mineralogic composition, and attempts to substitute bulk rock analysis for classification purposes normally lead to ambiguous or only generalized rock name determinations often inconsistent with mineralogies observed. Bulk rock chemical data of sedimentary rocks are nevertheless worth obtaining for purposes of comparison. For example, as mentioned above (page 78), differences in calcium content between otherwise nearly identical Sentinel Butte samples lend support to the interpretation that most Sentinel Butte calcite and dolomite is of secondary origin. Alternative explanations for carbonate grain differences between samples involve provenance, differential attrition during transport, or post-depositional dissolution. Such explanations seem unlikely considering the observed difference in carbonate content between presumably equivalent (in a provenance sense) basal sand and, even more convincingly, closely spaced lower yellow bed samples. Similar comparative chemical evaluations of sedimentary rocks, when allied with petrographic observations, may lead to interpretations of groundwater/rock interactions, explanations of rock colorations, and perhaps in certain cases the establishment of geochemical facies patterns.

## BENTONITE

The search for demonstrable bentonites in the Sentinel Butte Formation has yielded no examples beyond the single known bentonite described above. However, certain criteria have been developed that may yet lead to the discovery of new bentonites in the Fort Union Group.

It is commonly thought that volcanic glasses cannot survive long without altering to more thermodynamically stable phases. The majority of reported natural glasses are of Cenozoic age, normally Miocene or younger (Simons, 1962; Marshal, 1961). The existing literature, however, does contain many reports of much older natural glasses. The presence and characteristics of glass grains in the Sentinel Butte bentonite/ash validates other workers' (e.g., Marshal, 1961) suggestions that natural glasses are stable for long periods of geologic time (Forsman, 1984). A search for glass grains in Sentinel Butte claystones is a useful tool in the search for bentonites.

The geochemical transformation of glass to clay in the Sentinel Butte bentonite/ash has followed the same pattern of chemical change commonly reported for the origin of bentonites (Ross and Hendricks, 1945; Blatt et al., 1972; Pettijohn et al., 1973). Results of microprobe analysis of glass grains and their attached alteration products (montmorillonite) are given in Table 12. Silicon, sodium, and potassium were removed in the reactions while iron and magnesium were added. The high silicon content of the resulting montmorillonite appears to be a useful criterion in the search for additional Sentinel Butte (and probably other Fort Union) bentonites of rhyolitic derivation. The overall process of bentonite formation is commonly thought to involve incongruent dissolution of glass grains, with removal and addition of cations while a disordered silica-alumina framework is reconstituted to clay and excess silica is released in solution. Apparently magnesium and perhaps some iron are required for this transformation to lead to smectite. A rough comparison of the whole rock major and trace element composition of the three layers and the transition zones between those layers (Fig. 33 and Table 13) reveals the same general pattern of chemical change as that reported for the transformation of individual glass grains to clay.

Table 12. Microprobe Analyses of Glass Grains and their Alteration Products (Montmorillonite)

| | Glass | Clay | Clay Recalculated | Loss/Gain |
|---|---|---|---|---|
| $SiO_2$ | 78.86(77.38-80.25) | 72.24(67.96-75.26) | 59.53(48.25-71.23) | -19.35(-32.00 to -6.87)(s.d.=8.21) |
| $Al_2O_3$ | 14.17(13.65-15.19) | 17.41(14.29-19.60) | 14.17(13.65-15.19) | held constant |
| FeO* | 1.30(1.18-1.51) | 3.89(2.34-6.48) | 3.19(2.28-5.38) | +1.88(+4.01 to +0.83)(s.d.=0.98) |
| MgO | 0.23(0.00-0.46) | 2.03(1.31-3.00) | 1.64(1.10-2.26) | +1.41(+1.80 to +0.88)(s.d.=0.31) |
| CaO | 1.19(0.92-1.39) | 0.90(0.47-1.80) | 0.84(0.34-1.75) | -0.34(-0.71 to +0.36)(s.d.=0.36) |
| $Na_2O$ | 1.94(0.68-2.81) | 1.90(0.64-4.60) | 1.58(0.53-4.48) | -0.36(-2.07 to +1.67)(s.d.=1.10) |
| $K_2O$ | 2.10(1.78-2.60) | 1.22(0.53-1.96) | 1.02(0.39-1.74) | -1.08(-2.05 to -0.16)(s.d.=0.56) |
| $TiO_2$ | 0.05(0.00-0.20) | 0.16(0.00-0.41) | 0.13(0.00-0.32) | +0.08(+0.32 to -0.10)(s.d.=0.13) |

Note: Mean values given for 10 glass/clay associations. Ranges in parentheses. Calculated $H_2O$-free.
*Total iron as FeO.
Aluminum held constant.

Available evidence, including similarity in major element composition of glass grains (Table 6), and trends between layers in both lithologic (Fig. 22) and geochemical (Fig. 33) characteristics suggests that the Sentinel Butte bentonite/ash was at one time a single, fairly homogeneous, ash accumulation. This deposit is perhaps unique in that a well-preserved, old (>53 Ma.), ash layer remains, sandwiched between two well-developed bentonites.

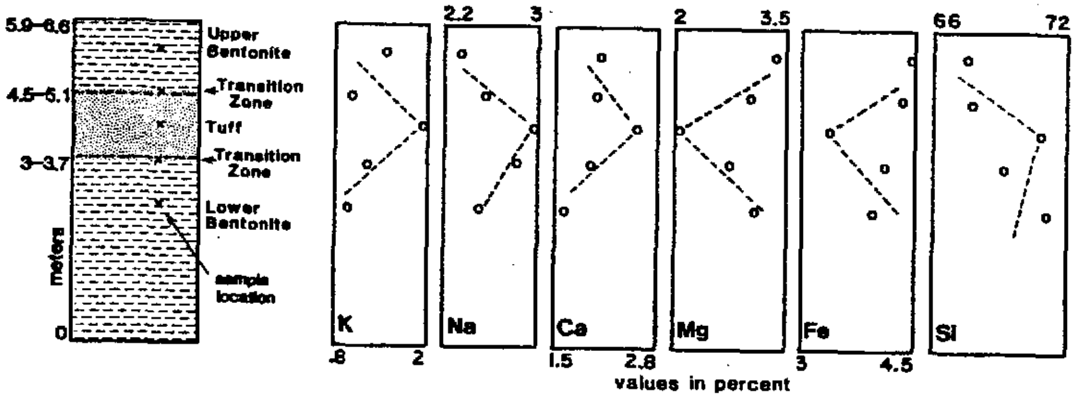


Figure 33. Variation in whole-rock major element composition within vertically sampled bentonite-ash-bentonite section. Data from Table 13.

Both the original Sentinel Butte and Marmarth ashes were probably deposited in water. The Marmarth ash is at least locally crossbedded and the Sentinel Butte bentonite/ash locally overlies a ripple-marked unit. A lacustrine environment of deposition is suggested for the Sentinel Butte bentonite/ash and might explain the great thickness (up to 4.5 m) of this deposit over such a large area (Fig. 21). The often cited passage from Grim (1953) that, "In order for bentonite to form, it is probably necessary for the ash to fall in water", and, "that the alteration to ash takes place soon after accumulation or possibly almost contemporaneously with accumulation", should not be interpreted as meaning that ashes landing in water must alter or that they necessarily alter quickly. It is clear from the presence of well-preserved glass grains in the Sentinel Butte and Marmarth bentonite/ash deposits that volcanic ashes do not necessarily alter to crystalline phases without significant influences other than the passage of time or deposition in

Table 13. Chemical Analyses of Whole-Rock Samples from 5 Levels of the Sentinel Butte Bentonite/Ash

| | Lower Bentonite | Transition Zone | Ash | Transition Zone | Upper Bentonite |
|---|---|---|---|---|---|
| | | | (values in percent) | | |
| $SiO_2$ | 71.07(±0.34) | 69.10(±0.74) | 70.74(±0.59) | 68.09(±0.32) | 67.41(±0.69) |
| $Al_2O_3$ | 16.57(±0.05) | 17.93(±0.37) | 16.16(±0.39) | 18.49(±0.07) | 18.32(±0.52) |
| FeO* | 3.94(±0.12) | 4.10(±0.33) | 3.33(±0.11) | 4.36(±0.14) | 4.50(±0.25) |
| MgO | 3.07(±0.61) | 2.75(±0.67) | 2.05(±0.63) | 3.01(±0.63) | 3.39(±0.57) |
| CaO | 1.56(±0.33) | 1.91(±0.36) | 2.55(±0.38) | 2.09(±0.60) | 2.04(±0.51) |
| $Na_2O$ | 2.49(±0.13) | 2.85(±0.54) | 2.98(±0.36) | 2.59(±0.31) | 2.36(±0.27) |
| $K_2O$ | 0.92(±0.14) | 1.21(±0.17) | 1.92(±0.23) | 1.07(±0.02) | 1.61(±0.21) |
| $TiO_2$ | 0.37(±0.05) | 0.18(±0.03) | 0.29(±0.16) | 0.30(±0.14) | 0.37(±0.10) |
| | | | (values in parts per million) | | |
| Ba | 393.92(±4%) | 490.49(±3%) | 665.70(±4%) | 529.05(±1%) | 237.57(±4%) |
| Ti | 910.24(±10%) | 1125.52(±10%) | 1223.43(±10%) | 1072.04(±5%) | 1078.44(±10%) |
| Mn | 127.19(±0.5%) | 252.26(±0.1%) | 298.49(±0.5%) | 235.57(±0.1%) | 152.18(±0.5%) |
| V | 22.81(±0.5%) | 22.65(±1%) | 22.37(±0.5%) | 27.11(±0.5%) | 24.69(±0.5%) |
| Sm | 0.91(±1%) | 0.98(±1%) | 0.99(±1%) | 0.99(±1%) | 0.77(±1%) |
| Ce | 53.88(±5%) | 52.03(±10%) | 50.05(±5%) | 59.89(±10%) | 48.42(±5%) |
| U | 1.37(±5%) | 1.89(±1%) | 2.07(±5%) | 1.86(±5%) | 1.10(±5%) |
| Th | 9.91(±0.5%) | 12.13(±0.5%) | 10.58(±0.5%) | 12.55(±1%) | 10.50(±0.5%) |
| Cr | 23.63(±7%) | 17.99(±10%) | 18.61(±7%) | 18.83(±10%) | 24.11(±7%) |
| La | 11.04(±0.5%) | 10.45(±1%) | 10.61(±0.5%) | 10.63(±1%) | 8.17(±0.5%) |
| As | 1.14(±5%) | 3.20(±1%) | 3.34(±1%) | 2.15(±1%) | 0.59(±5%) |
| Sc | 5.05(±1%) | 5.39(±1%) | 4.83(±1%) | 6.00(±1%) | 5.59(±1%) |
| Rb | 24.71(±15%) | 84.01(±10%) | 104.84(±10%) | 76.86(±10%) | 26.55( ±5%) |
| Zn | 75.0 | 75.0 | 75.0 | 75.0 | 75.0 |
| Co | 2.51(±1%) | 2.71(±1%) | 2.63(±1%) | 2.95(±0.5%) | 2.90(±1%) |
| Eu | 0.72(±5%) | 0.69(±5%) | 0.64(±5%) | 0.56(±5%) | 0.47(±5%) |
| Cs | 2.71(±1%) | 3.83(±1%) | 4.66(±1%) | 3.64(±1%) | 2.24(±1%) |
| Ni | 41.57(±15%) | 13.69(±25%) | 15.37(±20%) | 8.54(±25%) | 21.14(±25%) |
| Yb | 1.33(±1%) | 1.74(±1%) | 1.55(±1%) | 1.68(±1%) | 1.50(±1%) |

Note: Major elements: --analysis by microprobe. Calculated $H_2O$-free. Data in weight percent. Standard deviation in parentheses. Trace elements: --analysis by NAA (Weaver, 1978). Data in parts per million.
*Total iron as FeO.

water.

But what might explain the partial alteration to bentonite of the Sentinel Butte deposit and the preservation of its ash layer in a sandwiched manner? Iron and magnesium content in the glass-derived montmorillonite is greater than that available from the progenitor glass grains alone. These elements must have been contributed by mobile groundwater from outside the ash. It seems apparent that either the preserved ash layer was never exposed to sufficient quantities of mobile groundwater or that the chemistry of groundwater to which the ash was exposed was inappropriate for glass alteration to occur. The former hypothesis seems difficult to support, considering that this Paleocene deposit was probably below the groundwater table for most of its history and that water might pass through even "impermeable" clay beds given sufficient time. A possible explanation for the partial alteration involves a selective ion exclusion process. Element-enriched groundwater entering the original ash deposit from neighboring sediments may have caused glass alteration to proceed initially at the contact between the ash and those sediments. A resulting clay layer then may have acted as an element filter (perhaps a semipermeable membrane), allowing some water to pass through the clay, but excluding or limiting the passage of certain crucial ions into or out of the enclosed ash, thereby preventing further alteration of the deposit. This explanation is speculative at this point, but does seem somewhat attractive in that it doesn't require the ash layer to remain dry in order to be preserved. An ion-filtering mechanism is not formally proposed here, but possibilities include simple cation exchange reactions or perhaps semipermeable membrane processes. Previous literature suggests that semipermeable membrane processes occur only under deep (~1000 m) burial conditions or perhaps at shallower depths where solutions are very dilute (Drever, 1982, p. 81-82).

Modeling ancient groundwater flow is difficult, but an explanation involving some form of ion exclusion seems compatible with a simple model of a slowly rising groundwater table. As groundwater table rise continued above the now altered lower ash, crucial elements (e.g., Mg) may have been restricted from also rising. The groundwater might then have become replenished in these elements only when it contacted the sediments above the ash. Diffusion of these elements downward then may have led to development of the upper bentonite. The upper bentonite is consistently thinner than the lower bentonite, often much thinner, perhaps reflecting the relative energies of downward element diffusion and upward groundwater movement.

Any explanations offered for the sandwiching effect must account for the apparently uniform occurrence of this effect over the entire range of the Sentinel Butte ash; the ash is everywhere sandwiched by bentonite. Further study of this interesting deposit may provide evidence in support of various water driving and ion-filtering mechanisms.

The examination of the Sentinel Butte bentonite/ash is potentially the most valuable aspect of this study toward the realization of the earlier stated goal of determining which procedures are most useful for the comparison of Lower Tertiary rocks. Temporal relations between the various geographically separated formations of the Fort Union Group are not well understood. For example, it is not known whether rocks equivalent in age to the Sentinel Butte Formation occur either in the

Paleocene strata of the Powder River Basin or within the Tongue River Member of eastern Montana. A time-stratigraphic framework is needed to provide a common context within which to view the results obtained by various studies of the widespread Fort Union Group. Bentonites and ashes are extremely valuable in correlating and establishing the age-equivalence of sedimentary strata. They are also potentially datable by radiometric methods, and so may be of use in determining absolute ages and sedimentation rates.

There seems to be a common suggestion or at least inference in much existing literature that the Paleocene epoch was a time of volcanic inactivity in the Western Interior of North America. Robinson (1972), in referring to the Windy Gap Volcanics Member of the Middle Park Formation of north-central Wyoming, wrote: "If some of these volcanics are of Paleocene age they represent a rare lithology for the epoch." Armstrong (1978) wrote: "Except for volcanoes in the Adel Mountains and near the Black Hills, the first 10 m.y. of the Cenozoic was a time of igneous quiescence." Many authors do not explicitly suggest a lack of volcanism during the Paleocene epoch, but instead ignore the Paleocene, mentioning only the well-reported volcanism of the Cretaceous and post-Paleocene. A search of existing literature has generated a partial list of Western Interior igneous centers with possibly active Paleocene volcanism (Table 14). This list should not be construed as a contradiction to the statement that the literature negates Paleocene volcanism; most of the references of Table 14 do not mention Paleocene volcanism even though they give age ranges which include the Paleocene. The literature suggestions of volcanic inactivity exist in spite of what might be considered evidence to the contrary. Also, the list is meant

Table 14. *Western Interior Igneous Centers with Possibly Active Volcanism During the Paleocene Epoch*

| Igneous/Volcanic Center | Age Range | Reference (for age range) |
|---|---|---|
| Elkhorn Mountain Volcanic field, Montana | Late Cretaceous - Early Tertiary | Steven et al. (1972) |
| Boulder batholith, Montana | Late Cretaceous - Early Tertiary | Steven et al. (1972)<br>Tilling et al. (1968) |
| Idaho batholith, Idaho | Late Cretaceous - Eocene | McGookey et al. (1972) |
| NE-trending igneous belt through Colorado | Upper Cretaceous and Paleocene | Steven et al. (1972) |
| NW-trending belt from Black Hills of South Dakota to Sweetgrass Hills of Montana | Late Paleocene | Fountain (1981) |
| Devils Tower and Missouri Buttes, Wyoming | Paleocene - Eocene | Hill et al. (1975) |
| Judith Mountains, Montana | Late Cretaceous - Eocene | Marvin et al. (1980) |
| Little Rocky Mountains, Montana | Late Cretaceous - Paleocene | Marvin et al. (1980) |
| Adel Mountains, Montana | Late Cretaceous - Paleocene | Chadwick (1972)<br>Armstrong (1978) |

only as a suggestion of where Paleocene volcanoes may once have been.

The occurrence of volcanically derived deposits in the Fort Union Group and equivalent strata indicates active volcanism during the Paleocene epoch. At least two other Paleocene pyroclastic deposits in the Western Interior are known besides the Sentinel Butte bentonite/ash. Shafiqulah et al. (1964) have assigned a Paleocene age to bentonites that occur in the Brazeau and Paskapoo Formations of central and southern Alberta. Tuff stringers occur throughout the Big Dirty coal seam in the Lebo Formation of the Fort Union Formation in south-central Montana (C. Connor, USGS, personal communication, 1982). An apparently stream-reworked ash deposit occurs in Paleocene strata on the west flank of the Powder River Basin (R. Harris, Wyoming Geological Survey, written communication, 1983). Other Paleocene ash and bentonite deposits probably remain undiscovered in the rugged badlands terrain in which much of the Fort Union is exposed. The location and study of such deposits can do much for the correlation of Paleocene strata and the reconstruction of Laramide geologic history.

## CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

### Summary of Conclusions

1. Volcanic rock fragments dominate the lithic constituents of Sentinel Butte sandstones. A minor proportion of plutonic, sedimentary, and metamorphic rock fragments occurs throughout the formation with a significant increase in metamorphic rock fragment proportion in the uppermost Sentinel Butte Formation. Thus, mixed source rock types and/or regions supplied material for Sentinel Butte deposition, but the dominant available source material was volcanic.

2. Sentinel Butte sediments are fine grained and are comprised of a mineralogically immature assemblage of components leading to a general classification of feldspathic lithic arenite for sandstones. That sandstones can be classified as arenites reflects the winnowing influences of streamflow processes rather than any overall textural maturity for Sentinel Butte sediments. The dominant rock types present in the formation ~~is~~ mudstone.
   are siltstones and

3. Diagenesis of Sentinel Butte sediments has led to the authigenic growth of various minerals. Montmorillonite occurs as a pore-lining cement in most Sentinel Butte sandstones and many siltstones. Zeolites occur as a pore-filling material in several sandstones. Calcite and dolomite are the final cementing agents in Sentinel Butte sandstones, but are present in widely varying amounts in the samples examined. Most Sentinel Butte carbonate minerals appear to be authigenic.

4. The detrital clay mineral assemblage of the Sentinel Butte Formation is dominantly composed of sodium montmorillonite. Kaolinite is minor and chlorite and illite/mica may more appropriately be regarded as clay-size detrital flakes rather than as clay mineral material viewed as forming through alteration or weathering of preexisting material or authigenic growth.
5. The Sentinel Butte Formation contains a thick and widespread bentonite in which is preserved a layer of the original volcanic ash accumulation. This bentonite, together with others known in the Fort Union Group, has led to improved understanding of Paleocene volcanism, glass grain durability, and bentonite formation. It is probable that continued research, utilizing bentonites as chronostratigraphic units, will lead to an improved understanding of the time-stratigraphic relationships of Fort Union Group strata.
6. An overall understanding of the geologic history recorded in Paleocene strata will require an integration of the results of many petrologic studies of both distal and proximal Fort Union Group sediments.

## Concluding Statement and Suggestions for Further Work

In this study, the petrology of the Sentinel Butte Formation has been examined in a broad way. A particular aim of this study is to reveal new information about the formation that would point to specific areas of research worthy of more concentrated or specialized examination. Only through a cooperative integration of results of many studies will an eventual well-supported understanding of the geologic past recorded in Fort Union strata be gained. Much contributive work toward this end has been done (e.g., Stow, 1946; Brown, 1952; Courdin and Hubert, 1969; Royse, 1970), but much also remains to be done. For example, this study has provided petrographic evidence that suggests a difference in the provenance of basal and upper Sentinel Butte sandstones; however, detailed comparisons of the petrology of these sandstones can still be conducted. Specific comparisons of rock fragments, types and structural states of feldspars, and heavy mineral assemblages may yet reveal much about the history of these sandstones. This study is the first to point to the presence of certain authigenic minerals in the Sentinel Butte Formation. A comparison of the effects of diagenesis in different Lower Cenozoic formations may lead to models of past groundwater/rock interactions, may lead to explanations of color differences between formations, and may eventually lead to geochemical facies models and environmental reconstructions. This study is the first to examine the characteristics of volcanic ash and bentonite in the Paleocene strata of North Dakota in a search for other bentonites in these and neighboring strata.

Bentonites and ashes are potentially of great value in determining the time-stratigraphic relations between Fort Union strata. The search for and study of such deposits should continue. Further study of the Sentinel Butte bentonite/ash can provide information regarding the best way to make use of such deposits for correlation purposes. Long-distance correlation of ashes is best done through geochemical and statistical means (e.g., Sarna-Wojicki et al., 1979; Hahn et al., 1979). Although Huff (1983) has successfully geochemically correlated a bentonite formed under marine conditions, a test of the suitability of this procedure for bentonites formed in terrestrial settings has not been conducted. The Sentinel Butte bentonite/ash provides an excellent opportunity to assess the effects of variable diagenesis (common in terrestrial sediments) on the chemical signature of a terrestrial bentonite. The regional chemical variability of the unaltered sandwiched ash can be compared with both the regional and local chemical composition of the bentonites that have been derived from the originally thicker ash. Nonuniformity of the lateral differences in chemical composition of parent glass (from the ash) and authigenic clay (from the bentonites) can then be ascribed to differences in diagenesis along the course of the deposit. The Sentinel Butte bentonite/ash perhaps provides a unique opportunity for this type of evaluation, in that the remnant ash is preserved not just locally but occurs with the associated bentonites over an extensive area.

Although not directly suggested by results of this study, the possibility exists that a detailed examination of selected rock layers of the Sentinel Butte Formation might reveal diagenetic features compatible with an origin by soil-forming processes. Paleosols, incipient paleosols, or perhaps just diagenetic features similar to what may occur in soils might be detected through an appropriate study. Differences in calcite and dolomite contents and differences in etching of feldspars between samples examined in the present study as well as the outcrop occurrence of color banding and iron-oxide-cemented zones might have an explanation in pedogenic or related processes.

Sentinel Butte organic-rich and lignitic samples could be further studied in many ways. Extraction and detailed examination of organic materials variously preserved in Sentinel Butte samples may eventually lead to an understanding of the coal-forming process or processes which have led to North Dakota's lignites. Combined organic- and geochemical examination of a vertically closely spaced series of samples taken from a lignite seam and its over- and underlying sediments might reveal information regarding the chemical interaction between those layers during and after coal formation (Karner et al., 1984).

Further detailed study of Sentinel Butte clays might reveal additional differences between authigenic and detrital phases. Special techniques applicable to the examination of clay structure might reveal valuable information regarding formative mechanisms of authigenic clays and the durability of original stucture in redeposited (detrital) clays.

In addition to the specific studies mentioned above which pertain to the Sentinel Butte Formation, it is hoped that similar examinations of other Lower Cenozoic rock units in North Dakota, South Dakota, Montana, and Wyoming will be conducted so that information concerning different units can be compared and integrated to bring about an eventual well-documented understanding of the geologic history recorded in those units.

# APPENDICES

# APPENDIX A

# MEASURED SECTION DESCRIPTIONS AND SAMPLE LOCATIONS

Section: Sheep Butte (SHB) Date: 10 July, 1981
Location: NE 1/4, NE 1/4, NE 1/4, Sec. 15, T. 148 N., R. 103 W.,
McKenzie County, ND
Base of Section: Base of butte

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 117-125' | SHB-9 | 120.0' | Silt, unconsolidated, light-yellow-gray. Lower yellow bed? |
| 109-117' | | | Shale, silty, gray to brown. Mostly covered. |
| 102-109' | | | Claystone, silty, gray to brown. Semi popcorn-weathered. Becomes silty and iron-stained upward to dirt-like slope. |
| 87.5-102' | SHB-8 | 90.0' | Shale, silty, light-blue-gray. More resistant than underlying unit. Faintly orange color-banded. A cherty concretionary zone (1'-thick) at 95'. |
| 83-87.5' | | | Claystone, sandy. Blue-gray. Popcorn-weathered. Forms bench. Sentinel Butte bentonite? Sample BB#8. |
| 76-83' | SHB-7 | 83.0' | Sand, medium, light gray-brown. Uncemented. Weathers light gray and forms ledge. Upper contact not horizontal. |
| 68-76' | | | Shale, silty, faintly orange color-banded. Thin iron-cemented band near top. |
| 65.5-68' | SHB-6 | 67.0' | Claystone, blue-gray, popcorn-weathered. Forms bench. Contains white, irregular sandy masses (Sample Sheep Butte A). Sentinel Butte bentonite? |
| 20-65.5' | SHB-5<br>SHB-4<br>SHB-3<br>SHB-2 | 53.0'<br>43.9'<br>32.0'<br>23.8' | Alternating fine sand, silty shale, shaley silt. Gray to light-yellow. Orange color-banded. Disintegrated concretion-like zone at 24' (1'-thick) forms a small bench. 40 to 50' interval is more shaley. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 15-20' | | | Shale, silty, gray, orange color-banded. Becomes more silty upward resulting in less resistance to erosion and a rather dirt-like slope. |
| 12.5-15' | | | Shale, silty, gray. Abundant loosely iron-cemented slabs and chips offering some resistance to erosion. |
| 10.5-12.5' | | | Shale, silty, gray. Popcorny. Becomes brown upward. Upper 1' is very fissile "woody" organic-rich, brown to gray, silty shale. |
| 9.5-10.5' | SHB-10 | 10.0' | Silt, very white. Forms a ledge. Capped by a very thin blue-gray claystone. |
| 4-9.5' | | | Shale, silty, gray. Popcorny. Becomes more silty and brown upward, then again more clayey. |
| 0-4' | | | Slope wash up to lignite overlain by shale, gray-brown, organic-rich. |

Section: LX Ranch (LX)    Date: 8 July, 1981
Location: NW 1/4, NW 1/4, NE 1/4, Sec. 36 and SW 1/4, SE 1/4, Sec. 25, T. 148 N., R. 99 W., McKenzie County, ND
Base of Section: Section measured upward from a 1-1/2 foot lignite

| Unit Sample | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 400-410' | LX-M | | Sandstone, well lithified, yellow-gold to brown. Gruss at base. |
| 341-400' | | | Mostly covered. Some seemingly in-place silty shale. Yellow-brown at base. |
| 340-341' | | | Lignite upward to shale. |
| 324-340' | | | Covered. |
| 296-324' | LX-L | | Sand, fine, unconsolidated. Upper yellow bed. |
| 291-296 | | | Lignitic upward to lignitic shale. |
| 280-291' | | | Covered. |
| 276-280' | LX-K | | Clay, blue-gray, popcorn-weathered. Appears indistinguishable from Sentinel Butte bentonite. |
| 245-276' | | | Covered. |
| 233-245' | | | Sand, medium, light gray. Clayey (popcorny) bands and light orange bands. |
| 232-233' | | | Lignite. |
| 199-232' | LX-22 | 203.1' | Clay, silty, sandy. Forms dirt-like slope. |
| 195-199' | LX-21 | 195.2' | Shale, lignitic. Covered, must be dug for or found in gulleys. Base not seen. |
| 184-195' | | | Covered. |
| 180-184' | LX-J | | Clay, silty, blue-gray. Popcorn-weathered. |
| 163.5-180' | LX-19<br>LX-18 | 178.9'<br>170.5' | Sand, medium, white. Yellow-gray clayey (popcorny) bands, orange-yellow iron-stained bands and |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | segregated white lensoid sandy masses and iron-cemented nodules. |
| 157-163.5' | LX-17<br>LX-16<br>LX-I | 162.4'<br>157.9' | Shale and silty shale, banded (yellow-orange-gray-brown). Lower six inches is light blue popcorny shale. |
| 130-157' | LX-15<br>LX-14<br>LX-13<br>LX-H<br>LX-G | 148.1'<br>141.9'<br>136.7' | Siltstone, fine, mostly unlithified (sample LX-G).<br>A seemingly continuous indurated zone 1-1/2-foot-thick occurs in the middle of this unit, often with large slabs bearing rippled surfaces broken free (sample LX-H).<br>Mollusc fossil seen.<br>Capped by 1-1/2' white, organic-rich silty shale, in turn capped by 3 to 5-inch-thick black lignitic shale.Lower yellow bed. |
| 125-130' | LX-F | | Lignite. Overlain by few inches of silty shale. |
| 119-125' | | | Shale, silty, yellow brown to somber gray. Subdued orange-banded. Forms dirt-like slope. |
| 117-119' | | | Shale (~1'), gray, fissile.<br>Above is darker gray iron-stained shale which contains indurated iron-cemented horizons. A bench is formed on an iron-cemented horizon at 119'. |
| 116-117' | | | Shale, very white. Forms ledge. Very slight silt content detected by chewing. |
| 111-116' | LX-E | | Clay (Sentinel Butte bentonite?), blue-gray, popcorn-weathered. Material separating this unit from blue clay below is sand, not ash. Virtually all clay, no silt detected. Contains organic (Plant) remains. |
| 108.3-111' | | | Sand, medium, white. Popcorny bands. Contains organic (plant) remains. Fines upward to silty or |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | sandy shale capped by 3-4" of carbonaceous, brown to pink, lignitic, silty shale. |
| 105.5-108.3' | LX-11 | 107.5' | Clay, blue-gray. Very popcorny. Much organic (plant) remains. Lower Sentinel Butte bentonite? |
| 104.5-105.5' | | | Shale, blue-gray, sandy, silty. |
| 99-104.5' | LX-D | | Sand, white, medium. Iron-cemented bands near base. Contains very white, segregated, lensoid, sandy masses, up to several feet in maximum dimension (sample LX-C). Contains iron-bearing concretions. Becomes popcorny and darker gray in two or three thin zones just above the 100' mark. These zones contain some organic (plant) remains but it is not clear what causes the popcorn character. Perhaps are some authigenic clays. Orange iron-bands above 101'. |
| 97.5-99' | | | Lignite. Capped by few inches of very light gray shale with a small silt component. |
| 86-97.5' | LX-10 | 94.2' | Sand, medium, light gray to white. Orange iron-banded. Contains large log-like concretions. Top 5' lacks iron staining and contains leaf imprints. Fines upward and becomes very fine sand to silt (apparently lacking much clay) near top (as base for overlying lignite). |
| 82-86' | LX-9 | 85.0' | Shale, silty, brown. |
| 81-82' | | | Shale, silty, popcorn-weathered, iron-banded. Forms small bench at 82'. |
| 79-81' | | | Shale, silty, light blue, popcorn weathered. |
| 58-79' | LX-8<br>LX-7 | 76.4'<br>68.5' | Lignite. Overlain by shale, brown, organic-rich. A purple- |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | LX-6 | 61.2' | brown, two-inch, silty shale lies 2' above the lignite. Less organic and more silty upward. Subdued banding, buff brown to somber gray. Swelled, dried, semi-popcorny surface. |
| 55-58' | LX-B | | Lignite. Base not seen, but is at least 3' thick. |
| 50-55' | | | Covered. |
| 45-50' | LX-4 | 47.8' | Sand. |
| 39-45' | LX-3 | 42.4' | Sand, fine to medium, rilled. Less resistant to hillslope weathering than underlying sand. |
| 34-39' | | | Sand, fine to medium, rilled, iron stained in bands. Not indurated. |
| 33-34' | | | Shale, sandy. Bench-forming. Weathers into centimeter-size chips. |
| 25.5-33' | | | Shale, slightly silty, orange-yellow-gray-banded. Coarsens upward. Very sandy for upper 4-5'. Short bench at 33'. |
| 25-25.5' | | | Silt, carbonaceous. Grades upward to carbonaceous silty shale. |
| 18-25' | LX-A | | Shale, silty, light-gray. Overlain by darker gray popcorn-weathered clay. |
| 12-18' | LX-1 | 13.5' | Shale, light-gray, plant fossil-rich. Overlain by several feet of silty shale which is color-banded by iron-staining or perhaps by lithologic changes. Contains iron nodules and thin iron-cemented layers. |
| 5-12' | | | Shale, (2"), light-gray plant-fossil rich. Grades upward to sandy shale, alternating gray and light yellow brown. Light shale again near top, abruptly overlain by 11' of friable, fine |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | to medium sand. Lignite (5") caps the sand. Entire interval is color-banded. |
| 0-5' | | | Shale, light-gray, plant-fossil rich. Grading upward to silty, fine-sandy shale, then again plant-fossil rich shale capped by 2" of purple brown carbonaceous shale. |

Section: Kinley Plateau (KP) Date: 9 June, 1981
Location: SE 1/4, SW 1/4, NE 1/4, Sec. 25, t. 138 n., R. 102 W.,
Billings County, ND
Base of Section: Top of vegetated zone containing in-place petrified tree stumps approximately midway up from base of butte.

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 105-106.5' | | | Sandstone, medium, brown to gray. Resistant ledge-former. Caps this butte. Appears darker in color from a distance. |
| 103.5-105' | | | Sandstone, very fine, yellow-brown. Non-resistant. |
| 101-103.5' | | | Sandstone, medium, orange-brown to gray. Well indurated, resistant. Ledge-former. Appears darker brown from a distance. |
| 92-101' | KP-9 | 98.6' | Sandstone, very fine, gray. Less resistant than underlying unit. Contains yellow-orange iron-cemented beds 1 to 1-1/2" thick. Ripples preserved. |
| 91-92' | | | Sandstone, fine to medium, orange-gray to brown, indurated, cross-bedded. Incompletely cemented but forms a resistant ledge. Appear darker brown from a distance. |
| 84-91' | KP-8 | 86.9' | Shale, silty, yellow-gray to orange color-banded. Grades upward to shaley silt to fine sand at top of interval. |
| 82-84' | | | Shale, silty, yellow-brown to gray. Popcorn-weathered. |
| 80-82' | | | Shale, carbonaceous, brown to gray. |
| 69.5-80' | | | Shale, silty, to silt, shaley. Orange, yellow-brown, and gray color-banded. |
| 66-69.5' | | | Clay, yellow-brown to gray. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 64-66' | KP-7 | 65.1' | Shale, lignitic. Base probably within covered interval. |
| 51-64' | | | Covered. |
| 49-51' | | | Clay, Brownish-gray. Popcorn-weathered. |
| 24-49' | KP-6<br>KP-5<br>KP-4 | 44.5'<br>35.7'<br>27.2' | Shale, silty to silt, shaley. Light gray to yellow-brown color-banded. More resistant than unit below and rilled on surface. |
| 12-24' | KP-3 | 19.3' | Shale, gray. Contains abundant fossil plant fragments. |
| 6-12' | KP-2 | 12.0' | Shale, carbonaceous, brown to gray. |
| 0-6' | KP-1 | 5.4' | Covered. |

additional samples:

Kinley A -- very white, sandy material underlying a bentonite-appearing, bluish-gray claystone below base of section.

Kinley B -- clay above Kinley A

Section: 7= Ranch (7=) Date: 11 July, 1981
Location: SW 1/4, NE 1/4, SE 1/4, Sec. 32, T. 146 N., R. 102 W., McKenzie County, ND
Base of Section: Lignite (HT?), well-exposed here, well-developed, often burned and overlain by scoria.

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | Petrified wood is abundant throughout this section. |
| 199.5-206' | | | Silt, shaley, brown. Dirt-like. Weathers gray. Iron-stained. |
| 198-199.5' | | | Lignite. |
| 193-198' | | | Covered. |
| 185-193' | | | Sand, fine, shaley. |
| 179-185' | | | Silty, dirt-like slope. |
| 165-179' | 7= F | | Shale, silty, sandy, gray to brown. Orange color-banded. Contains iron nodules and irregular white masses. White mass sampled (7=F). |
| 161-165' | | | Shale, sandy, gray to brown. Largely covered. |
| 160-161' | | | Lignite. |
| 156-160' | | | Shale, blue-gray, popcorny. |
| 154-156' | | | Lignite. Overlain by few inches of brownish gray, organic-rich shale. |
| 149.5-154' | 7= 15<br>7= E | 149.9' | Shale, blue-gray, popcorny. Contains a 1" lignite at 151'. |
| 148-149.5' | 7= 14 | 146.1' | Lignite. Overlain by brown, organic-rich shale. |
| 142.5-148' | | | Sand, fine to medium, yellow. Unconsolidated. Lower yellow bed? Sample (7=E). |
| 137.5-142.5' | | | Claystone, sandy, brown. Forms a popcorny slope, rather dirt-like. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 123-137.5' | | | Claystone, silty, blue-brown-gray. Dirt-like slope, becoming sandy at 137.5'. |
| 122-123' | 7= 13 | 122.9' | Siltstone. Iron-cemented. Forms shelf. |
| 119-122' | | | Lignite. Covered. Estimated to be 2' thick. |
| 107-119' | 7= 12 | 110.3' | Sand, fine, light gray. Sparse concretions and nodules. |
| 102.6-107' | 7= D<br>7= C | | Lignite. Base covered, presumed silty. Overlain by several inches light-brown organic-rich shaley silt which grades(?) up to medium sand. Thin iron-cemented zone at 107'. Samples: 7=C (lignite), 7=D (shaley silt). |
| 100-102.6' | | | Shale, blue-gray, popcorn-weathered. Grades upward to silty shale. |
| 57-100' | 7= 11<br>7= 10<br>7= 9<br>7= 8<br>7= 7 | 97.5'<br>87.1'<br>76.8'<br>67.2'<br>57.9' | Alternating sand, silt, clay. Thin (1") lignitic zone at 60'. Fossil plant remains and a fossil gastropod seen. 3" lignitic zone at 83' overlain by gray shale becoming more silty upward. Thin (1") iron-cemented zone forms very small bench at 93.5'. Sand coarsens to fine at 90' then quickly grades to silty or very fine sandy at 99'. Overlain by popcorny shale at 100'. |
| 54-57' | | | Lignite. Overlain by 1-1/2" of brown, organic-rich slightly silty shale. |
| 50-54' | | | Shale, silty, sandy. Locally covered. |
| 47-50' | | | Shale, blue-gray, popcorny. A 1" carbonaceous and lignitic |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | zone at 50' is overlain by several inches of light-gray organic-remains-bearing shale. |
| 33-47' | 7= 4 | 33.7' | Shale, silty to very fine sandy. Brownish-gray. Orange color-banded. Iron-nodule bearing. |
| 31.5-33' | 7= B | | Lignite. Sample 7=B. |
| 27-31.5' | 7= A | | Claystone, silty, gray to brown. More organic-rich upward. Contains several (4-8) thin beds of "woody" organic-rich material (sample 7=A) grading upward to lignite. |
| 0-27' | 7= 3<br>7= 2<br>7= 1 | 26.6'<br>20.1'<br>14.6' | Alternating sand, silt, clay, in varying proportions. Rilled where more sandy, popcorny where more clayey and silty. Orange, gray, and light-gray color-banded. Contains thin (1") iron-cemented zones and concreions. Sandy portions are fine to medium. Finer-grained near top. Contains some widely scattered white pods (carbonate?) |

additional samples:

7= G -- basal sandstone near 7= measured section location

7= H -- white, irregular sandy masses within a blue-gray popcorn-weathered claystone north of road, west of section site

Section: Sentinel Butte (SB) Date: June, 1980
Location: NE 1/4, NW 1/4, NE 1/4, Sec. 8, T. 139 N., R. 104 W.,
Billings County, ND
Base of Section: Base of basal sand exposure.

| Unit Interval | sample | Sample Position | Unit Description |
|---|---|---|---|
| 365-375' | SB-1 | | Sandstone, medium, gray-white, iron-stained. |
| 350-365' | SB-2<br>SB-3<br>SB-4 | | Sandstone, fine, white, well indurated. Resistant unit. Horizontal weathering pattern. Appears to have four members: a slight slope-forming member at base, overlain by a horizontally weathered section, followed by a 2' darker section, with a 2-3' cap of very white fine-grained sandstone. |
| 334-350' | SB-5 | | Sandstone, fine, yellow, indurated. Contains trace fossils (worm tubes, burrows, or root casts?). |
| 329-334' | SB-6 | | Shale, lignitic, dark brown-gray. |
| 322-329' | | | Sandstone, fine, gray, iron-stained. |
| 310-322' | SB-7 | | Sandstone, fine, buff yellow. Coarsens upward to medium sandstone. Partially lithified. well indurated in coarser portion near top. |
| 305-310' | | | Shale, brown. Grades upward to lignitic shale. |
| 295-305' | | | Sand, gray, slope-forming. |
| 293.5-295' | | | Lignite. |
| 281.5-293.5' | | | Shale, sandy, silty, slope-forming. |
| 275.5-281.5' | | | Sandstone, fine, yellow. Indurated. |
| 275-275.5' | SB-8<br>SB-9 | | Lignite. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 272-275' | SB-10 | | Siltstone, non-resistant. |
| 269-272' | | | Lignite. |
| 253-269' | SB-11 | | Sandstone, very fine, yellow-white. Fairly resistant in lower portion, slope-forming near top. |
| 236-253' | SB-12 | | Sandstone, yellow, indurated. contains fossil leaves and cones. Grades upward to fine to very fine, white, cross-bedded sandstone. |
| 228-236' | SB-13 | | Siltstone, slope-forming. Locally resistant and concretion-bearing. |
| 227-228' | | | Sandstone, silty, very well indurated. |
| 219-227' | | | Sandstone, very fine to medium. Fines upward. |
| 214-219' | | | Silt, light yellow, friable. |
| 213-214' | SB-14 | | Sandstone, fine to medium, cross-bedded. |
| 210-213' | SB-15 | | Lignite. |
| 208-210' | SB-16 | | Shale to silt, dark brown-gray. |
| 198-208' | | | Silt and clayey silt. Slope-forming. Mostly covered. |
| 171-198' | SB-17 | | Sandstone, fine to very fine. Cross-bedded. Very friable. |
| 147.5-171' | SB-18 | | Siltstone to shaley silt, buff-yellow, non-resistant. |
| 145-147.5' | SB-19 | | Lignite and lignitic shale. Mostly covered. |
| 142-145' | SB-20 | | Shale, silty, light brown-gray. |
| 140-142' | | | Shale, brown-gray, organic-rich. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 120-140' | | | Silt to shaley silt, buff-yellow. Not very resistant, but more resistant than underlying bed. Lower yellow bed? |
| 60.5-120' | | | Sandstone, silty, fine, buff brown to white. Local lignite or lignitic. Entire interval slope-forming. Largely covered. |
| 42.5-60.5' | SB-21 | | Sandstone, very fine, and shale, silty (alternating). Coarser zones somewhat lithified and concretionary. Small scale cross-bedding obscured by surface weathering, but lignitic material locally thinly concentrated along cross-bedding surfaces. |
| 40-42.5' | SB-22 | | Sand, very fine, (few inches). Overlain by gray shale. |
| 39-40' | SB-23 | | Sand, fine, (few inches). Overlain by purple-brown silty shale. |
| 29-39' | SB-24 | | Sand, fine, gray and shale, dark gray, (alternating). Absence of concretions noticeable. Less resistant than underlying unit and forms nearly flat bench-like slope. Fines upward to clay. |
| 17-29' | SB-25 | | Sand, fine to medium, and silt, shaley, (alternating). Contact between lithologies often rich in organic remains and plant fragment imprints. Fairly resistant. |
| 0-17' | SB-26 | | Sandstone, fine to medium gray. Cross-bedding preserved within many lensoid or cannonball-shaped concretions. Rilled weathering pattern. Basal sandstone. |

*specific sample locations not recorded

Section: Lost Bridge (LB) Date: 6 July, 1981
Location: SW 1/4, NE 1/4, SW 1/4, Sec. 34, T. 148 N., R. 95 W.,
Dunn County, ND
Base of Section: Top of Lignite (HT?)

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 210-310' | | | Covered, except for local lignite exposures. Probably is all fine-grained carbonaceous and lignitic. |
| 197-210' | LB-14 | 202.2' | Alternating sand, silt, shale, in varying proportions. Color-banded by iron-staining. Contains some concretions and seemingly cross-bedded pods and lensoid white sandy masses. |
| 192-197' | LB-13 | 194.8' | Shale, yellow-brown. Weathers white. More carbonaceous upward. |
| 188-192' | | | Covered. |
| 186-188' | LB-12 | 187.7' | Shale, silty, lignitic, carbonaceous. |
| 183-186' | | | Sand, shaley, gray. |
| 164-183' | | | Lignitic interval. Mostly covered. Abundant petrified stumps. |
| 158-164' | | | Alternating sand, silt, shale in varying proportions. Iron-stained, concretion-bearing. Contains individual light-gray sandy "pods" several feet in diameter. |
| 156-158' | | | Lignite. |
| 147-156' | LB-9 | 154.4' | Shale, sandy, Sand, shaley, shale, silty, and sand. Yellow-gray, iron-stained, color-banded, concretion-bearing. Finer near top. |
| 144.5-147' | | | Shale, sandy, gray, non-resistant. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 140-144.5' | LB-8 | 142.5' | Sand, shaley, light-gray. Coarser-grained than underlying unit; causes slope to steepen somewhat. |
| 136-140' | | | Shale, silty, light-gray. Semi popcorn-weathered. |
| 134-136' | LB-7 | 134.1' | Sand, shaley, light-gray. Rather conspicuous unit. A 4", fissile, fossiliferous, silty shale in the middle of this unit. |
| 130.5-134' | | | Sand, shaley, yellow to gray. Contains scattered small (few inches) iron-cemented nodules. |
| 119.5-130.5' | LB-6 | 128.8' | Sand, shaley, yellow-gray. Fines upward. Iron-cemented-nodule and concretion-bearing. Reddish iron-stained yellow-gray sandy concretion layer near top. Above, a thin (1-1/2") red, iron-cemented layer locally forms a cap. |
| 102-119.5' | LB-5 | 117.6' | Alternating lignitic and organic-rich shale. Uppermost lignite is capped by sand. |
| 90.5-102' | LB-3 | 96.7' | Silt, shaley, to shale, silty. Yellow-gray, color-banded. Upper 2' more shaley. Concretion-bearing. |
| 88-90.5' | LB-2 | 90.1' | Lignite. Capped by few inches of very light-gray, plant-fossil-rich shale that resembles coal ash (often powdery). |
| 78.5-88' | | | Shale, very light-gray, very fossiliferous (plants). Silt content increases upward, then more shaley upward. |
| 77-78.5' | | | Lignite. |
| 73-77' | | | Shale, silty, light-gray, yellow-orange color-banded. Breaks into |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| | | | small (several centimeters) blocks. Contains scattered weathered Iron-nodules. |
| 5-73' | | | Covered. |
| 0-5' | | | Silt, shaley, to Shale, silty. Orange-yellow to yellow-gray. |

additional samples:

Lost Bridge A -- white sandy pod, perhaps limestone
Lost Bridge B -- light gray claystone, fossil-rich, capping lignite at 90.5'
Lost Bridge C -- lower yellow bed from east of ranch house

Section: Mannhaven (Mann) Date: 7 June, 1981
Location: NE 1/4, SE 1/4, NE 1/4, Sec. 12, T. 146 N., R. 85 W.,
Mercer County, ND
Base of Section: Base of butte.

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 83.2-113.2' | | | Shale, silty, yellow-brown. two feet of lignite at 92'. Non-resistant, forming a fairly grassy slope often covered with slopewash debris. |
| 82.4-83.2' | Mann-8 | 83.2' | Shale, gray. |
| 80.4-82.4' | | | Shale, brownish gray. Grades upward to silt and then to carbonaceous shale. |
| 65.3-80.4' | Mann-7 | 70.4' | Sand, fine, gray. Resistant and rilled on surface. Abundant fossil plant remains near top. |
| 62.5-65.3' | | | Shale, silty, blue-gray, carbonaceous. Popcorn-weathered surface. |
| 60.5-62.5' | | | Shale, brown-gray, carbonaceous. |
| 60-60.5' | | | Lignite. |
| 54-60' | Mann-6 | 58.3' | Shale, silty, blue-gray. Popcorn weathered on surface. |
| 0-54' | Mann-5<br>Mann-4<br>Mann-3<br>Mann-2<br>Mann-1 | 46.8'<br>35.9'<br>25.4'<br>15.4'<br>7.4' | Alternating shale, silty; silt, shaley; shale, silty, sandy; sand, shaley, silty; and sand, fine. Color-banded by iron-staining. Contains small reddish concretions. Colors alternate light yellow-gray, blue-gray, orange to buff brown or gray. Weather into surface rilles or popcorn depending on proportion of grain sizes present. Coarser sections rilled, finer (clayey) portions popcorny. A few thin (1-2") organic to lignitic shale zones present. A 10" lignite present at 15'. |

Section: Masonic Butte (MB) Date: 6 June, 1981
Location: NW 1/4, NE 1/4, NE 1/4, Sec. 14, T. 144 N., R. 84 W.,
McLean County, ND
Base of Section: At first exposure of rock above grass-covered slope.

| Unit Interval | sample | Sample Position | Unit Description |
|---|---|---|---|
| 103.0-104.5' | | | Lignite. |
| 102.3-103.0' | | | Claystone, carbonaceous, gray to brown. |
| 97.3-102.3' | | | Silt, green-gray. |
| 97.2-97.3' | | | Lignite. |
| 96.0-97.2' | | | Sandstone, very fine, silty. |
| 93.0-96' | MB-9 | 95.4' | Siltstone, clayey. Dull yellow brown with orange iron oxide concretionary bands. Lignitic claystone near top. |
| 80.0-93.0' | MB-8 | 86.8' | Sandstone, very fine, silty. Uppermost foot indurated. Weathers buff yellow. |
| 79.5-80.0' | MB-7 | 80.0' | Lignite. |
| 77.5-79.5' | | | Siltstone, clayey to claystone, silty. Fossil plant fragments common. |
| 74.5-77.5' | | | Siltstone, sandy, brown. |
| 66-74.5' | MB-6 | 68.3' | Claystone, greenish gray. |
| 62-66' | | | Claystone, silty, gray to tan. Orange concretionary layers. |
| 53-62' | | | Claystone, silty. Fossil plant fragments in upper portion. |
| 51-53' | | | Lignite. |
| 49.5-51' | MB-5 | 50.4' | Claystone, brown, carbonaceous. |
| 48-49.5' | | | Claystone. Thin (~1") lignite at base. |
| 45.5-48' | | | Sandstone, very fine, silty. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 43-45.5' | | | Claystone, silty, light-brown. Orange color-banded. |
| 38-43' | MB-4 | 41.2' | Sandstone, very fine, silty. Light brown with orange color bands. Contains lensoid sandstone bodies. |
| 33-38' | MB-3 | 35.1' | Claystone, silty. Iron-stained concretionary color bands. |
| 24.5-33' | | | Sandstone, fine, clayey, gray to brown. Orange color banded. |
| 24-24.5' | | | Claystone, silty, light gray. |
| 23.3-24' | | | Lignite. |
| 23-23.3' | | | Claystone, gray. Contains carbonaceous fossil plant fragments. |
| 20.5-23' | MB-2 | 22.1' | Siltstone, sandy, gray-brown. Fossil plant fragments abundant. |
| 18-20.5' | | | Claystone, silty. Gray-brown. orange bands. contains fossil plant fragments. |
| 17-18' | | | Sandstone, very fine, silty. clayey silt and silty clay bands. |
| 3.8-17' | MB-1 | 12.6' | Claystone, silty to silt, clayey. Gray-brown with orange bands, in upper half. |
| 3.5-3.8' | | | Lignite. |
| 0-3.5' | | | Siltstone, clayey. Light brown to orange color-banded. |

Section: Edge of a Glacier (EG) Date: June, 1980
Location: SE 1/4, NW 1/4, Sec. 31, T. 38 N., R. 104 W.,
McKenzie County, ND
Base of Section: Base of butte

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 237-247' | Edge-3 | | Sand, very fine, white to light yellow. Unconsolidated at surface. Cross bedding preserved beneath surface. Vertically oriented fossil organic matter (roots). |
| 226-237' | | | Silt, yellow clayey. Forms slope which covers lower yellow bed. |
| 186.8-226' | | | Clay, sandy, silty, gray. Is iron stained and contains white pods similar to 146.5-151.5' interval. Interrupted 8-9' from base and again 19' from base by 8" of lignite. Becomes less resistant upward, becoming a loose "dirt" slope. |
| 184.8-186.8' | | | Lignite. |
| 174.8-184.8' | | | Clay, silty, and silt, clayey (alternating). Popcorn-weathers. |
| 174.5-174.8' | | | Shale, fissile, blue-gray. Plant-fragment rich. Breaks into medium size chips. |
| 169.9-174.5' | EG-17 | 173.1' | Sand, fine-grained, iron-stained (banded). Somewhat rilled. Contains large (1 m) pods of white sandstone with what looks like disturbed bedding. Increased clay component at top. |
| 169.6-169.9' | EG-16<br>EG-A | | Organic material. Appears almost "woody". Capped by thin (~2") indurated, white sandstone (sample EG-A). |
| 168.3-169.6' | EG-15 | | Clay, sandy, gray. Somewhat popcorn weathered. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 168-168.3' | EG-14 | | Sandy material, blue-gray. Breaks into small chips. |
| 163-168' | EG-13 | 165.0' | Clay, blue-gray, popcorn-weathered. Forms a short bench. Is upper Sentinel Butte bentonite. |
| 159-163' | EG-12 | 161.0' | Silt, clayey, white, horizontally laminated. Weathers out as "pillars" or columns resembling stacked pankakes. Is the Sentinel Butte ash. |
| 154-159' | EG-11 | 157.5' | Clay, blue-gray, popcorn-weathered. Flows when wet, so drapes underlying unit, making thickness determination difficult. Forms a large bench. Is the lower Sentinel Butte Bentonite. |
| 153-154' | EG-10 | | Shale, blue-gray. Lithified. Breaks along horizontal planes. Well preserved water ripples with 3 to 4-inch-wavelength. |
| 129.9-153' | EG-9<br>EG-9B | 138.3' | Shale, silty, sandy, iron-stained. Some carbonaceous zones. (sample EG-9B, "woody" zone). |
| 129.5-129.9' | EG-8 | | Lignite grading upward to shale. |
| 128-129.5' | EG-7 | | Shale, buff yellow. Breaks easily into very small chips. |
| 125-128' | EG-6 | | Shale, gray, silty. Somewhat less resistant than underlying unit. |
| 105.5-125' | EG-5 | 123.4' | Shale, sandy, gray to light blue-gray, orange-banded, iron-stained. Popcorn-weathered where finer grained. Contains at least one 1" organic shale zone. |
| 108.5-115.5' | EG-4 | 108.8' | Shale, gray, organic-rich. Less lignitic and less "woody" than underlying unit. |

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 107-108.5' | EG-3 | | Shale, lignitic. Very organic-rich, looks "woody". |
| 100-107' | EG-2 | | Clayey zone. Semi popcorn-weathered. Less rilled than underlying unit. |
| 0-100' | EG-1 | 13.8' | Sand, medium, white to light gray. Very rilled, concretion-bearing. |

additional samples:
Edge of a Glacier 1 -- lower yellow bed
EGLYB-1 -- lower yellow bed below Edge of a Glacier 1
Edge 1C -- concretion from lower yellow bed

Section: Ash Coulee (AC) Date: 12 June, 1981
Location: NW 1/4, NE 1/4, NE 1/4, Sec. 8, T. 142 N., R. 100 W.,
Billings County, ND
Base of Section: At contact with Bullion Creek Formation; a lignite (the HT?)

| Unit Interval | Sample | Sample Position | Unit Description |
|---|---|---|---|
| 75-84' | AC-9 | 83.4' | Shale, silty, gray, yellow to orange color-banded. Contains reddish iron-cemented layers. |
| 74-75' | AC-A | | Shale, carbonaceous, light gray. Contains abundant fossil plant fragments, very well preserved. |
| 71-74' | AC-8 | 71.4' | Lignite. |
| 59.5-71' | AC-7 | 62.2' | Shale, silty, to silt, shaley. Alternating light gray and yellow stained layers. Thin carbonaceous layers occur within the more shaley portions. |
| 33-59.5' | AC-6<br>AC-5<br>AC-4 | 56.8'<br>44.2'<br>35.0' | Shale, silty. Alternating gray, brown, yellow color-banded. Concretion-bearing. Abruptly coarsens to fine to medium gray-white sand for top 4.5 to 6'. Upper sandy zone contains a 1' indurated zone. |
| 32.5-33' | | | Lignitic zone. |
| 20-32.5' | AC-3 | 29.0' | Shale, silty, to silt, shaley. Orange color-banded. Iron-cemented thin layers. Concretion-bearing. Upper 2.5' more shaley. |
| 17.5-20' | | | Shale, gray. Contains two 1" lignitic intervals. |
| 10.5-17.5' | AC-2 | 16.1' | Shale. Alternating carbonaceous and lignitic. |
| 3-10.5' | AC-1 | 6.3' | Claystone, brown-gray to gray. Contains petrified stumps. |
| 0-3' | AC-B | | Lignite. Overlies yellow silt which is locally baked and reddened. Local baked zones and brown carbonaceous zones. |

## Additional Samples, Collected Non-Randomly

| | |
|---|---|
| Square Butte A-E<br>(SQB A-E) | Sequence of samples from basal sandstone outlier north of Square Butte, central Golden Valley County.<br>A: rilled, light gray sandstone (at base of sequence)<br>B: iron-cemented "concretionary" band material.<br>C: clayey siltstone above B.<br>D: silty claystone above C.<br>E: white slabs (black on inside) which cap sequence. |
| SU-A | Light gray to white sand similar to, but above, basal sandstone at 10.5 mile mark along south loop road of Theodore Roosevelt National Park, South Unit. From top of hill, south side of road. Contains large sandstone concretions. |
| SU-B | Basal sandstone from backside of exposure south of road exactly at mile marker 10. Finer grained here than at Square Butte. |
| SU-C | Petrified wood from above SU-B. |
| BR-A | Basal sandstone from exposure north side of Blacktail Road. |
| SS-1 | A white, medium sand, very friable, cross-bedded, semi-consolidated. From right side of road just below top of hill north of Sully Springs RR crossing (Billings County). |
| SS-2 | White, medium sandstone 100 yards north of RR tracks at "Petrified Forest" north of Sully Creek Road, about 1.4 miles southwest of Sully Springs RR crossing. Royse and Hennen's "basal sand"? |
| LYB-1 | White silt capping lower yellow bed east of Edge of Glacier sign, on west side of major gulley that approaches road. |
| LYB-2 | Lower yellow bed material from same location. |
| Long X D | Lower yellow bed from river side of hill south of road near "Long X Trail" sign in North Unit of T.R. Park. |

| | |
|---|---|
| Long X C | Popcorn-weathered clay bench below lower yellow bed. |
| Slump Block 1 | Blue-gray clay layer sampled as possible bentonite near "Slump Block" attraction in North Unit of T.R. Park. |
| Marmarth | Ash from 4.6-m-thick section shown in Figure 26. |

Additional samples of Sentinel Butte bentonite/ash:

from exposure southeast of "Interpretive Shelter" at "River Bend Overlook" in North Unit of Theodore Roosevelt National Park:

| | |
|---|---|
| Bent-1 | lower bentonite bench. |
| Bent-2 | laminated, very fine, white siltstone (ash). |
| Bent-3 | upper bentonite bench. |
| Bent-4 | light gray to white sandstone overlying upper bench. |
| Bent-5 | popcorn-weathered, organic-fragment-rich silty claystone overlying Bent-4. |

from "Edge of a Glacier" overlook in North Unit of park:

| | |
|---|---|
| UBB-1 | thin (few centimeters) gradational zone between upper clay bench and ash. |
| LBB-1 | similar gradational zone between lower bench and ash. |

from "Cedar Canyon" along park road in North Unit (west of Caprock Coulee):

| | |
|---|---|
| BB-1 | ash adjacent to road; just before road curves west to rise onto prairie. |

from east wall of Squaw Creek Valley, beyond North Unit boundary (NE NE SW Sec. 18):

| | |
|---|---|
| BB-2 | ash, white. 4-3/4' thick here. |
| BB-3 | upper clay. |
| BB-4 | brown, "woody" clayey material from 1" bed above upper bench. |
| BB-5 | a popcorn-weathered clay unit above the upper bentonite bench. |
| BB-6 | ledge-forming sandstone above BB-5. |
| BB-7 | claystone above BB-6. |
| BB-8 | lower yellow bed. |

| | |
|---|---|
| BB-9 | lower Sentinel Butte bentonite bench. |
| BB-10 | dull white barium mineral (barite) locally concentrated on and below surface of lower bentonite bench. |

from "Zoar Church" site, NE Sec. 29, T 149 N, R 99 W, McKenzie Co.:

| | |
|---|---|
| BB-11 | ash. |
| BB-12 | ash. |
| BB-13 | sandstone above upper bentonite bench. |
| BB-14 | gray shale underlying lower bentonite bench. Appears "rippled" on surface, but this may be a weathering effect. |
| BB-15 | cherty chips from disintegrated ovoid to spherical masses within lower bentonite. |
| BB-16 | barite fragmments from lower bentonite bench. Occurs in large circular masses. |
| BB-17 | 3rd popcorn clay bench from this site (above 3-layer sequence). |
| BB-18 | from gradational zone between laminated ash and upper bentonite. |

# APPENDIX B

# DISAGGREGATION AND SAND:SILT:CLAY DETERMINATION PROCEDURE

1. Obtain 15 grams of sample. Crush between fingers to pea-size fragments.

2. Soak sample in distilled water to disaggregate. Use only as much water as necessary.

3. Wet sieve sample through 63 µm screen. Clays will pass rapidly. Continue to rinse silt through screen. To prevent retention of large volumes of water:

   a) rinse silt through screen over a clean bucket.
   b) decant water from bucket after silt has settled to bottom.
   c) rinse silt grains from bucket into the beaker with clay.

4. Allow beaker containing silt and clay to remain undisturbed overnight. Check for flocculation of clay by visual inspection or by withdrawing a small volume of suspended material and checking for adequate Brownian motion of clay particles using a microscope.

5. If flocculated, add dispersant or centrifuge and decant repeatedly with distilled water. The following formula (from Jackson, 1969) is useful for determining centrifuge speeds and times:

$$t_{min} = \frac{63.0 \times 10^8 n \times \log_{10} R/S}{N^2 \times D_\mu^2 \times S}$$

where; $n$ = viscosity at existing temperature
$N$ = RPM
$D_\mu$ = particle size in µm
$S$ = difference in specific gravity of liquid and particle
$R$ = radius from spin axis to top of sediment layer
$S$ = radius from spin axis to top of water column

6. Silt may be obtained by pouring off the clay. Rewet silt and decant repeatedly (into dish with clay) until no more clay is liberated from the silt. Pour excess clear water from the silt fraction, distribute the silt evenly and thinly on the walls of an evaporating dish and allow it to dry. The silt can then be gathered by rubbing a finger along the walls of the dish. Sand caught on screen in step 3 can be dried and gathered in a similar manner.

7. Weigh sand and silt fractions separately. Clay weight can then be determined by difference from the starting weight of 15 grams. An alternate method is to pipette, dry, and weigh a known volume of clay suspension from the clay beaker. Multiplying this weight by the original number of pipette volumes contained in the clay beaker gives the total clay weight.

# APPENDIX C

# SAND:SILT:CLAY PERCENTAGES AND GRAIN SIZE CLASSIFICATIONS

Table 15. Sand:Silt:Clay Percentages and Textural Classification

| Sample | %Sand | %Silt | %Clay | Classification |
|---|---|---|---|---|
| EG-1 | 72 | 19 | 9 | sand |
| EG-3 | -- | -- | -- | LIGNITIC |
| EG-4 | -- | -- | -- | LIGNITIC |
| EG-5 | <1 | 42 | 58 | MUD |
| EG-8 | -- | -- | -- | LIGNITIC |
| EG-9 | 0 | 34 | 66 | MUD TO CLAY |
| EG-11 | <1 | 20 | 80 | CLAY |
| EG-13 | 1 | 44 | 55 | MUD |
| EG-16 | -- | -- | -- | LIGNITIC |
| EG-17 | 60 | 22 | 18 | MUDDY SAND |
| SB-1 | -- | -- | -- | *INDURATED SAND* |
| SB-7 | 34 | 61 | 5 | SANDY SILT |
| SB-11 | 20 | 67 | 12 | SANDY SILT |
| SB-12 | 66 | 33 | 1 | SILTY SAND |
| SB-17 | 34 | 65 | <1 | SANDY SILT |
| SB-18 | 87 | 13 | <1 | SILTY SAND |
| SB-21 | 32 | 58 | 10 | SANDY SILT |
| SB-24 | <1 | 52 | 48 | MUD |
| SB-25 | 80 | 12 | 8 | MUDDY SAND |
| SB-26 | 16 | 63 | 20 | SANDY SILT |
| 7= 1 | 10 | 55 | 35 | SANDY MUD |
| 7= 2 | 5 | 61 | 34 | MUD TO SILT |
| 7= 3 | <1 | 63 | 37 | MUD |
| 7= 4 | <1 | 56 | 44 | MUD |
| 7= 7 | <1 | 71 | 29 | SILT |
| 7= 8 | <1 | 34 | 65 | MUD TO CLAY |
| 7= 9 | 2 | 70 | 28 | SILT |
| 7= 10 | 1 | 25 | 74 | MUD |
| 7= 12 | 5 | 81 | 14 | SILT |
| LB-2 | -- | -- | -- | LIGNITIC |
| LB-3 | <1 | 56 | 44 | MUD |
| LB-5 | -- | -- | -- | LIGNITIC |
| LB-6 | <1 | 65 | 34 | MUD TO SILT |
| LB-7 | <1 | 73 | 26 | SILT |
| LB-8 | 14 | 50 | 36 | SANDY MUD |
| LB-9 | <1 | 67 | 32 | SILT TO MUD |
| LB-12 | -- | -- | -- | LIGNITIC |
| LB-13 | <1 | 37 | 62 | MUD |
| LB-14 | 4 | 78 | 18 | SILT |

Table 15 --continued

| Sample | %Sand | %Silt | %Clay | Classification |
|---|---|---|---|---|
| SHB-1 | 8 | 66 | 26 | SILT |
| SHB-2 | <1 | 59 | 41 | MUD |
| SHB-3 | 16 | 74 | 10 | SANDY SILT |
| SHB-4 | 0 | 49 | 51 | MUD |
| SHB-5 | <1 | 66 | 33 | SILT TO MUD |
| SHB-6 | 7 | 23 | 70 | CLAY |
| SHB-7 | 24 | 37 | 39 | SANDY MUD |
| SHB-8 | <1 | 42 | 57 | MUD |
| SHB-9 | <1 | 98 | 2 | SILT |
| LX-3 | 29 | 57 | 14 | SANDY SILT |
| LX-5 | <1 | 60 | 39 | MUD |
| LX-6 | <1 | 55 | 45 | MUD |
| LX-8 | <1 | 58 | 42 | MUD |
| LX-9 | 2 | 71 | 27 | SILT |
| LX-11 | <1 | 6 | 93 | CLAY |
| LX-15 | 1 | 98 | 1 | SILT |
| LX-16 | 2 | 59 | 39 | MUD |
| LX-17 | <1 | 43 | 57 | MUD |
| LX-19 | <1 | 59 | 41 | MUD |
| LX-22 | 8 | 91 | 1 | SILT |
| MANN-1 | <1 | 74 | 25 | SILT |
| MANN-2 | -- | -- | -- | LIGNITIC |
| MANN-3 | 2 | 83 | 15 | SILT |
| MANN-4 | -- | -- | -- | LIGNITIC |
| MANN-5 | 54 | 32 | 14 | SILTY SAND |
| MANN-6 | 2 | 32 | 66 | CLAY |
| MANN-7 | 68 | 13 | 19 | MUDDY SAND |
| MANN-8 | 0 | 46 | 54 | MUD |
| AC-1 | <1 | 38 | 61 | MUD |
| AC-2 | -- | -- | -- | LIGNITIC |
| AC-3 | <1 | 71 | 29 | SILT |
| AC-4 | 0 | 24 | 76 | CLAY |
| AC-5 | <1 | 65 | 35 | MUD TO SILT |
| AC-6 | 54 | 29 | 17 | MUDDY SAND |
| AC-7 | <1 | 74 | 26 | SILT |
| AC-8 | -- | -- | -- | LIGNITIC |
| AC-9 | 15 | 58 | 27 | SANDY SILT |

Table 15 --continued

| Sample | %Sand | %Silt | %Clay | Classification |
|---|---|---|---|---|
| KP-2 | -- | -- | -- | LIGNITIC |
| KP-3 | 0 | 57 | 43 | MUD |
| KP-4 | <1 | 76 | 24 | SILT |
| KP-5 | 4 | 74 | 22 | SILT |
| KP-6 | <1 | 68 | 32 | SILT |
| KP-7 | -- | -- | -- | LIGNITIC |
| KP-8 | 9 | 39 | 52 | MUD |
| KP-9 | 18 | 80 | 2 | SANDY SILT |
| MB-1 | 2 | 75 | 23 | SILT |
| MB-2 | 1 | 82 | 17 | SILT |
| MB-4 | 4 | 64 | 32 | SILT TO MUD |
| MB-5 | 6 | 88 | 6 | SILT |
| MB-6 | 3 | 42 | 55 | MUD |
| MB-7 | -- | -- | -- | LIGNITIC |
| MB-8 | 46 | 53 | <1 | SANDY SILT |
| MB-9 | 1 | 98 | 1 | SILT |

# APPENDIX D

# MICROPROBE DATA: VOLCANIC ROCK FRAGMENTS

Table 16. Microprobe Analyses of Sentinel Butte Volcanic Rock Fragments

part I -- Upper Sandstone

| specimen: | 1g | 2g | 3g | 4g | 5g | 6g | $7p_1$ | $7p_2$ | |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 62.41 | 59.21 | 85.71 | 61.23 | 64.12 | 58.74 | 68.11 | 70.02 | 69.34 |
| $Al_2O_3$ | 19.92 | 16.83 | 7.77 | 21.59 | 20.26 | 19.33 | 19.01 | 15.88 | 18.97 |
| FeO* | 1.92 | 1.19 | 0.00 | 2.69 | 0.88 | 7.46 | 0.00 | 0.27 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.60 | 0.00 | 4.88 | 0.00 | 0.00 | 0.00 |
| CaO | 2.13 | 9.13 | 0.00 | 2.48 | 3.07 | 0.97 | 0.15 | 1.56 | 0.01 |
| $Na_2O$ | 4.88 | 3.65 | 0.35 | 3.95 | 5.69 | 7.84 | 12.73 | 2.89 | 10.61 |
| $K_2O$ | 7.59 | 8.90 | 6.02 | 6.17 | 5.98 | 0.12 | 0.00 | 8.56 | 0.82 |
| $TiO_2$ | 1.15 | 0.82 | 0.15 | 0.74 | 0.00 | 0.41 | 0.00 | 0.15 | 0.16 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.27 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.24 | 0.00 |
| ClO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.00 |
| $SO_3$ | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.32 | 0.00 |
| Ab | 44.15 | | 8.02 | | | | | | 94.66 |
| An | 10.67 | | 0.00 | | | | | | 0.50 |
| Or | 45.18 | | 91.98 | | | | | | 4.83 |

| specimen: | 8p | $9p_1$ | $9p_2$ | 8g | $10p_1$ | $10p_2$ | $10p_3$ | $11p_1$ | $11p_2$ |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.27 | 67.37 | 65.59 | 70.45 | 58.58 | 65.84 | 35.87 | 65.83 | 66.68 |
| $Al_2O_3$ | 20.45 | 19.94 | 20.18 | 14.88 | 23.51 | 19.32 | 16.58 | 20.25 | 20.47 |
| FeO* | 1.79 | 0.44 | 0.87 | 2.21 | 1.59 | 0.30 | 31.60 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.60 | 0.37 | 0.00 | 0.00 | 12.11 | 0.00 | 0.00 |
| CaO | 0.65 | 0.52 | 0.78 | 1.44 | 8.38 | 0.65 | 1.38 | 0.00 | 0.00 |
| $Na_2O$ | 10.33 | 11.62 | 11.59 | 6.59 | 7.57 | 5.89 | 0.84 | 1.07 | 0.96 |
| $K_2O$ | 0.11 | 0.11 | 0.21 | 1.97 | 0.18 | 7.44 | 0.31 | 11.85 | 11.58 |
| $TiO_2$ | 0.00 | 0.00 | 0.18 | 1.66 | 0.19 | 0.36 | 1.31 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.31 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| ClO | 0.17 | 0.00 | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $SO_3$ | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 | 0.00 | 0.00 | 0.00 |
| Ab | 96.0 | 97.0 | 95.3 | 75.9 | 61.4 | 52.9 | | 95.3 | 95.6 |
| An | 3.3 | 2.4 | 3.5 | 9.2 | 37.6 | 3.2 | | 4.7 | 4.4 |
| Or | 0.7 | 0.6 | 1.1 | 14.9 | 1.0 | 43.9 | | 0.0 | 0.0 |

part II -- Basal Sandstone

| specimen: | $1p_1$ | 1g | $1p_2$ | 2g | $2p_1$ | $2p_2$ | 3p | 3g | 4g |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 57.45 | 60.32 | 54.40 | 65.15 | 56.45 | 57.42 | 57.83 | 68.80 | 72.91 |
| $Al_2O_3$ | 27.64 | 25.12 | 28.01 | 19.32 | 27.61 | 26.92 | 26.10 | 16.91 | 15.45 |
| FeO* | 0.00 | 0.43 | 0.40 | 0.79 | 0.33 | 0.35 | 0.49 | 1.21 | 0.53 |
| MgO | 0.00 | 0.00 | 0.44 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 8.68 | 8.23 | 10.12 | 1.34 | 9.21 | 9.05 | 8.42 | 2.46 | 2.59 |
| $Na_2O$ | 6.60 | 4.70 | 5.73 | 2.64 | 5.94 | 5.98 | 6.34 | 3.69 | 3.87 |
| $K_2O$ | 0.45 | 1.04 | 0.23 | 10.42 | 0.46 | 0.28 | 0.62 | 6.17 | 4.46 |
| $TiO_2$ | 0.00 | 0.00 | 0.45 | 0.00 | 0.00 | 0.00 | 0.00 | 0.45 | 0.19 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 | 0.00 | 0.00 |
| ClO | 0.18 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $SO_3$ | 0.00 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.31 | 0.00 |
| Ab | 56.5 | 47.3 | 49.9 | | 52.3 | 53.5 | 55.6 | | 47.0 |
| An | 41.0 | 45.8 | 48.7 | | 44.9 | 44.8 | 40.8 | | 12.3 |
| Or | 2.5 | 6.9 | 1.3 | | 2.7 | 1.6 | 3.5 | | 35.6 |

Table 16 part II --continued

| specimen: | 4p | 5g | $5p_1$ | $5p_2$ | 6g | $6p_1$ | $6p_2$ | $6p_3$ | 7g |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 55.66 | 60.19 | 54.58 | 58.11 | 78.30 | 54.08 | 55.07 | 55.91 | 66.35 |
| $Al_2O_3$ | 27.35 | 18.03 | 28.13 | 26.25 | 12.75 | 29.37 | 28.17 | 27.41 | 18.19 |
| FeO* | 0.29 | 5.91 | 0.69 | 0.44 | 0.29 | 0.21 | 0.34 | 0.35 | 1.07 |
| MgO | 0.00 | 0.28 | 0.00 | 0.31 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 |
| CaO | 9.49 | 2.73 | 11.35 | 8.63 | 1.43 | 10.64 | 10.13 | 9.65 | 0.41 |
| $Na_2O$ | 6.13 | 4.30 | 4.59 | 5.32 | 2.28 | 5.49 | 5.75 | 5.61 | 0.59 |
| $K_2O$ | 0.55 | 7.25 | 0.66 | 0.94 | 4.77 | 0.21 | 0.36 | 0.59 | 12.80 |
| $TiO_2$ | 0.29 | 1.08 | 0.00 | 0.00 | 0.18 | 0.00 | 0.18 | 0.26 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 |
| ClO | 0.00 | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $SO_3$ | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.29 |
| Ab | 52.2 |  | 40.6 | 49.7 |  | 47.7 | 49.6 | 47.1 |  |
| An | 44.7 |  | 55.5 | 44.5 |  | 51.1 | 48.3 | 37.1 |  |
| Or | 3.1 |  | 3.8 | 5.8 |  | 1.2 | 2.0 | 3.4 |  |

| specimen: | 7p | 8g | 9p | 9g | 10g | 11g | $11p_1$ | $11p_2$ | $12p_1$ |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 74.02 | 69.36 | 52.41 | 53.21 | 75.53 | 70.81 | 52.25 | 51.84 | 53.79 |
| $Al_2O_3$ | 11.89 | 16.07 | 0.00 | 0.00 | 13.38 | 15.09 | 29.54 | 29.84 | 29.63 |
| FeO* | 1.86 | 0.88 | 8.54 | 8.44 | 0.54 | 0.80 | 0.59 | 1.34 | 0.75 |
| MgO | 0.22 | 0.00 | 38.55 | 37.27 | 0.00 | 0.14 | 0.00 | 0.19 | 0.00 |
| CaO | 2.51 | 0.49 | 0.00 | 0.14 | 0.43 | 1.46 | 12.80 | 12.26 | 11.20 |
| $Na_2O$ | 3.35 | 3.96 | 0.00 | 0.00 | 3.45 | 4.03 | 4.68 | 4.38 | 5.40 |
| $K_2O$ | 1.95 | 8.93 | 0.00 | 0.20 | 6.49 | 6.16 | 0.14 | 0.15 | 0.23 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 1.18 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 0.00 | 0.00 | 0.00 |
| ClO | 0.17 | 0.00 | 0.23 | 0.33 | 0.18 | 0.12 | 0.00 | 0.00 | 0.00 |
| $SO_3$ | 4.03 | 0.31 | 0.27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ab |  |  |  |  | 43.3 | 45.3 | 39.5 | 38.9 | 46.0 |
| An |  |  |  |  | 3.0 | 9.1 | 59.7 | 60.2 | 52.7 |
| Or |  |  |  |  | 53.7 | 45.6 | 0.8 | 0.9 | 1.3 |

| specimen: | $12p_2$ | $12p_3$ | $13p_1$ | 13g | $13p_2$ | 14g | 15g |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.88 | 53.08 | 55.36 | 75.34 | 36.08 | 75.59 | 76.83 |
| $Al_2O_3$ | 28.27 | 29.13 | 27.96 | 11.90 | 14.39 | 13.86 | 12.45 |
| FeO* | 0.96 | 0.92 | 0.43 | 1.80 | 23.35 | 0.52 | 0.50 |
| MgO | 0.33 | 0.00 | 0.19 | 0.00 | 9.60 | 0.00 | 0.00 |
| CaO | 10.87 | 12.18 | 9.90 | 1.06 | 0.21 | 1.21 | 1.22 |
| $Na_2O$ | 5.10 | 4.58 | 5.58 | 2.98 | 1.07 | 3.23 | 1.14 |
| $K_2O$ | 0.38 | 0.11 | 0.33 | 5.30 | 8.86 | 5.59 | 7.60 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.25 | 0.00 | 0.42 | 0.00 | 0.26 |
| ClO | 0.21 | 0.00 | 0.00 | 0.19 | 0.25 | 0.00 | 0.00 |
| $SO_3$ | 0.00 | 0.00 | 0.00 | 0.16 | 0.18 | 0.00 | 0.00 |
| Ab | 44.9 | 40.2 | 49.5 | 42.2 |  | 42.6 | 16.7 |
| An | 52.9 | 59.1 | 48.5 | 8.3 |  | 8.8 | 9.9 |
| Or | 2.2 | 0.6 | 1.9 | 49.4 |  | 48.6 | 73.4 |

*Total iron as FeO.
Calculated $H_2O$-free. Normalized to 100%.
subscripts: g = groundmass, p = phenocryst
Basal sandstone sample EG-1. Upper sandstone sample LX-M.

# APPENDIX E

# MICROPROBE DATA: FELDSPARS

Table 17. Microprobe Analyses of Sentinel Butte Upper Sand and Basal Sand Feldspars

UPPER SAND

| grain: | 1a | 1b | 2a | 2b | 3a | 3b | 4a | 4b | 5a | 5b | 6a | 6b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 56.47 | 57.63 | 62.56 | 64.50 | 57.99 | 59.22 | 64.74 | 66.06 | 60.50 | 61.97 | 58.37 | 59.31 |
| $Al_2O_3$ | 26.11 | 26.65 | 18.83 | 19.42 | 24.83 | 25.35 | 18.75 | 19.13 | 23.18 | 23.76 | 24.79 | 25.20 |
| FeO* | 0.00 | 0.00 | 0.00 | 0.00 | 0.49 | 0.50 | 0.00 | 0.00 | 0.27 | 0.27 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 8.83 | 9.01 | 0.46 | 0.48 | 7.10 | 7.25 | 0.53 | 0.55 | 4.82 | 4.94 | 7.39 | 7.51 |
| $Na_2O$ | 5.85 | 5.97 | 4.25 | 4.38 | 6.67 | 6.81 | 6.66 | 6.80 | 8.48 | 8.69 | 7.32 | 7.43 |
| $K_2O$ | 0.49 | 0.50 | 10.34 | 10.66 | 0.85 | 0.87 | 7.17 | 7.31 | 0.36 | 0.37 | 0.24 | 0.25 |
| $TiO_2$ | 0.23 | 0.24 | 0.54 | 0.57 | 0.00 | 0.00 | 0.14 | 0.15 | 0.00 | 0.00 | 0.30 | 0.30 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 97.98 | 100.00 | 97.00 | 100.00 | 97.93 | 100.00 | 97.99 | 100.00 | 97.61 | 100.00 | 98.41 | 100.00 |
| Ab | 52.9 | | 37.6 | | 59.8 | | 57.1 | | 74.5 | | 63.3 | |
| An | 44.1 | | 2.2 | | 35.2 | | 2.5 | | 23.4 | | 35.3 | |
| Or | 2.9 | | 60.1 | | 5.0 | | 40.4 | | 2.1 | | 1.4 | |

| grain: | 7a | 7b | 8a | 8b | 9a | 9b | 10a | 10b | 11a | 11b | 12a | 12b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.26 | 59.71 | 65.30 | 66.22 | 64.30 | 64.16 | 64.91 | 67.08 | 60.78 | 61.67 | 67.25 | 67.71 |
| $Al_2O_3$ | 24.40 | 25.01 | 20.16 | 20.44 | 18.40 | 18.36 | 18.74 | 19.37 | 23.17 | 23.51 | 20.00 | 20.14 |
| FeO* | 0.00 | 0.00 | 0.24 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.60 | 0.61 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 6.70 | 6.87 | 2.20 | 2.23 | 0.25 | 0.24 | 0.64 | 0.66 | 4.97 | 5.05 | 0.77 | 0.78 |
| $Na_2O$ | 7.37 | 7.56 | 9.02 | 9.14 | 2.74 | 2.73 | 7.68 | 7.94 | 7.98 | 8.09 | 11.29 | 11.37 |
| $K_2O$ | 0.83 | 0.85 | 1.71 | 1.73 | 14.13 | 14.10 | 4.78 | 4.95 | 1.05 | 1.07 | 0.00 | 0.00 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.17 | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 97.56 | 100.00 | 98.63 | 100.00 | 100.23 | 100.00 | 96.75 | 100.00 | 98.55 | 100.00 | 99.31 | 100.00 |
| Ab | 63.3 | | 79.4 | | 22.5 | | 68.7 | | 69.8 | | 96.4 | |
| An | 31.8 | | 10.7 | | 1.1 | | 3.1 | | 24.1 | | 3.6 | |
| Or | 4.7 | | 9.9 | | 76.4 | | 28.2 | | 6.1 | | 0.0 | |

| grain: | 13a | 13b | 14a | 14b | 15a | 15b | 16a | 16b | 17a | 17b | 18a | 18b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.05 | 58.65 | 58.73 | 59.33 | 57.47 | 59.29 | 54.49 | 56.51 | 63.08 | 63.32 | 61.97 | 62.68 |
| $Al_2O_3$ | 25.56 | 25.83 | 24.90 | 25.15 | 24.78 | 25.57 | 26.07 | 27.04 | 21.08 | 21.16 | 22.45 | 22.70 |
| FeO* | 0.28 | 0.28 | 0.39 | 0.39 | 0.00 | 0.00 | 0.00 | 0.00 | 0.40 | 0.40 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 8.29 | 8.38 | 6.96 | 7.03 | 7.10 | 7.33 | 9.88 | 10.25 | 3.32 | 3.33 | 4.56 | 4.61 |
| $Na_2O$ | 6.21 | 6.28 | 7.72 | 7.80 | 7.09 | 7.31 | 5.65 | 5.86 | 6.92 | 6.95 | 8.45 | 8.54 |
| $K_2O$ | 0.41 | 0.41 | 0.29 | 0.30 | 0.26 | 0.26 | 0.33 | 0.34 | 4.82 | 4.84 | 1.16 | 1.17 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.30 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.17 | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 98.97 | 100.00 | 98.99 | 100.00 | 96.93 | 100.00 | 96.42 | 100.00 | 99.62 | 100.00 | 98.89 | 100.00 |
| Ab | 56.1 | | 65.6 | | 63.4 | | 49.9 | | 58.0 | | 72.0 | |
| An | 41.4 | | 32.7 | | 35.1 | | 48.2 | | 15.4 | | 21.5 | |
| Or | 2.4 | | 1.6 | | 1.5 | | 1.9 | | 26.6 | | 6.5 | |

Table 17 —continued

BASAL SAND

| grain: | 1a | 1b | 2a | 2b | 3a | 3b | 4a | 4b | 5a | 5b | 6a | 6b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 60.70 | 61.34 | 63.18 | 63.09 | 64.58 | 64.87 | 59.90 | 62.04 | 65.60 | 66.62 | 65.52 | 65.69 |
| $Al_2O_3$ | 23.68 | 23.94 | 18.67 | 18.64 | 22.10 | 22.20 | 22.77 | 23.57 | 18.33 | 18.61 | 18.61 | 18.66 |
| FeO* | 0.00 | 0.00 | 0.37 | 0.37 | 0.00 | 0.00 | 0.00 | 0.00 | 0.19 | 0.20 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 5.71 | 5.77 | 0.18 | 0.18 | 3.13 | 3.14 | 5.53 | 5.73 | 0.47 | 0.47 | 0.58 | 0.58 |
| $Na_2O$ | 8.66 | 8.76 | 0.56 | 0.56 | 9.75 | 9.79 | 8.36 | 8.66 | 5.17 | 5.25 | 5.32 | 5.33 |
| $K_2O$ | 0.19 | 0.19 | 16.67 | 16.64 | 0.00 | 0.00 | 0.00 | 0.00 | 8.72 | 8.85 | 9.42 | 9.44 |
| $TiO_2$ | 0.00 | 0.00 | 0.52 | 0.52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.30 |
| Total | 98.94 | 100.00 | 100.15 | 100.00 | 99.56 | 100.00 | 96.56 | 100.00 | 98.48 | 100.00 | 99.75 | 100.00 |
| Ab | 72.5 | | 4.9 | | 84.9 | | 73.2 | | 46.3 | | 44.9 | |
| An | 26.4 | | 0.8 | | 15.1 | | 26.8 | | 2.3 | | 2.7 | |
| Or | 1.1 | | 94.3 | | 0.0 | | 0.0 | | 51.4 | | 52.3 | |

| grain: | 7a | 7b | 8a | 8b | 9a | 9b | 10a | 10b | 11a | 11b | 12a | 12b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 59.76 | 60.22 | 53.37 | 53.97 | 61.03 | 63.34 | 55.93 | 56.96 | 60.94 | 59.86 | 56.61 | 56.42 |
| $Al_2O_3$ | 24.36 | 24.56 | 27.77 | 28.09 | 18.46 | 19.17 | 26.20 | 26.69 | 25.18 | 24.73 | 27.15 | 27.05 |
| FeO* | 0.00 | 0.00 | 0.79 | 0.80 | 0.00 | 0.00 | 0.24 | 0.24 | 0.23 | 0.22 | 0.26 | 0.26 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 6.98 | 7.04 | 11.48 | 11.61 | 0.30 | 0.32 | 9.13 | 9.30 | 6.31 | 6.20 | 10.00 | 9.96 |
| $Na_2O$ | 7.83 | 7.89 | 5.09 | 5.15 | 3.09 | 3.21 | 6.24 | 6.35 | 8.93 | 8.77 | 6.04 | 6.01 |
| $K_2O$ | 0.28 | 0.29 | 0.37 | 0.38 | 12.08 | 12.54 | 0.45 | 0.46 | 0.00 | 0.00 | 0.30 | 0.30 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 1.37 | 1.42 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.22 | 0.00 | 0.00 |
| Total | 99.21 | 100.00 | 98.87 | 100.00 | 96.33 | 100.00 | 98.19 | 100.00 | 101.81 | 100.00 | 100.36 | 100.00 |
| Ab | 65.9 | | 43.6 | | 27.6 | | 53.9 | | 71.9 | | 51.3 | |
| An | 32.5 | | 54.3 | | 1.5 | | 43.5 | | 28.1 | | 47.0 | |
| Or | 1.6 | | 2.1 | | 70.9 | | 2.6 | | 0.0 | | 1.7 | |

| grain: | 13a | 13b | 14a | 14b | 15a | 15b | 16a | 16b | 17a | 17b | 18a | 18b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.55 | 54.44 | 56.10 | 57.02 | 58.24 | 58.00 | 56.36 | 57.08 | 64.71 | 64.77 | 57.80 | 58.43 |
| $Al_2O_3$ | 27.78 | 28.24 | 26.24 | 26.67 | 25.84 | 25.75 | 26.31 | 26.65 | 18.34 | 18.36 | 25.85 | 26.14 |
| FeO* | 0.47 | 0.48 | 0.45 | 0.46 | 0.26 | 0.26 | 0.34 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 11.17 | 11.35 | 9.04 | 9.19 | 6.08 | 8.05 | 9.13 | 9.25 | 0.27 | 0.27 | 8.19 | 8.28 |
| $Na_2O$ | 4.92 | 5.00 | 6.26 | 6.36 | 7.25 | 7.22 | 5.96 | 6.03 | 0.44 | 0.44 | 6.45 | 6.52 |
| $K_2O$ | 0.34 | 0.34 | 0.29 | 0.30 | 0.34 | 0.34 | 0.44 | 0.44 | 16.14 | 16.16 | 0.23 | 0.24 |
| $TiO_2$ | 0.14 | 0.15 | 0.00 | 0.00 | 0.38 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.39 | 0.39 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 98.37 | 100.00 | 98.38 | 100.00 | 100.39 | 100.00 | 98.75 | 100.00 | 99.90 | 100.00 | 98.91 | 100.00 |
| Ab | 43.5 | | 54.7 | | 60.7 | | 52.8 | | 3.9 | | 57.9 | |
| An | 54.5 | | 43.6 | | 37.4 | | 44.7 | | 1.3 | | 40.7 | |
| Or | 2.0 | | 1.7 | | 1.9 | | 2.5 | | 94.8 | | 1.4 | |

Table 17 --continued

| grain: | 19a | 20a | 20b |
|---|---|---|---|
| $SiO_2$ | 65.76 | 57.57 | 58.28 |
| $Al_2O_3$ | 20.07 | 25.91 | 26.23 |
| FeO* | 0.41 | 0.00 | 0.00 |
| MgO | 0.00 | 0.00 | 0.00 |
| CaO | 1.83 | 8.25 | 8.35 |
| $Na_2O$ | 9.57 | 6.65 | 6.74 |
| $K_2O$ | 2.19 | 0.39 | 0.40 |
| $TiO_2$ | 0.17 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 |
| Total | 100.00 | 98.77 | 100.00 |
| | | | |
| Ab | 79.6 | 58.0 | |
| An | 8.4 | 39.7 | |
| Or | 12.0 | 2.3 | |

*Total iron as FeO.

a = unnormalized data, b = data normalized to 100 percent.

# APPENDIX F

# CLAY MINERALOGY OF SAMPLES

Table 18. Clay Mineralogy of Sentinel Butte Samples

| SAMPLE | MONT. | I/M | CHLOR. | KAOL.* |
|---|---|---|---|---|
| (peak heights) | | | | |
| EG-1 | 44 | nd | nd | nd |
| EG-5 | 24 | 5 | 7 | nd |
| EG-9 | 35 | 11 | 9 | nd |
| EG-11 | 55 | 2 | 2 | nd |
| EG-13 | 93 | 2 | <1 | <1 |
| EG-17 | 87 | tr | <1 | nd |
| SB-7 | nd | 8 | 8 | nd |
| SB-11 | nd | 14 | 13 | nd |
| SB-12 | nd | 13 | 4 | nd |
| SB-17 | nd | 8 | 4 | nd |
| SB-18 | <1 | 8 | <1 | <1 |
| SB-21 | 45 | 2 | 1 | nd |
| SB-24 | 50 | 4 | 5 | 5 |
| SB-25 | 45 | 1 | 2 | 2 |
| SB-26 | 90 | 4 | 5 | 1 |
| 7= 1 | 34 | 6 | 5 | 3 |
| 7= 2 | 36 | 7 | 6 | 3 |
| 7= 3 | 100 | 5 | 6 | nd |
| 7= 4 | 62 | 6 | 6 | nd |
| 7= 7 | 34 | 9 | 9 | 4 |
| 7= 8 | 14 | 13 | 12 | 10 |
| 7= 9 | 82 | 4 | 5 | 3 |
| 7= 10 | 20 | 5 | 9 | 5 |
| 7= 12 | 100 | 2 | 2 | 2 |
| LB-3 | 62 | 8 | 12 | 6 |
| LB-6 | 45 | 4 | 6 | 6 |
| LB-7 | 70 | 6 | 5 | 6 |
| LB-8 | 40 | 3 | 3 | 3 |
| LB-9 | 6 | 6 | 6 | 5 |
| LB-13 | 27 | 9 | 3 | nd |
| LB-14 | 50 | 4 | 4 | 4 |
| SHB-1 | 8 | 3 | nd | 5 |
| SHB-2 | 20 | 7 | 6 | 5 |
| SHB-3 | 89 | 5 | 4 | 2 |
| SHB-4 | 6 | 3 | 4 | 3 |
| SHB-5 | 24 | 4 | 7 | 5 |

Table 18 --continued

| Sample | Mont. | I/M | Chlor. | Kaol.* |
|---|---|---|---|---|
| SHB-6 | 6 | 2 | 4 | 2 |
| SHB-7 | 100 | 2 | 3 | nd |
| SHB-8 | 38 | 4 | 1 | nd |
| SHB-9 | 15 | 6 | 6 | nd |
| LX-3 | 80 | nd | <1 | nd |
| LX-4 | 34 | 4 | 5 | 5 |
| LX-6 | 38 | 7 | 5 | 5 |
| LX-8 | 23 | 3 | 3 | 2 |
| LX-9 | 40 | 3 | 3 | 2 |
| LX-11 | 23 | 4 | 4 | 2 |
| LX-15 | 17 | 8 | 7 | nd |
| LX-16 | 18 | 7 | 7 | nd |
| LX-17 | 65 | 5 | 4 | 2 |
| LX-19 | 100 | 3 | nd | 4 |
| LX-22 | 10 | 5 | 3 | nd |
| MANN-1 | 46 | 6 | 6 | 3 |
| MANN-3 | 68 | 2 | 3 | <1 |
| MANN-5 | 69 | 2 | 3 | 2 |
| MANN-6 | 37 | 3 | <1 | 2 |
| MANN-7 | 100 | 3 | 3 | 1 |
| MANN-8 | 17 | 4 | 2 | nd |
| AC-1 | 50 | 5 | 5 | 4 |
| AC-3 | 76 | 2 | 4 | 1 |
| AC-4 | 8 | 6 | 6 | 4 |
| AC-5 | 50 | 2 | 3 | 1 |
| AC-6 | 100 | 2 | 3 | 1 |
| AC-7 | 60 | 1 | 1 | 1 |
| AC-9 | 100 | 2 | 1 | tr |
| KP-3 | 33 | 6 | 6 | 5 |
| KP-4 | 21 | 1 | 1 | 1 |
| KP-5 | 42 | 1 | 1 | 1 |
| KP-6 | 10 | 3 | 3 | 1 |
| KP-8 | 13 | 9 | 7 | nd |
| KP-9 | 2 | 6 | 5 | nd |

Table 18 --continued.

| SAMPLE | MONT. | I/M | CHLOR. | KAOL.* |
|---|---|---|---|---|
| MB-1 | 70 | 5 | 3 | 4 |
| MB-2 | 100 | 3 | 3 | 3 |
| MB-4 | 92 | 2 | 2 | 2 |
| MB-5 | 7 | 1 | tr | 2 |
| MB-6 | 90 | 13 | 10 | 10 |
| MB-8 | 7 | 4 | 3 | 4 |
| MB-9 | 7 | 2 | 2 | 2 |

abbreviations: mont.=montmorillonite, I/M=illite/mica, chlor.= Chlorite, Kaol.=kaolinite, tr=trace, nd=not determined.
Note: Data reported are from ethylene glycol-solvated samples. The reader is cautioned against drawing conclusions from diffraction intensity comparisons between samples. Although sample preparation methods were kept uniform, some samples were x-rayed over two years apart under different instrument allignment and calibration conditions.
The data presented is meaningful primarily in a qualitative sense.
*Intensities determined by proportioning the 7 Å chlorite/kaolinite peak according to the intensity differences between the 3.53 Å chlorite and 3.56 Å kaolinite peaks.

# APPENDIX G

# MICROPROBE DATA: ZEOLITES

Table 19. Microprobe Analyses of Sentinel Butte Zeolites

| specimen: | 1a | 1b | 2a | 2b | 3a | 3b | 4a | 4b | 5a | 5b |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 72.86 | 74.79 | 76.46 | 73.99 | 68.64 | 74.55 | 62.53 | 73.81 | 72.05 | 74.23 |
| $Al_2O_3$ | 15.60 | 16.02 | 17.28 | 16.71 | 15.38 | 16.70 | 14.87 | 17.55 | 16.08 | 16.58 |
| FeO* | 0.31 | 0.32 | 0.00 | 0.00 | 0.26 | 0.28 | 0.00 | 0.00 | 0.00 | 0.00 |
| MgO | 0.66 | 0.68 | 0.97 | 0.93 | 0.57 | 0.62 | 0.43 | 0.51 | 1.08 | 1.11 |
| CaO | 2.51 | 2.57 | 1.88 | 1.81 | 1.47 | 1.60 | 1.56 | 1.84 | 2.96 | 3.05 |
| $Na_2O$ | 2.96 | 3.04 | 4.46 | 4.32 | 2.83 | 3.07 | 2.49 | 2.94 | 2.68 | 2.76 |
| $K_2O$ | 2.51 | 2.58 | 2.31 | 2.24 | 2.59 | 2.81 | 2.71 | 3.20 | 1.97 | 2.03 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.25 | 0.13 | 0.15 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.12 | 0.00 | 0.00 | 0.21 | 0.22 |
| ClO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 97.41 | 100.00 | 103.35 | 100.00 | 92.08 | 100.00 | 84.72 | 100.00 | 96.91 | 100.00 |
| number of ions on the basis of 72 oxygens | | | | | | | | | | |
| Si | | 28.88 | | 28.56 | | 28.53 | | 28.15 | | 28.56 |
| Al | | 7.26 | | 7.61 | | 7.46 | | 7.74 | | 7.49 |
| Fe | | 0.10 | | 0.00 | | 0.09 | | 0.00 | | 0.00 |
| Mg | | 0.39 | | 0.53 | | 0.35 | | 0.28 | | 0.64 |
| Ca | | 1.07 | | 0.75 | | 0.66 | | 0.76 | | 1.26 |
| Na | | 2.26 | | 3.23 | | 2.24 | | 2.09 | | 2.04 |
| K | | 1.27 | | 1.10 | | 1.39 | | 1.58 | | 1.00 |
| Si/Al | | 3.98 | | 3.75 | | 3.82 | | 3.64 | | 3.81 |
| specimen: | 6a | 6b | 7a | 7b | 8a | 8b | 9a | 9b | 10a | 10b |
| $SiO_2$ | 64.09 | 74.28 | 67.23 | 74.27 | 57.48 | 62.74 | 52.55 | 61.83 | 51.95 | 64.03 |
| $Al_2O_3$ | 14.38 | 16.67 | 14.68 | 16.22 | 22.69 | 24.77 | 22.02 | 25.91 | 19.43 | 23.94 |
| FeO* | 0.00 | 0.00 | 0.00 | 0.00 | - 0.00 | 0.00 | 0.00 | 0.00 | 0.14 | 0.18 |
| MgO | 0.66 | 0.77 | 0.76 | 0.84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 2.83 | 3.28 | 2.55 | 2.82 | 0.08 | 0.09 | 0.00 | 0.00 | 0.10 | 0.12 |
| $Na_2O$ | 4.19 | 4.87 | 4.35 | 4.81 | 11.35 | 12.40 | 10.23 | 12.04 | 9.16 | 11.30 |
| $K_2O$ | 0.11 | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 | 0.22 | 0.16 | 0.20 |
| $TiO_2$ | 0.00 | 0.00 | 0.18 | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.19 | 0.23 |
| MnO | 0.00 | 0.00 | 0.67 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| ClO | 0.00 | 0.00 | 0.08 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 86.26 | 100.00 | 90.50 | 100.00 | 91.60 | 100.00 | 84.98 | 100.00 | 81.13 | 100.00 |
| number of ions on the basis of 72 oxygens | | | | | | | | | | |
| Si | | 28.57 | | 28.65 | | 2.43 | | 2.50 | | 2.48 |
| Al | | 7.42 | | 7.28 | | 1.12 | | 1.09 | | 1.06 |
| Fe | | 0.00 | | 0.00 | | 0.00 | | 0.01 | | 0.01 |
| Mg | | 0.44 | | 0.48 | | 0.00 | | 0.00 | | 0.00 |
| Ca | | 1.36 | | 1.17 | | 0.00 | | 0.00 | | 0.00 |
| Na | | 3.48 | | 3.50 | | 0.90 | | 0.71 | | 0.79 |
| K | | 0.06 | | 0.00 | | 0.00 | | 0.01 | | 0.01 |
| Si/Al | | 3.85 | | 3.93 | | 2.17 | | 2.29 | | 2.34 |

Table 19 —continued

| specimen: | 11a | 11b | 12a | 12b | 13a | 13b | 14a | 14b | 15a | 15b |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 61.99 | 75.11 | 54.86 | 73.03 | 53.09 | 74.24 | 57.80 | 75.64 | 51.50 | 59.51 |
| $Al_2O_3$ | 13.23 | 16.03 | 11.71 | 15.59 | 11.29 | 15.79 | 11.32 | 14.81 | 22.33 | 25.80 |
| FeO* | 0.00 | 0.00 | 0.32 | 0.42 | 0.25 | 0.34 | 0.28 | 0.36 | 0.37 | 0.43 |
| MgO | 0.37 | 0.45 | 0.34 | 0.46 | 0.30 | 0.42 | 0.19 | 0.25 | 0.00 | 0.00 |
| CaO | 1.31 | 1.58 | 1.27 | 1.70 | 1.26 | 1.76 | 0.58 | 0.76 | 0.00 | 0.00 |
| $Na_2O$ | 4.26 | 5.16 | 5.92 | 7.88 | 4.38 | 6.12 | 5.40 | 7.07 | 11.92 | 13.78 |
| $K_2O$ | 1.27 | 1.67 | 0.69 | 0.92 | 0.95 | 1.33 | 0.78 | 1.02 | 0.27 | 0.31 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.15 | 0.17 |
| ClO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.09 | 0.00 | 0.00 |
| Total | 82.53 | 100.00 | 75.11 | 100.00 | 71.52 | 100.00 | 76.42 | 100.00 | 86.54 | 100.00 |
| number of ions on the basis of 72 oxygens | | | | | | | | | | |
| Si | | 29.05 | | 28.67 | | 28.95 | | 29.31 | | 2.25 |
| Al | | 7.15 | | 7.00 | | 7.01 | | 6.58 | | 1.17 |
| Fe | | 0.00 | | 0.14 | | 0.11 | | 0.12 | | 0.01 |
| Mg | | 0.25 | | 0.26 | | 0.23 | | 0.14 | | 0.00 |
| Ca | | 0.66 | | 0.72 | | 0.75 | | 0.32 | | 0.00 |
| Na | | 3.68 | | 5.57 | | 4.26 | | 4.95 | | 1.00 |
| K | | 0.83 | | 0.47 | | 0.68 | | 0.52 | | 0.01 |
| Si/Al | | 4.06 | | 4.09 | | 4.13 | | 4.45 | | 2.01 |

*Total iron as FeO.

a = unnormalized data, b = data normalized to 100 percent. Specimens: 1) clinoptilolite shown in Figure 14a, 2) clinoptilolite shown in Figure 14e, 3,4) clinoptilolite shown in Figure 14c, 5) clinoptilolite shown in Figure 14b, 6,7) mordenite(?) shown in Figure 14d, 8) analcime shown in Figure 16d, 9) analcime shown in Figure 15d, 10) analcime shown in Figure 16a, 11-14) clinoptilolite shown in Figure 14f, 15) analcime shown in Figure 15b.

Note: Water content not determined. Unit cell contents determined on water-free basis for purposes of comparison. Analysis of non-flat surfaces accounts for some of the analytical uncertainty of water content, which might otherwise be approximated by difference from the percentage total.

# APPENDIX H

## GRAIN SIZE DATA FROM THE SENTINEL BUTTE BENTONITE/ASH AND THE MARMARTH ASH

Table 20. Pipette Analysis Grain Size Data from the Sentinel Butte Bentonite/Ash

sample: BB-3 starting weight: 13.4146 g

| size (μm) | weight (g) | indiv. % | cumul. % coarser | indiv. % silt (>2 μm) | cumul. % silt |
|---|---|---|---|---|---|
| 44 | 13.3475 | 0.5 | 0.5 | 1.85 | 1.85 |
| 31 | 13.1675 | 1.34 | 1.84 | 4.95 | 6.80 |
| 22 | 13.0475 | 0.90 | 2.74 | 3.33 | 10.13 |
| 16 | 12.8725 | 1.30 | 4.04 | 4.80 | 14.93 |
| 8 | 11.9000 | 7.25 | 11.29 | 26.79 | 41.72 |
| 4 | 10.7175 | 8.82 | 10.11 | 32.59 | 74.31 |
| 2 | 9.7850 | 6.95 | 27.06 | 25.68 | 99.99 |
| 1 | 8.5000 | 9.58 | 36.64 | | |

sample: LBB-1 starting weight: 14.499

| size (μm) | weight (g) | indiv. % | cumul. % coarser | indiv. % silt (>2 μm) | cumul. % silt |
|---|---|---|---|---|---|
| 44 | 14.3175 | 1.25 | 1.25 | 2.23 | 2.23 |
| 31 | 13.6700 | 4.47 | 5.72 | 7.97 | 10.20 |
| 22 | 13.3750 | 2.03 | 7.75 | 3.62 | 13.82 |
| 16 | 11.8825 | 10.30 | 18.05 | 18.36 | 32.18 |
| 8 | 8.7375 | 21.69 | 39.74 | 38.66 | 70.84 |
| 4 | 7.3500 | 9.57 | 49.31 | 17.06 | 87.90 |
| 2 | 6.3650 | 6.79 | 56.10 | 12.11 | 100.00 |
| 1 | 5.2125 | 7.95 | 64.05 | | |

sample: BB-2 starting weight: 14.3290 g

| size (μm) | weight (g) | indiv. % | cumul. % coarser | indiv. % silt (>2 μm) | cumul. % silt |
|---|---|---|---|---|---|
| 44 | 14.0425 | 2.00 | 2.00 | 2.20 | 2.20 |
| 31 | 12.2650 | 12.40 | 14.40 | 13.63 | 15.83 |
| 22 | 11.2150 | 7.33 | 21.73 | 8.06 | 23.89 |
| 16 | 8.4975 | 18.97 | 40.70 | 20.85 | 44.74 |
| 8 | 3.4300 | 35.36 | 76.06 | 38.87 | 83.61 |
| 4 | 1.8925 | 10.73 | 86.79 | 11.79 | 95.40 |
| 2 | 1.2925 | 4.19 | 90.98 | 4.60 | 100.00 |
| 1 | 0.8400 | 3.16 | 94.14 | | |

Table 20 --continued

sample: UBB-1 starting weight: 14.5900 g

| size (μm) | weight (g) | indiv. % | cumul. % coarser | indiv. % silt (>2 μm) | cumul. % silt |
|---|---|---|---|---|---|
| 44 | 14.4100 | 1.23 | 1.23 | 1.73 | 1.73 |
| 31 | 13.9575 | 3.11 | 4.34 | 4.37 | 6.10 |
| 22 | 13.0975 | 5.89 | 10.23 | 8.28 | 14.38 |
| 16 | 11.2900 | 12.39 | 22.62 | 17.43 | 31.81 |
| 8 | 7.2825 | 27.47 | 50.09 | 38.64 | 70.45 |
| 4 | 5.3950 | 12.93 | 63.02 | 18.19 | 88.64 |
| 2 | 4.2175 | 8.07 | 71.09 | 11.35 | 99.98 |
| 1 | 3.3750 | 5.78 | 76.87 | | |

sample: BB-9 starting weight: 14.0900 g

| size (μm) | weight (g) | indiv. % | cumul. % coarser | indiv. % silt (>2 μm) | cumul. % silt |
|---|---|---|---|---|---|
| 44 | 14.0625 | 0.20 | 0.20 | 0.70 | 0.70 |
| 31 | 13.7175 | 2.44 | 2.64 | 8.50 | 9.20 |
| 22 | 13.6675 | 0.36 | 3.00 | 1.25 | 10.45 |
| 16 | 13.2825 | 2.73 | 5.73 | 9.51 | 19.96 |
| 8 | 11.8900 | 9.88 | 15.61 | 34.41 | 54.37 |
| 4 | 10.8975 | 7.05 | 22.66 | 24.56 | 78.93 |
| 2 | 10.0450 | 6,05 | 28.71 | 21.07 | 100.00 |
| 1 | 9.3425 | 4.98 | 33.69 | | |

Table 21. Pipette Analysis Grain Size Data from the Marmarth Ash

sample: Marmarth starting weight: 8.6725 g (+ 4.6188 g sand)

| size (μm) | weight (g) | indiv. % | cumul. % coarser |
|---|---|---|---|
| 63 | 8.6725 | 34.75 | 34.75 |
| 44 | 4.9250 | 28.20 | 62.95 |
| 31 | 2.3220 | 19.58 | 82.53 |
| 22 | 1.4300 | 6.71 | 89.24 |
| 16 | 1.1950 | 1.77 | 91.01 |
| 8 | 0.9450 | 1.88 | 92.89 |
| 4 | 0.8125 | 1.00 | 93.89 |
| 2 | 0.7275 | 0.64 | 94.53 |
| 1 | 0.6625 | 0.48 | 95.01 |

# APPENDIX I

## MICROPROBE DATA: <2 µm CLAY

Table **22**. *Microprobe Analyses of Selected <2 µm Clay Samples**

| sample: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 68.44 | 66.14 | 66.84 | 62.06 | 58.31 | 60.33 | 60.64 | 59.72 | 64.76 | 64.12 | 58.26 | 55.37 |
| $Al_2O_3$ | 20.06 | 19.98 | 20.02 | 22.52 | 23.62 | 19.80 | 23.44 | 21.82 | 9.29 | 20.56 | 15.06 | 21.61 |
| FeO* | 4.06 | 4.82 | 4.55 | 7.48 | 7.54 | 7.57 | 4.41 | 5.79 | 2.34 | 5.97 | 5.74 | 4.58 |
| MgO | 3.65 | 3.67 | 3.51 | 1.91 | 3.12 | 2.75 | 1.43 | 2.35 | 2.73 | 2.70 | 2.80 | 2.11 |
| CaO | 1.10 | 0.74 | 0.97 | 0.74 | 0.92 | 1.52 | 0.51 | 1.37 | 4.56 | 1.21 | 3.75 | 1.29 |
| $Na_2O$ | 1.83 | 3.46 | 2.84 | 2.54 | 1.75 | 3.93 | 3.11 | 5.12 | 10.54 | 2.91 | 7.57 | 13.30 |
| $K_2O$ | 0.39 | 0.33 | 0.63 | 1.93 | 3.63 | 0.42 | 2.49 | 0.48 | 1.52 | 1.23 | 2.72 | 0.43 |
| $TiO_2$ | 0.11 | 0.11 | 0.31 | 0.48 | 0.77 | 0.76 | 1.08 | 0.38 | 0.38 | 0.43 | 0.42 | 0.20 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.88 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.13 | 0.12 | 0.00 | 0.00 | 0.11 | 0.00 | 0.00 | 0.22 | 0.00 | 0.05 | 0.21 | 0.00 |
| ClO | 0.10 | 0.12 | 0.00 | 0.00 | 0.10 | 0.65 | 0.04 | 0.62 | 0.38 | 0.05 | 0.53 | 0.37 |
| $SO_3$ | 0.13 | 0.51 | 0.33 | 0.34 | 0.13 | 0.39 | 2.85 | 2.13 | 3.50 | 0.77 | 2.94 | 0.74 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

| sample: | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 59.50 | 68.64 | 53.93 | 51.75 | 53.94 | 63.22 | 66.06 | 63.85 | 68.47 | 68.75 | 67.41 | 68.59 |
| $Al_2O_3$ | 21.05 | 17.39 | 21.49 | 21.66 | 23.83 | 19.05 | 19.91 | 21.61 | 15.69 | 17.97 | 18.63 | 19.24 |
| FeO* | 4.22 | 3.67 | 6.91 | 5.60 | 7.34 | 4.70 | 5.07 | 5.76 | 3.60 | 4.02 | 4.24 | 4.57 |
| MgO | 2.44 | 4.06 | 2.78 | 2.55 | 2.94 | 3.32 | 2.39 | 1.74 | 3.01 | 2.93 | 3.13 | 3.31 |
| CaO | 0.38 | 1.21 | 1.06 | 0.89 | 2.35 | 0.88 | 0.99 | 0.45 | 4.18 | 1.19 | 1.14 | 2.42 |
| $Na_2O$ | 10.84 | 3.39 | 9.89 | 10.75 | 2.72 | 7.31 | 4.03 | 2.01 | 3.53 | 3.48 | 3.17 | 1.25 |
| $K_2O$ | 0.25 | 0.54 | 2.01 | 1.98 | 3.10 | 0.32 | 0.37 | 3.67 | 0.50 | 0.48 | 0.67 | 0.50 |
| $TiO_2$ | 0.56 | 0.48 | 0.72 | 0.42 | 0.34 | 0.24 | 0.13 | 1.21 | 0.09 | 0.20 | 0.42 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.11 | 0.25 | 0.25 | 0.00 | 0.13 | 0.00 | 0.08 | 0.00 | 0.07 | 0.00 | 0.18 | 0.00 |
| ClO | 0.11 | 0.19 | 0.19 | 0.47 | 0.55 | 0.27 | 0.25 | 0.00 | 0.26 | 0.21 | 0.30 | 0.00 |
| $SO_3$ | 0.54 | 0.18 | 0.77 | 3.93 | 2.76 | 0.69 | 0.72 | 0.70 | 0.60 | 0.77 | 0.71 | 0.12 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

*samples: 1) Blue Bed 2, glass-derived authigenic clay from middle ash of Sentinel Butte bentonite/ash, 2) Blue Bed 3, glass-derived authigenic clay from upper Sentinel Butte bentonite, 3) Blue Bed 1, glass-derived authigenic clay from lower Sentinel Butte bentonite, 4) Mann-6, detrital montmorillonite, 5) LX-K, montmorillonite of unknown origin, 6) EG-1, authigenic precipitated pore-lining montmorillonite, 7) Slump Block 1, montmorillonite of unknown origin, 8) SU-B, authigenic precipitated pore-lining montmorillonite, 9) 7-10, detrital montmorillonite, 10) Long X-C, montmorillonite of unknown origin, 11) AC-4, detrital montmorillonite, 12) Square Butte A, authigenic precipitated pore-lining montmorillonite, 13) BR-A, authigenic precipitated pore-lining montmorillonite, 14) Marmarth, glass-derived authigenic montmorillonite from Marmarth ash, 15) LX-17, detrital montmorillonite, 16) AC-1, detrital montmorillonite, 17) MB-6, detrital montmorillonite, 18) EG-13, glass-derived authigenic montmorillonite from upper Sentinel Butte bentonite, 19) EG-11, glass-derived authigenic montmorillonite from lower Sentinel Butte bentonite, 20) LX-E, montmorillonite of unknown origin, 21) EG-12, glass-derived authigenic montmorillonite from Sentinel Butte ash, 22) BB-9, glass-derived authigenic montmorillonite from lower Sentinel Butte bentonite, 23) BB-3, glass-derived authigenic montmorillonite from upper Sentinel Butte bentonite, 24) BB-2, glass-derived authigenic montmorillonite from Sentinel Butte ash.

# APPENDIX J

# DISCRIMINANT SCORES FROM CLAY SAMPLE GROUPS

Table 23. Discriminant Scores from Samples Plotted in Figure 29.

| Sample | DTRL VS G.D. | DTRL VS PRCPT | DTRL VS UNKNWN | G.D. VS PRCPT | G.D. VS UNKNWN | PRCPT VS UNKNWN |
|---|---|---|---|---|---|---|
| SQB-A (P) | | -6.92 | | -14.12 | | 16.66 |
| BR-A (P) | | -8.27 | | -5.34 | | 12.10 |
| MARM (GD) | -22.92 | | | 17.08 | 16.87 | |
| LX-17 (D) | 18.60 | 4.96 | 9.15 | | | |
| AC-1 (D) | 20.85 | 4.68 | 9.85 | | | |
| MB-6 (D) | 18.21 | 9.83 | 4.43 | | | |
| EG-13 (GD) | -9.66 | | | 2.59 | 11.53 | |
| EG-11 (GD) | -9.31 | | | 1.55 | 7.74 | |
| LX-E (U) | | | -11.02 | | -23.77 | -26.29 |
| EG-12 (GD) | -12.34 | | | 6.67 | 12.78 | |
| BB-9 (GD) | -16.01 | | | 9.63 | 10.84 | |
| BB-3 (GD) | -14.92 | | | 9.56 | 10.17 | |
| BB-2 (GD) | -19.94 | | | 12.16 | 15.33 | |
| BENT-2 (GD) | -25.46 | | | 16.57 | 17.82 | |
| BENT-3 (GD) | -19.17 | | | 10.79 | 15.82 | |
| BENT-1 (GD) | -19.15 | | | 12.50 | 13.55 | |
| MANN-6 (D) | 8.24 | 2.44 | -1.17 | | | |
| LX-K (U) | | | -4.76 | | -16.15 | -18.23 |
| EG-1 (P) | | -5.80 | | -12.71 | | 16.66 |
| SBK-10 (U) | | | -7.66 | | -14.15 | -12.57 |
| SU-B (P) | | -7.42 | | -8.73 | | 13.30 |
| 7= 10(D) | 11.97 | 7.11 | 7.76 | | | |
| LX-"C" (U) | | | -1.53 | | 1.87 | 0.42 |
| AC-4 (D) | 24.84 | 12.97 | 9.74 | | | |
| (element) | (% contr.) | | | | | |
| SIO2 | 61 | 2 | 46 | 82 | 15 | 13 |
| AL2O3 | -1 | 13 | 31 | -19 | -15 | 2 |
| FEO | 12 | 1 | -1 | 13 | 5 | -2 |
| MGO | 14 | -1 | -2 | 30 | 25 | -1 |
| CAo | -1 | -3 | 12 | 0 | 4 | 2 |
| NA2O | -3 | 0 | -4 | -8 | 1 | -3 |
| K2O | 19 | 89 | 16 | 1 | 66 | 88 |

abbreviations: DTRL = Detrital, PRCPT = Precipitate, UNKNWN = Unknown, G.D. = Glass-Derived, P =Precipitate, D = Detrital, GD = Glass-Derived U = Unknown

Table 24. Discriminant Scores of "Potential Bentonite" Clays Plotted in Figure 30.

| Sample | DTRL VS G.D. | UNKNWN VS G.D. |
|---|---|---|
| BB-17 | -4.83 | 6.83 |
| BB-5 | -12.99 | 6.21 |
| 7= 15 | 15.33 | -25.70 |
| LX-A | 17.12 | -23.78 |
| BADLANDS 3 | 21.34 | -8.15 |
| SHB-6 | 6.48 | -2.64 |
| KINLEY B | 18.06 | -25.88 |
| SB-C | 24.40 | -26.47 |
| LX-11 | 11.73 | -14.15 |
| LX-J | 6.04 | -12.31 |
| SHB-1 | -5.90 | 3.02 |
| BB-7 | 5.15 | -1.91 |

abbreviations: DTRL = detrital, UNKWN = unknown, G.D. = glass-derived

# APPENDIX K

# PROXIMATE/ULTIMATE DATA FROM LIGNITIC SAMPLES

Table 25. Proximate/Ultimate Analyses of Sentinel Butte Lignitic Samples

| | C | H | N | S | ASH | $H_2O$ | VM | BTU | O | H/C | O/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample: LB-2 | | | | | | | | | | | |
| As Determined: | 38.64 | 4.02 | 0.63 | 0.63 | 21.6 | 19.1 | 30.3 | 6027 | 15.38 | | |
| Dry: | 47.76 | 2.33 | 0.78 | 0.78 | 26.7 | | | | 21.65 | | |
| Moisture and Ash-Free: | 65.16 | 3.17 | 1.06 | 1.06 | | | | | 29.54 | 0.54 | 0.34 |
| Sample: MB-7 | | | | | | | | | | | |
| As Determined: | 23.15 | 4.51 | 0.60 | 2.47 | 27.1 | 33.6 | 30.5 | 3263 | 8.57 | | |
| Dry: | 34.86 | 1.13 | 0.90 | 3.72 | 40.8 | | | | 18.58 | | |
| Moisture and Ash-Free | 58.91 | 1.91 | 1.53 | 6.28 | | | | | 31.37 | 0.39 | 0.40 |
| Sample: SBK-3 | | | | | | | | | | | |
| As Determined: | 39.19 | 3.39 | 0.91 | 0.93 | 20.1 | 15.4 | 37.8 | 5915 | 20.08 | | |
| Dry: | 46.32 | 1.97 | 1.08 | 1.10 | 23.8 | | | | 25.73 | | |
| Moisture and Ash-Free: | 60.76 | 2.58 | 1.41 | 1.44 | | | | | 33.80 | 0.51 | 0.42 |
| Sample: KP-7 | | | | | | | | | | | |
| As Determined: | 15.65 | 1.34 | 0.26 | 0.80 | 68.0 | 4.5 | 19.0 | 2417 | 9.45 | | |
| Dry: | 16.39 | 0.88 | 0.27 | 0.84 | 71.2 | | | | 10.42 | | |
| Moisture and Ash-Free: | 56.91 | 3.04 | 0.95 | 2.91 | | | | | 36.19 | 0.64 | 0.48 |
| Sample: Mann-2 | | | | | | | | | | | |
| As Determined: | 51.48 | 4.76 | 0.77 | 1.26 | 7.3 | 16.5 | 36.6 | 8573 | 17.93 | | |
| Dry: | 61.65 | 3.49 | 0.92 | 1.51 | 8.7 | | | | 23.73 | | |
| Moisture and Ash-Free: | 67.56 | 3.82 | 1.01 | 1.65 | | | | | 25.95 | 0.67 | 0.29 |

TABLE 25 --continued

| | C | H | N | S | ASH | $H_2O$ | VM | BTU | O | H/C | O/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample: <u>SB-9</u> | | | | | | | | | | | |
| As Determined: | 30.38 | 3.06 | 0.65 | 0.60 | 43.1 | 9.4 | 31.8 | 4702 | 12.81 | | |
| Dry: | 33.53 | 2.22 | 0.72 | 0.66 | 47.6 | | | | 15.27 | | |
| Moisture and Ash-Free: | 63.96 | 4.23 | 1.37 | 1.26 | | | | | 29.18 | 0.79 | 0.34 |
| Sample: <u>SB-16</u> | | | | | | | | | | | |
| As Determined: | 7.35 | 1.24 | 0.26 | 0.54 | 78.3 | 5.2 | 13.3 | 0590 | 7.11 | | |
| Dry: | 7.75 | 0.69 | 0.27 | 0.57 | 82.6 | | | | 8.12 | | |
| Moisture and Ash-Free: | 44.55 | 3.99 | 1.58 | 3.27 | | | | | 46.62 | 1.07 | 0.79 |
| Sample: <u>LX-21</u> | | | | | | | | | | | |
| As Determined: | 34.51 | 5.75 | 0.49 | 1.10 | 13.1 | 34.9 | 30.3 | 5495 | 10.24 | | |
| Dry: | 53.01 | 2.83 | 0.75 | 1.55 | 20.1 | | | | 21.76 | | |
| Moisture and Ash-Free: | 66.37 | 3.55 | 0.94 | 1.94 | | | | | 27.20 | 0.64 | 0.31 |
| Sample: <u>SB-19</u> | | | | | | | | | | | |
| As Determined: | 27.53 | 4.30 | 0.70 | 4.06 | 26.5 | 26.7 | 38.2 | 5518 | 10.21 | | |
| Dry: | 37.56 | 1.79 | 0.95 | 5.54 | 36.1 | | | | 18.06 | | |
| Moisture and Ash-Free: | 58.82 | 2.80 | 1.50 | 8.68 | | | | | 28.20 | 0.57 | 0.36 |
| Sample: <u>EG-3</u> | | | | | | | | | | | |
| As Determined: | 44.85 | 3.47 | 0.84 | 1.24 | 17.5 | 11.3 | 38.5 | 6909 | 20.80 | | |
| Dry: | 50.56 | 2.49 | 0.95 | 1.40 | 19.7 | | | | 24.90 | | |
| Moisture and Ash-Free: | 62.99 | 3.10 | 1.18 | 1.74 | | | | | 30.99 | 0.59 | 0.37 |
| Sample: <u>AC-B</u> | | | | | | | | | | | |
| As Determined: | 42.77 | 5.98 | 0.91 | 0.32 | 2.6 | 33.4 | 31.9 | 6947 | 14.02 | | |
| Dry: | 64.22 | 3.37 | 1.37 | 0.48 | 3.9 | | | | 26.66 | | |
| Moisture and Ash-Free: | 66.83 | 3.50 | 1.42 | 0.50 | | | | | 27.75 | 0.62 | 0.31 |

TABLE 25 --continued

| | C | H | N | S | ASH | $H_2O$ | VM | BTU | O | H/C | O/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample: <u>7= C</u> | | | | | | | | | | | |
| As Determined: | 51.24 | 4.32 | 1.10 | 0.80 | 1.1 | 11.8 | 43.4 | 8236 | 29.64 | | |
| Dry: | 58.10 | 3.40 | 1.25 | 0.91 | 1.2 | | | | 35.14 | | |
| Moisture and Ash-Free: | 58.83 | 3.44 | 1.26 | 0.92 | | | | | 35.55 | 0.70 | 0.45 |
| Sample: <u>AC-8</u> | | | | | | | | | | | |
| As Determined: | 39.42 | 4.20 | 0.92 | 0.88 | 15.0 | 21.9 | 34.3 | 6105 | 17.68 | | |
| Dry: | 50.47 | 2.24 | 1.18 | 1.13 | 19.2 | | | | 25.78 | | |
| Moisture and Ash-Free: | 62.47 | 2.77 | 1.46 | 1.39 | | | | | 31.90 | 0.53 | 0.38 |
| Sample: <u>LX-F</u> | | | | | | | | | | | |
| As Determined: | 48.78 | 4.16 | 0.79 | 1.53 | 9.6 | 15.9 | 39.9 | 7596 | 19.24 | | |
| Dry: | 58.00 | 2.83 | 0.94 | 1.82 | 11.4 | | | | 25.01 | | |
| Moisture and Ash-Free: | 65.48 | 3.20 | 1.06 | 2.05 | | | | | 28.21 | 0.58 | 0.32 |
| Sample: <u>EG-8</u> | | | | | | | | | | | |
| As Determined: | 51.49 | 3.63 | 0.77 | 1.08 | 10.4 | 11.7 | 39.7 | 8074 | 20.93 | | |
| Dry: | 58.31 | 2.63 | 0.87 | 1.22 | 11.8 | | | | 25.17 | | |
| Moisture and Ash-Free: | 66.10 | 2.98 | 0.99 | 1.39 | | | | | 28.55 | 0.54 | 0.32 |
| Sample: <u>AC-2</u> | | | | | | | | | | | |
| As Determined: | 44.40 | 4.48 | 1.04 | 1.64 | 12.6 | 17.5 | 38.4 | 7099 | 18.34 | | |
| Dry: | 53.82 | 3.06 | 1.26 | 1.99 | 14.4 | | | | 25.47 | | |
| Moisture and Ash-Free: | 63.52 | 3.61 | 1.49 | 2.35 | | | | | 29.04 | 0.68 | 0.34 |
| Sample: <u>7= B</u> | | | | | | | | | | | |
| As Determined: | 52.46 | 4.47 | 0.86 | 0.98 | 5.9 | 16.6 | 37.4 | 8297 | 18.73 | | |
| Dry: | 62.90 | 3.13 | 1.03 | 1.18 | 7.1 | | | | 24.66 | | |
| Moisture and Ash-Free: | 67.69 | 3.37 | 1.11 | 1.26 | | | | | 26.56 | 0.59 | 0.29 |

TABLE 25 --continued

| | C | H | N | S | ASH | $H_2O$ | VM | BTU | O | H/C | O/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample: <u>LX-B</u> | | | | | | | | | | | |
| As Determined: | 50.37 | 4.41 | 0.70 | 0.81 | 4.5 | 18.8 | 38.0 | 7796 | 20.41 | | |
| Dry: | 62.03 | 2.84 | 0.86 | 1.00 | 5.5 | | | | 27.80 | | |
| Moisture and Ash-Free: | 65.67 | 3.04 | 0.91 | 1.06 | | | | | 29.35 | 0.55 | 0.34 |
| Sample: <u>SBK-9</u> | | | | | | | | | | | |
| As Determined | 51.75 | 4.28 | 1.00 | 0.58 | 4.4 | 15.1 | 40.2 | 8093 | 22.89 | | |
| Dry: | 60.95 | 3.05 | 1.18 | 0.68 | 5.2 | | | | 28.90 | | |
| Moisture and Ash-Free: | 64.29 | 3.22 | 1.24 | 0.72 | | | | | 30.53 | 0.60 | 0.36 |
| Sample: <u>EG-16</u> | | | | | | | | | | | |
| As Determined: | 5.26 | 0.93 | 0.18 | 0.32 | 84.3 | 4.7 | 10.5 | 0338 | 4.31 | | |
| Dry: | 5.52 | 0.42 | 0.19 | 0.34 | 88.5 | | | | 5.03 | | |
| Moisture and Ash-Free: | 47.82 | 3.67 | 1.64 | 2.91 | | | | | 43.96 | 0.92 | 0.69 |

# APPENDIX L

## CORRELATION COEFFICIENTS AND SUMMARY STATISTICS FOR LIGNITIC SAMPLES

Table 26. Correlation Coefficients Between Proximate and Ultimate Variables Determined for Sentinel Butte Lignitic Samples

(moisture-and-ash-free basis)

| | Rank | Color | C | H | N | S | O | H/C |
|---|---|---|---|---|---|---|---|---|
| Color | .437 | | | | | | | |
| C | .731 | .331 | | | | | | |
| H | .065 | .256 | -.096 | | | | | |
| N | -.329 | -.068 | -.609 | -.019 | | | | |
| S | -.580 | -.167 | -.410 | -.402 | .414 | | | |
| O | -.600 | -.302 | -.952 | -.159 | .500 | .124 | | |
| H/C | -.481 | .141 | ----- | ----- | .347 | -.068 | .693 | |
| O/C | -.672 | -.302 | ----- | .202 | .527 | .213 | ----- | ----- |

Summary Statistics

| Variable | N | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|---|
| Rank | 20 | 7.80 | 3.29 | 1.00 | 11.00 |
| Color | 18 | 1.63 | 0.32 | 1.30 | 2.20 |
| Carbon | 20 | 61.73 | 6.21 | 44.55 | 67.69 |
| H | 20 | 3.25 | 0.52 | 1.91 | 4.23 |
| N | 20 | 1.25 | 0.24 | 0.91 | 1.64 |
| S | 20 | 2.24 | 1.98 | 0.50 | 8.68 |
| O | 20 | 31.52 | 5.46 | 25.95 | 46.62 |
| H/C | 20 | 0.64 | 0.15 | 0.39 | 1.07 |
| O/C | 20 | 0.39 | 0.13 | 0.29 | 0.79 |

(as-determined basis)

| | Rank | Color | C | H | N | S | ASH | $H_2O$ | VM | BTU | O | H/C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Color | .437 | | | | | | | | | | | |
| C | .767 | .426 | | | | | | | | | | |
| H | .538 | .366 | .709 | | | | | | | | | |
| N | .712 | .278 | .849 | .671 | | | | | | | | |
| S | -.246 | -.155 | -.033 | .248 | .096 | | | | | | | |
| ASH | -.713 | -.426 | -.937 | -.892 | -.861 | -.144 | | | | | | |
| $H_2O$ | .166 | .074 | .221 | .824 | .270 | .416 | -.533 | | | | | |
| VM | .686 | .260 | .904 | .713 | .895 | .307 | -.916 | .317 | | | | |
| BTU | .732 | .464 | .990 | .740 | .851 | .062 | -.944 | .262 | .923 | | | |
| O | .687 | .253 | .880 | .422 | .847 | -.144 | -.765 | -.086 | .895 | .852 | | |
| H/C | -.484 | .142 | ----- | ----- | -.493 | -.389 | .699 | -.569 | -.646 | -.546 | -.376 | |
| O/C | -.672 | -.302 | ----- | -.808 | -.634 | -.242 | .839 | -.533 | -.789 | -.817 | ----- | ----- |

Summary Statistics

| Variable | N | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|---|
| Rank | 20 | 7.80 | 3.29 | 1.00 | 11.00 |
| Color | 18 | 1.63 | 0.32 | 1.30 | 2.20 |
| C | 20 | 37.53 | 14.92 | 5.26 | 52.46 |
| H | 20 | 3.83 | 1.34 | 0.93 | 5.98 |
| N | 20 | 0.72 | 0.26 | 0.18 | 1.10 |
| S | 20 | 1.13 | 0.85 | 0.32 | 4.06 |
| ASH | 20 | 23.65 | 25.17 | 1.10 | 84.30 |
| $H_2O$ | 20 | 17.20 | 9.15 | 4.50 | 34.90 |
| VM | 20 | 33.00 | 8.99 | 10.50 | 43.40 |
| BTU | 20 | 5899.50 | 2491.32 | 338.00 | 8573.00 |
| O | 20 | 15.94 | 6.25 | 4.31 | 29.64 |
| H/C | 20 | 0.64 | 0.15 | 0.39 | 1.07 |
| O/C | 20 | 0.39 | 0.13 | 0.29 | 0.79 |

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