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The Sedimentology and Stratigraphy of the Sentinel Butte Formation Around Beicegel Creek, McKenzie County, North Dakota

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THE SEDIMENTOLOGY AND STRATIGRAPHY OF THE SENTINEL BUTTE FORMATION AROUND BEICEGEL CREEK, MCKENZIE COUNTY, NORTH DAKOTA

by

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This thesis, submitted by Joseph L. Stone in partial fulfillment of the requirements for the Degree of Master of Arts from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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ABSTRACT

Approximately 580 ft of the Sentinel Butte Formation (Paleocene) is exposed within this study area. A stratigraphic and sedimentologic study of these exposures was done in order to gather new information about the formation, to interpret paleodepositional environments, and to possibly develop an overall depositional model.

Stratigraphic analysis identified four major sand units within the study area, separated by intervals of mudstone and lignite. The lowermost sandstone unit is identified as the Basal Sandstone (Royse 1967). All of the sandstone units exhibit sedimentary structures that suggest a fluvial source for their deposition. They tend to be laterally consistent and when mapped show a meandering trend. This along with the existence of floodplain and back swamp deposits in close proximity to these sands leads to the hypothesis that this interval of Sentinel Butte sediments were deposited by a meandering fluvial system.

Sedimentologic analysis of the Basal Sandstone determined that it should be classified as a medium-grain (Wentworth) litharenite (Folk, 1980). The analysis of the upper sand showed that this unit should be classified as a fine-grained (Wentworth) litharenite to sublitharenite. The basal sand textural analysis produced mean grain size of 2.18ϕ, while the upper sand showed a mean grain size of 3.05ϕ. Compositionally the basal sand had high percentages of volcanic and sedimentary rock fragments, while the upper sand lacked a significant volcanic fragment component and was composed mostly of quartz and sedimentary rock fragments.

CHAPTER 1

PURPOSE OF STUDY

This project had three main goals. The first goal was to establish the stratigraphic framework of the Sentinel Butte Formation (Paleocene) in the exposures of the Beicegel and Bummer Creek drainages. The Sentinel Butte Formation has never been studied in detail within this area. The second goal was to interpret this in terms of depositional environments for these sediments identified during field studies. The third goal was to construct a depositional model for the Sentinel Butte Formation in this area.

Most study of the Sentinel Butte Formation has focused on the exposures found in and around the North Unit of Theodore Roosevelt National Park. For this study, I have chosen a new area in order to provide additional information on the Sentinel Butte Formation (Fig. 1).

The Beicegel and Bummer Creek drainages are located in south- central McKenzie County, North Dakota (T. 145 & 146 N., R. 100 & 101 W.) (Fig. 2). Specifically, this area encompasses the north side of the Beicegel Creek drainage, along Beicegel Creek road, and most of the Bummer Creek drainage. The study area is located in the heart of the Little Missouri River National Grasslands and, except for a few cattle ranches, is very sparsely populated. However, access to the area is excellent, given the existence of numerous oil field roads. The western boundary of the study area is the Little Missouri River and it extends east-southeast paralleling Beicegel Creek Road.

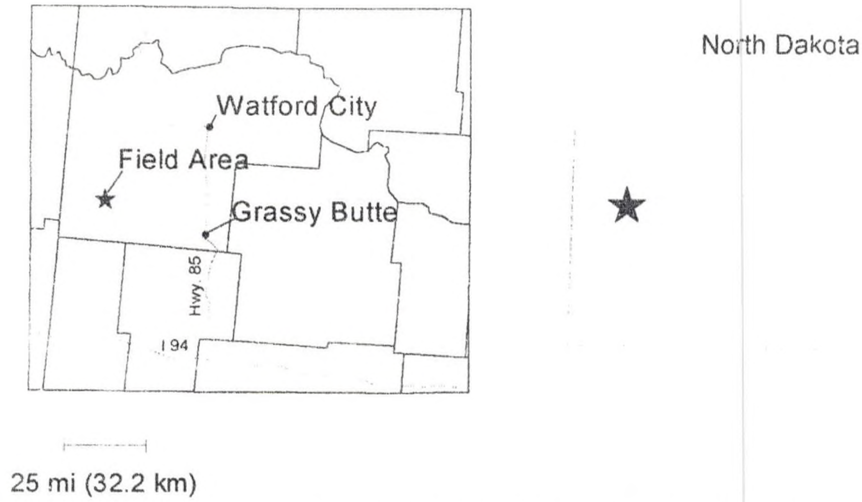


Figure 1. Index Map of the Study Area

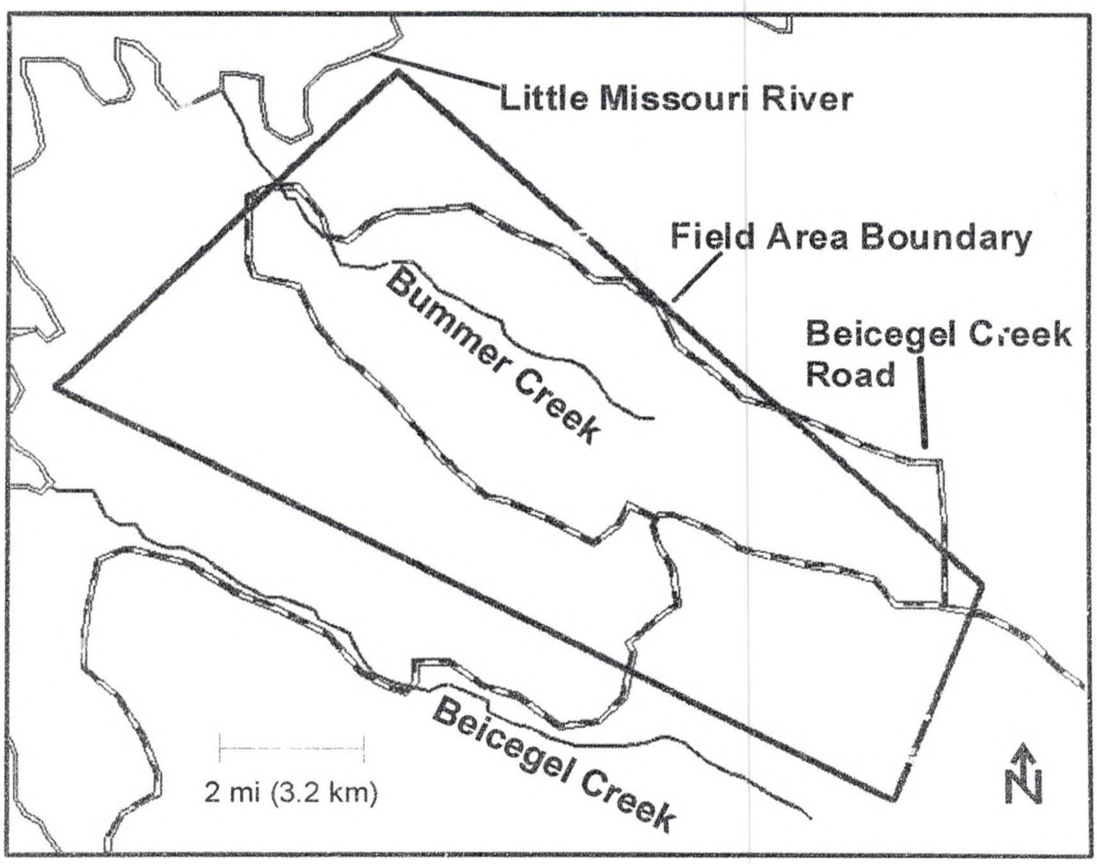


Figure 2. Field Area

The exposures in this field area were excellent, with the upper section of the Bullion Creek Formation and over three-quarters of the Sentinel Butte Formation available for study. In total, the study area covers approximately 36 mi^2.

CHAPTER 2

PREVIOUS WORK

The stratigraphic nomenclature of the Upper Cretaceous and Paleogene sediments of the northern plains have been intensively debated for several decades. Formational contacts have been arranged and rearranged several times and a detailed outline of the succession of these arrangements is beyond the scope of this thesis. Below is an abbreviated discussion of the history relevant to this study. For further information, the reader is referred to the numerous publications listed under References.

Early Work

Meek and Hayden (1862) first formalized the surficial sediments of the Williston Basin in the northern plains. They named strata exposed along the Missouri River the Fort Union Group for exposures near Fort Union. Later, Leonard (1908) divided the Fort Union Group into three informal members, the lower, middle, and upper. Thom and Dobbin (1924) defined the upper member on the basis of its somber color and referred to it as the Sentinel Butte Shale Member of the Fort Union Formation. They also included the Tongue River member (Bullion Creek Formation for this usage) in the Fort Union Formation. The underlying Cannonball and Ludlow Formations were grouped together into the Lance Formation, which also included the Cretaceous Hell Creek Formation. In the late 1960s and early 1970s Royse, (1967, 1970) conducted the first, stratigraphic and sedimentological study of the Sentinel Butte interval. He concluded that the Sentinel Butte Member was distinct and extensive enough to elevate it to formational status. He proposed that the Fort Union interval should be referred to as a Group made up of the Ludlow, Cannonball, Bullion Creek and Sentinel Butte Formations. In the 1970s the Slope Formation was recognized as a lithic unit between the Cannonball and Bullion Creek Formation. (Fig. 3) This nomenclature was proposed by Clayton (1977) and is still in use by the North Dakota Geological Survey today. It should be noted that differing opinions still exist regarding this succession and that Montana and others do not recognize the Bullion Creek or Slope Formations. Carlson (1983) points out that the Bullion Creek Formation in North Dakota is the stratigraphic equivalent to the Tongue River Formation in the Powder River Basin and therefore should also be referred to in North Dakota as the Tongue River Formation. Hartman (1999) provides new information regarding the chronostratigrapy of the Fort Union Group. He sees the use of the Slope Formation as unwarranted and doesn't consider it a valid formation within the Fort Union Group. However, for this study, the stratigraphic nomenclature currently used by the North Dakota Geological Survey will be used.

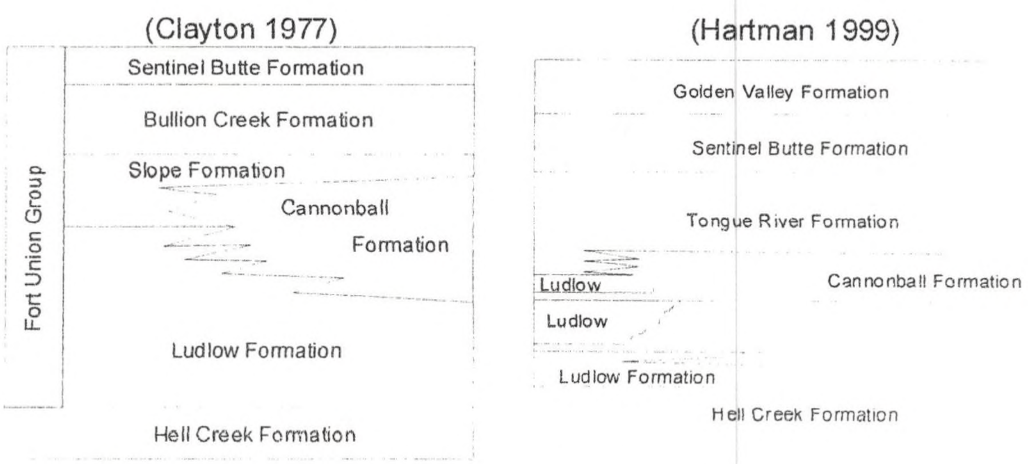


Figure 3. Generalized Geologic Columns of the Fort Union Group in North Dakota.

Stratigraphic Studies

Through his research, Royse (1967) was able to produce the first comprehensive stratigraphic column detailing the stratigraphy of the Sentinel Butte Formation. By identifying several distinct lithologic units, Royse has made possible the accurate correlation of lithic units from one outcrop to another. In ascending order, these distinct lithologic units are the Basal Sandstone, a blue bed, a lower yellow bed, an upper yellow bed, and an Upper Sandstone (Royse, 1967). Perhaps the most noted interval within the Sentinel Butte Formation is the "blue bed" or the Sentinel Butte Bentonite/Ash layer extensively studied by Forsman (1985). The bed is known to occur over large areas in and around the North Unit of Theodore Roosevelt National Park. Forsman identified three distinct layers within the Sentinel Butte Bentonite: (1) a lower 1-4 m thick bentonite; (2) a middle, 0.5 to 0.5 m thick gray silt; and (3) an upper, 0.5 to1.5 m thick bentonite. The middle silt layer is described as being finely laminated and was determined to be volcanic tuff (Forsman, 1985). Thirty feet (9.1 m) above this bentonite lies the lower yellow bed of the Sentinel Butte Formation. Like the "Sentinel Butte Bentonite" this lower yellow bed is described as laterally extensive encompassing the area around the North Unit of Theodore Roosevelt National Park. The upper yellow bed of the Sentinel Butte Formation identified by Royse is approximately 430 ft (131 m) above the floodplain in the North Unit of Theodore Roosevelt National Park. However, the lateral extent of this bed has not been determined because much of the upper portion of the Sentinel Butte Formation has been removed by erosion. Because of this erosion, exposures of the Upper Sandstone unit of the Sentinel Butte Formation are scarce. Where observed, this sandstone is described as medium-grained, cross-bedded, moderately well sorted, and usually oxidized (Royse, 1970). Again, the precise stratigraphic position of this Upper Sandstone is difficult to determine. In most cases, it is the uppermost exposed layer of the Sentinel Butte Formation and can be observed in close stratigraphic proximity to the overlying sediments of the Golden Valley Formation (Royse, 1967).

Depositional Environment Studies

Once the stratigraphic nomenclature of these sediments was generally agreed upon, interest shifted from the general stratigraphy of the units to questions dealing with detailed sedimentology and depositional environments. Throughout these studies several different hypothesis have been presented concerning a model for deposition. Currently, there are three schools of thought. Jacob (1976) developed a marine-deltaic model of deposition for both the Bullion Creek and Sentinel Butte Formations. He interpreted this interval as representing a large prograding delta, advancing toward a regressing Cannonball Sea. The Bullion Creek was interpreted as a lower delta plain deposit and the Sentinel Butte was considered to be an upper delta plain deposit. Jacob (1976, p. 33) believed that the laterally extensive lignite deposits of the Bullion Creek, along with "trough shaped, nonbraided, low sinuosity stream deposits" are characteristic of sediments within a lower delta plain environment. He then compared the Bullion Creek Formation deposits with the nonlaterally extensive lignites and the abundant elongate, "high-sinuosity" stream deposits of the Sentinel Butte Formation. Jacob (1976 p. 33) considered the deposits to be the product of upper delta plain deposition.

The second depositional model proposed is called the "tectonic fluvial" model by Winczewski (1982) and Winczewski and Groenewold (1982). This study relied on subsurface geophysical data gathered from 225 well sites in western North Dakota. The authors constructed numerous cross sections that resulted in the recognition of repeating intervals of detrital deposition capped by extensive lignites. These intervals formed the basis for a tectonic-fluvial model. This model postulates that deposition of the Bullion Creek and Sentinel Butte Formations resulted from the diversion eastward of a northward-flowing fluvial system that originated in the Powder River Basin of Wyoming. The diversion of this system is believed to have been initiated by subsidence of the Williston Basin. The diversion was eventually cut off by sediment accumulation and, therefore, was rediverted back to the north, ending one sequence (Winczewski and Groenewold, 1982).

These two models both present opposing ideas on the dominant factor controlling the deposition of the Sentinel Butte Formation. Jacob's delta plain model suggests that accumulation of the Sentinel Butte Formation was ultimately controlled by the propagation eastward of a delta plain. This suggests that the Cannonball Sea was somewhere present in the upper mid-west during Sentinel Butte time. The tectonic fluvial model suggests that accumulation of Sentinel Butte Formation sediments were controlled by the rhythmic subsidence of the Williston Basin, diverting a northward flowing fluvial system east through western North Dakota, producing a series of depositional cycles.

Daly (1985) provided a third interpretation for Bullion Creek-Sentinel Butte sediment deposition. He rejected both the deltaic and tectonic fluvial models. Daly questioned Jacob's interpretation simply because Jacob drew his conclusions based on data from a very small area. Daly indicated that an application of this model basin-wide is unwarranted and more stratigraphic information from else where in the basin is needed to substantiate it. Daly rejects Winczewski's tectonic fluvial model because of a lack of evidence of a northward flowing fluvial system in eastern Montana. Instead he proposed that these units were deposited by low-gradient steams that flowed eastward across a broad alluvial plain.

There has been little detailed stratigraphic and sedimentologic work done with the surficial deposits within the area of the current study. Wallick (1984) conducted a study similar to the current one along the western side of the Little Missouri River in southern McKenzie County. Wallick compared the sedimentology of the Bullion Creek Formation with that of the overlying Sentinel Butte Formation. With these data, he was able to provide a comparison of the depositional environments for both formations and found subtle differences in their sedimentology. His comparisons were based on mineralogical and textural data, with the Bullion Creek exhibiting a higher percentage of reworked clastic carbonate grains and the Sentinel Butte showing higher percentages of volcanic and sedimentary rock fragments and plagioclase. On the basis of this difference, Wallick (1984) concluded that the Bullion Creek Formation represented basin-derived reworked sediment, while the Sentinel Butte Formation represented fresh detrital material derived from a renewed source outside the basin.

Previous Work in the Grassy Butte Area

Meldahl (1956) completed a Master's thesis on the general geology of the Grassy Butte area. Meldahl's project area encompassed the current study area, as well as extending farther south and west. The purpose of his study was to provide general geologic data for the area and to identify possible lignite resources. Meldahl did not provide any interpretation of depositional environments or models.

CHAPTER 3

METHODS

Fieldwork for this project was completed during the summer of 2001. Approximately five trips were made to the field area totaling 30 days of fieldwork. Eighteen stratigraphic sections were measured using a Brunton compass and a Jacob's staff (Fig. 4). The sections were chosen based on their accessibility and the quality of exposure.

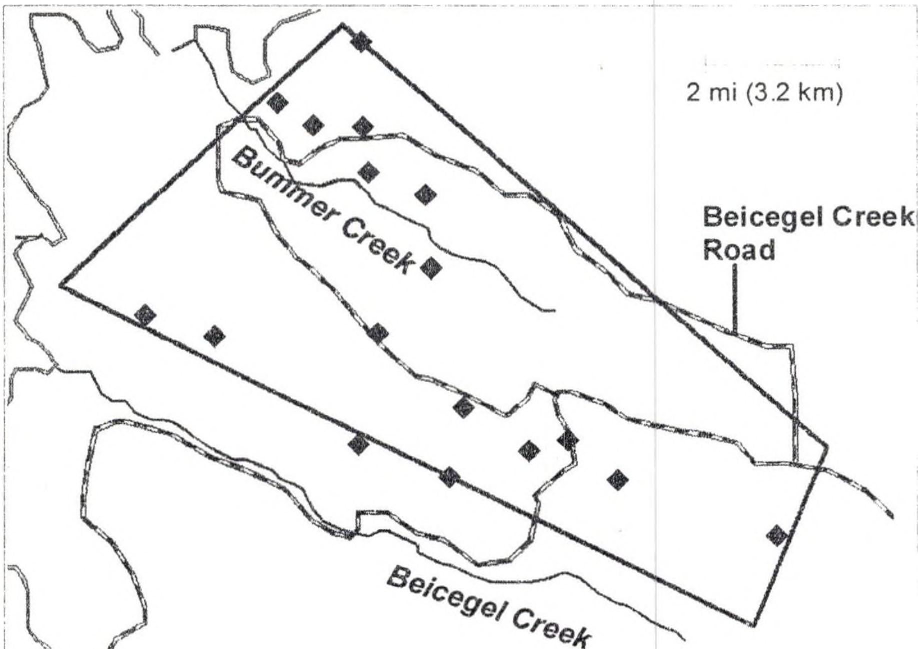


Figure 4. Locations of Measured Sections on the Watford City 1:250000 Series Quadrangle.

Most sections were begun at or near the bottom of the valley and continued up to the tops of the surrounding buttes. A Magellan GPS 315 receiver was used to assist in the accurate location of these sections. Detailed notes were taken describing the lithologic characteristics of the rock, the transition from one lithology to another, any sedimentary structures present, and the thickness of each successive unit. A graphical representation of this data is provided and discussed in detail in the following sections of this thesis.

Samples were taken of two distinct sandstone bodies found within the study area. Six samples were taken of the Basal Sandstone, two from the base, two from the middle, and two from the upper portions. Two samples were taken also from an Upper Sandstone found approximately 48 ft (15 m) above the lower yellow bed. There was also an unusual lithology found in association with this Upper Sandstone, a sedimentary breccia. It was also sampled. This lithology has not been previously reported from the Sentinel Butte Formation.

All of these samples were made into thin sections or used to prepare grain mounts, which were point counted using a petrographic microscope. On the basis of this point count data, the mineralogical composition of each unit was documented and rock classifications determined. The results of such analysis provide a means by which variations in the composition of the Sentinel Butte Sandstone could be determined.

The stratigraphic and sedimentologic data gathered were used to determine the specific depositional environments for each individual unit and to provide a depositional model for the formation within the study area.

All maps within this thesis were created using ArcView™ version 3.2. Cross sections were created using Surfer™ version 7. Graphical editing was done in Corel Draw™ and/or Corel Photo Paint™ version 8. The base map for all maps within this thesis was taken from the USGS Watford City 1:250000 series quadrangle.

CHAPTER 4

STRATIGRAPHY OF THE SENTINEL BUTTE FORMATION

Royse (1970) reported that the Sentinel Butte Formation is approximately 380 to 620 ft (115.8 m to 188.9 m) thick. Within the current study area, a thickness of approximately 580 ft (177 m) of the Sentinel Butte Formation is exposed. In the bottoms of the drainages, several feet of the underlying Bullion Creek Formation is present. On the uppermost buttes in the western sections of the study area, both the lower and in one case the upper yellow beds are exposed (Fig. 5).

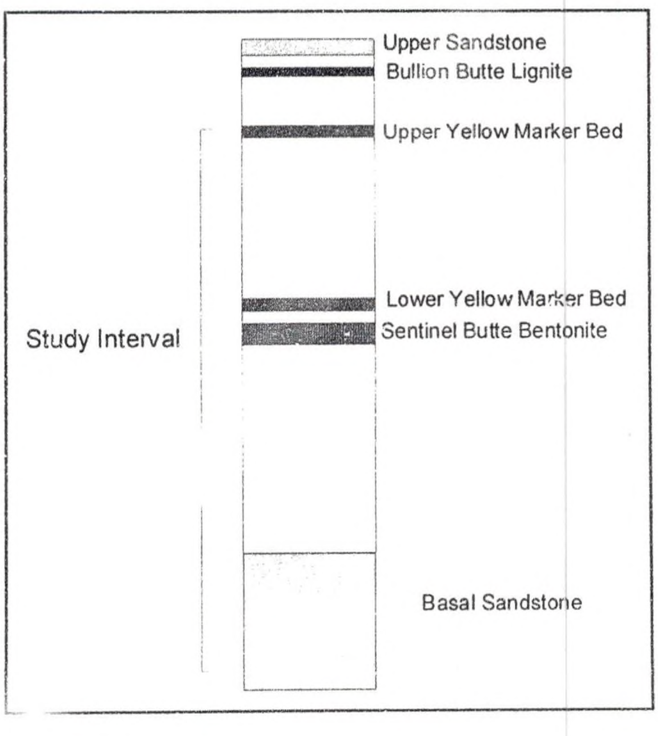


Figure 5. Generalized Stratigraphic Column for the Sentinel Butte Formation (after Royse1970.)

Sentinel Butte-Bullion Creek Contact

The contact between the Sentinel Butte Formation (Ts) and underlying Bullion Creek (Tb) Formation is most easily identified by a marked change in color (Royse, 1970). The Bullion Creek sediments are bright yellow, which is a distinct contrast to the gray sediments of the Sentinel Butte Formation. However, in some areas this color change is less obvious. In the study area, the most consistent means for identifying Tb/Ts contact is the recognition of the Sentinel Butte Basal Sandstone (Fig. 6).

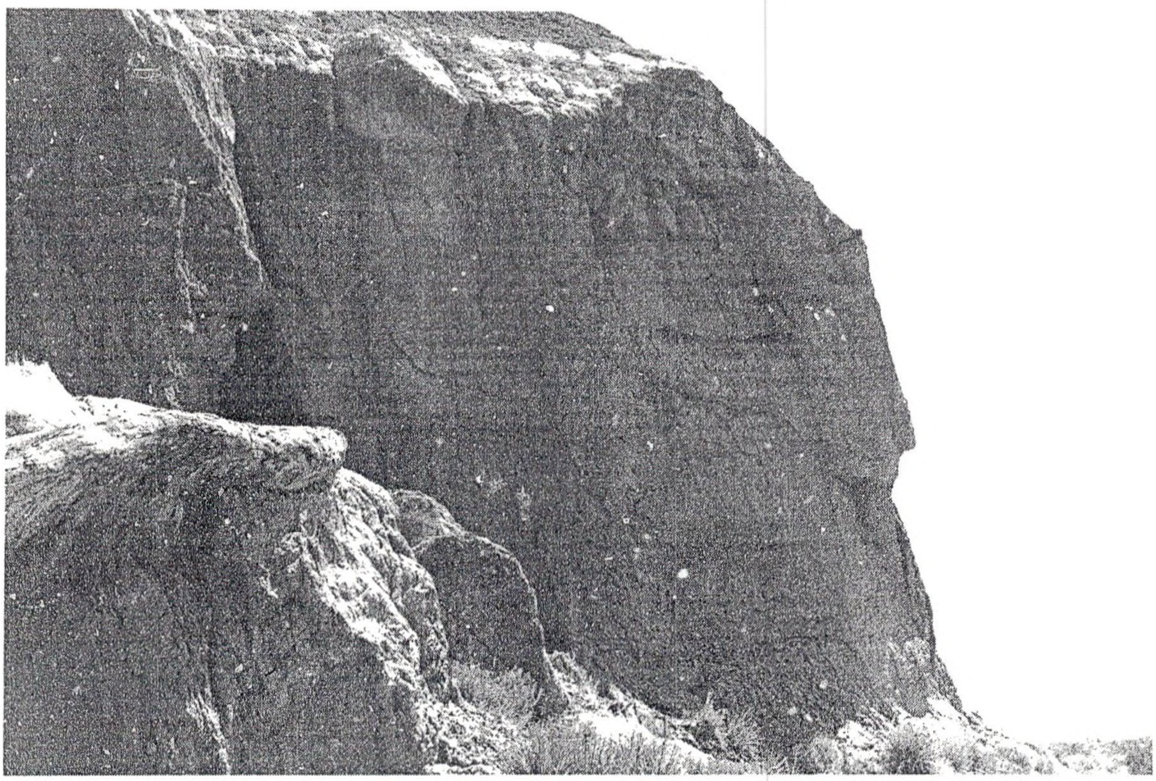


Figure 6. Exposure of the Basal Sandstone of the Sentinel Butte Formation. The outcrop is approximately 24 ft (7.3 m) in height.

Basal Sandstone

In most cases within this study area, the Basal Sandstone of the Sentinel Butte Formation is the first unit immediately overlying the Bullion Creek Formation (Fig. 6). The Basal Sandstone is a light gray (N 7) (Munsell rock color chart) medium to fine- grained sandstone. In outcrop, it forms very steep rilled slopes, which makes access to these exposures extremely difficult. A complete section of the Basal Sandstone was measured as 86 ft thick and as thin as 10 ft (Figs. 9 and 10). In general, thick sections of the sandstone occur in the western portions of the study area. The unit becomes progressively less exposed to the south and east until it is completely covered. An inferred isopach map of the Sentinel Butte Basal Sandstone is given in Figure 7.

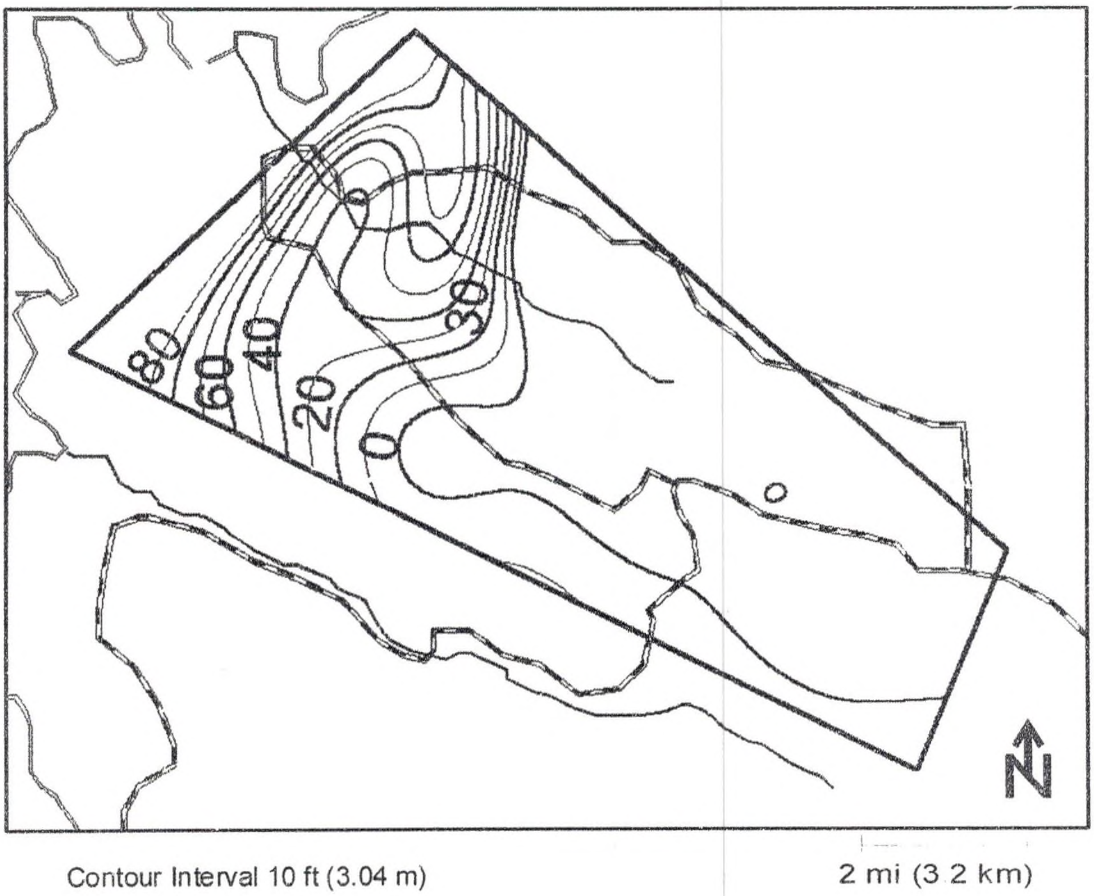


Figure 7. Inferred Isopach Map of the Basal Sandstone of the Sentinel Butte Formation.

Cross-sectional views of the relationships of the units within the field area are given in Figures 9 through 11. Cross section locations are shown on Figures 9 through 11. Figure

8 gives the lithologic symbols for these sections. These figures will be continually referred to throughout the remainder of this section.

Figure 8. Cross Section Lithologic Symbols.

Mudrock and Lignite

The Basal Sandstone of the Sentinel Butte Formation is overlain by an interval of interbedded silt and clay rich sediments, and lignite. For simplification all sediments of silt to clay size shall be referred to as mudrock. The lignite beds are generally thin (< 5 ft) and tend to be laterally continuous. As is evident in the cross sections, in some cases a particular lignite unit could be correlated for several miles. In other cases lignite beds pinch out rather quickly. The lignite beds are frequently covered, but in such cases could be traced by a line of vegetation growing along the slope within the lignite. The lignite was predominantly very woody with numerous root traces. Often these units are organic-rich shale rather than true lignite. In many cases, large, in growth position, petrified stumps are observed within lignite beds. These mudrock units were normally very thick and varied from siltstone to clayey siltstone. These intervals ranged in color from a light olive gray (5Y 6/1) to yellow gray (5Y 7/2). Bedding is typically very difficult to observe because the sediments are fine grained and extensively weathered. The only observable bedding features for these units were trace occurrences of planar laminations within the clay-rich layers.

Sandstone Unit 1

In Measured Sections 1, 6, 7 and 11 there is a small tabular sandstone bed overlying the first mudrock interval (Figs. 9, 10 and 11). Sandstone Unit 1 is approximately 110 ft (34 m) above the Basal Sandstone Sentinel Butte Sandstone. It ranges from about 15 ft (4.5 m) in Measured Section 11, to only 9 ft (2.7 m) in Section 1 (Figs. 9 and 10). It pinches out quickly from Measured Section 10 to 11 and from 11 to 13 (Fig .11). However, it is persistent from Section 11 north to Section 7 and then west through Sections 6 and 1 (Figs. 9 and 10). Sandstone Unit 1 has a definite linear trend northeast through the center of the study area up to approximately Measured Section 7 and then abruptly turns northwest. Sandstone Unit 1 is overlain by another interval of silt and clay that shares the same characteristics as that overlying the Basal Sandstone.

Sandstone Unit 2

Approximately 311 ft (94.7 m) above the Basal Sandstone is a second sandstone unit. Sandstone Unit 2 occurs in Measured Section 8, but pinches out from 8 to 7 and from 8 to 16 (Fig. 9). However, this unit is traceable from Measured Section 8 to 9 (Fig. 10). It is possible that the same sandstone unit is also present in Sections 17 and 18 (Fig. 9), as it is approximately the same lithology and thickness as the sandstone observed in 8 and 9, and is in approximately the same stratigraphic position (Figs. 9 and 10). The river or stream that deposited this sandstone may have meandered south out of the study area and then turned back north reentering the area. Above Sandstone Unit 2 is another mudrock interval similar to those previously described. A sandstone percentage map for Sandstone Units 1 and 2 is given in Figure 12.

Lower Yellow Marker Bed

Approximately 366 ft (111.5 m) above the Basal Sandstone of the Sentinel Butte Formation is the Lower Yellow Marker bed (Figs. 9, 10 and 11). Besides the Basal Sandstone, this unit is the most laterally traceable unit within the study area. The Lower Yellow Marker Bed comprises the majority of the upper exposure of the Sentinel Butte Formation in this field area. Only in Sections 8 and 17 were units overlying the lower yellow bed observed (Fig. 9). The thickness of the Lower Yellow Marker Bed varied laterally (Fig. 9). In Measured Section 17, where a complete thickness of the bed was measured; it was approximately 24 ft (7.3 m) thick. An isopach map of the Lower Yellow Marker Bed is given in Figure 13.

Upper Yellow Marker Bed

In Section 17 (Fig. 11), the Upper Yellow Marker Bed was found to be 102 ft (31 m) above the Lower Yellow Marker Bed. This bed is 13 ft (3.9 m) thick in Measured Section 17.

Upper Sandstone

The fourth sandstone is approximately at the same stratigraphic horizon as the Upper Yellow Marker Bed and occurs at only one locality. This exposure will be referred to here as the Upper Sandstone. This unit should not be confused with the Upper Sentinel Butte Sandstone of Royse (1967, 1970), Peck (1992) or Forsman (1985), as this unit is well below that stratigraphic level. However, in this field area it is the highest occurrence of sand within the Sentinel Butte Formation.

The Upper Sandstone forms a very prominent outcrop and is one of the most impressive exposures in this area (Fig. 14). It is approximately 37 ft (11.2 m) thick and can be traced laterally for only about 200 ft (60.9 m). It is exposed in only one location within the study area (Fig. 15). As with the preceding sandstone units, a detailed description of the sedimentology of this unit will be discussed in the following section.

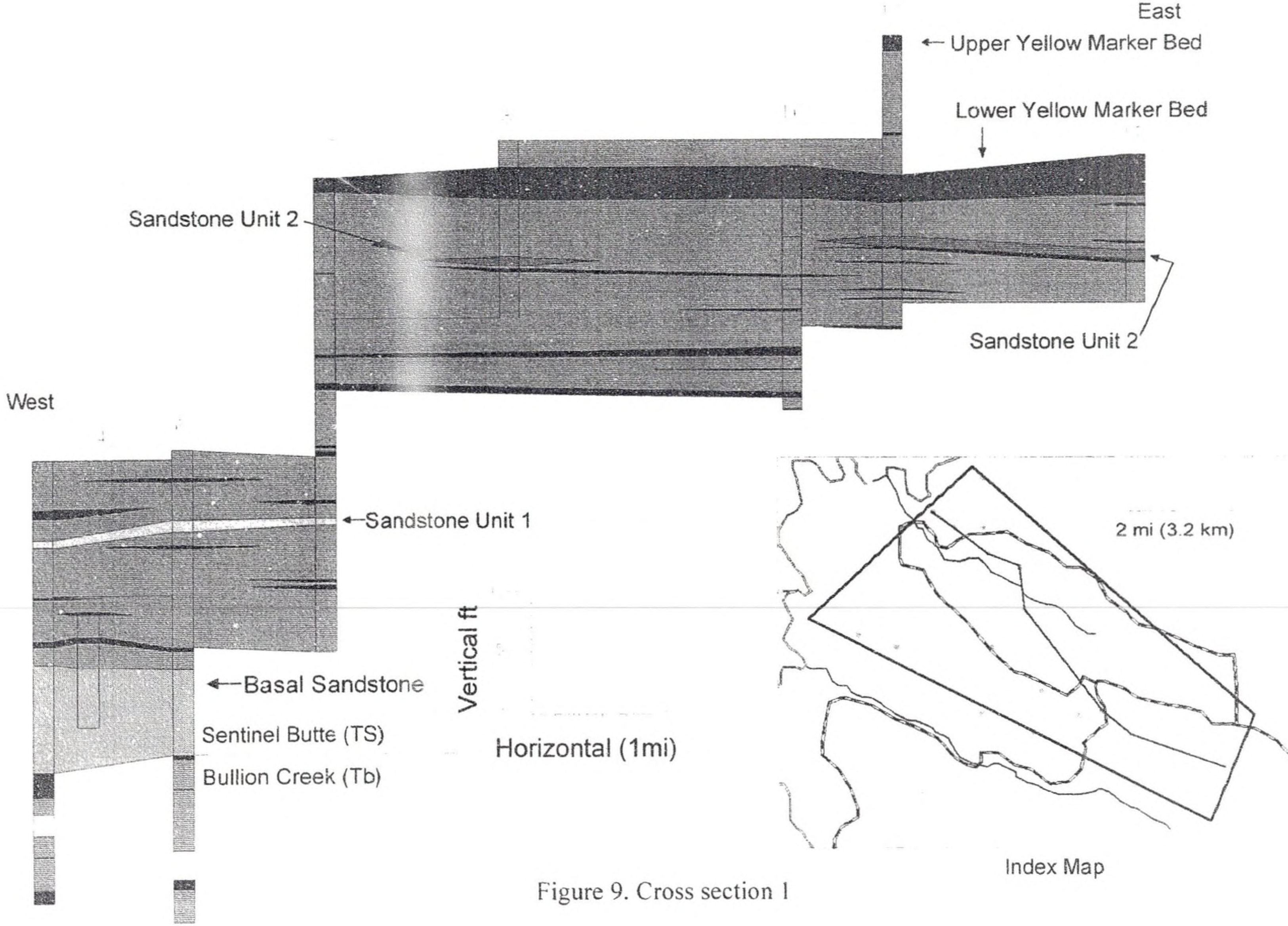


Figure 9. Cross section 1

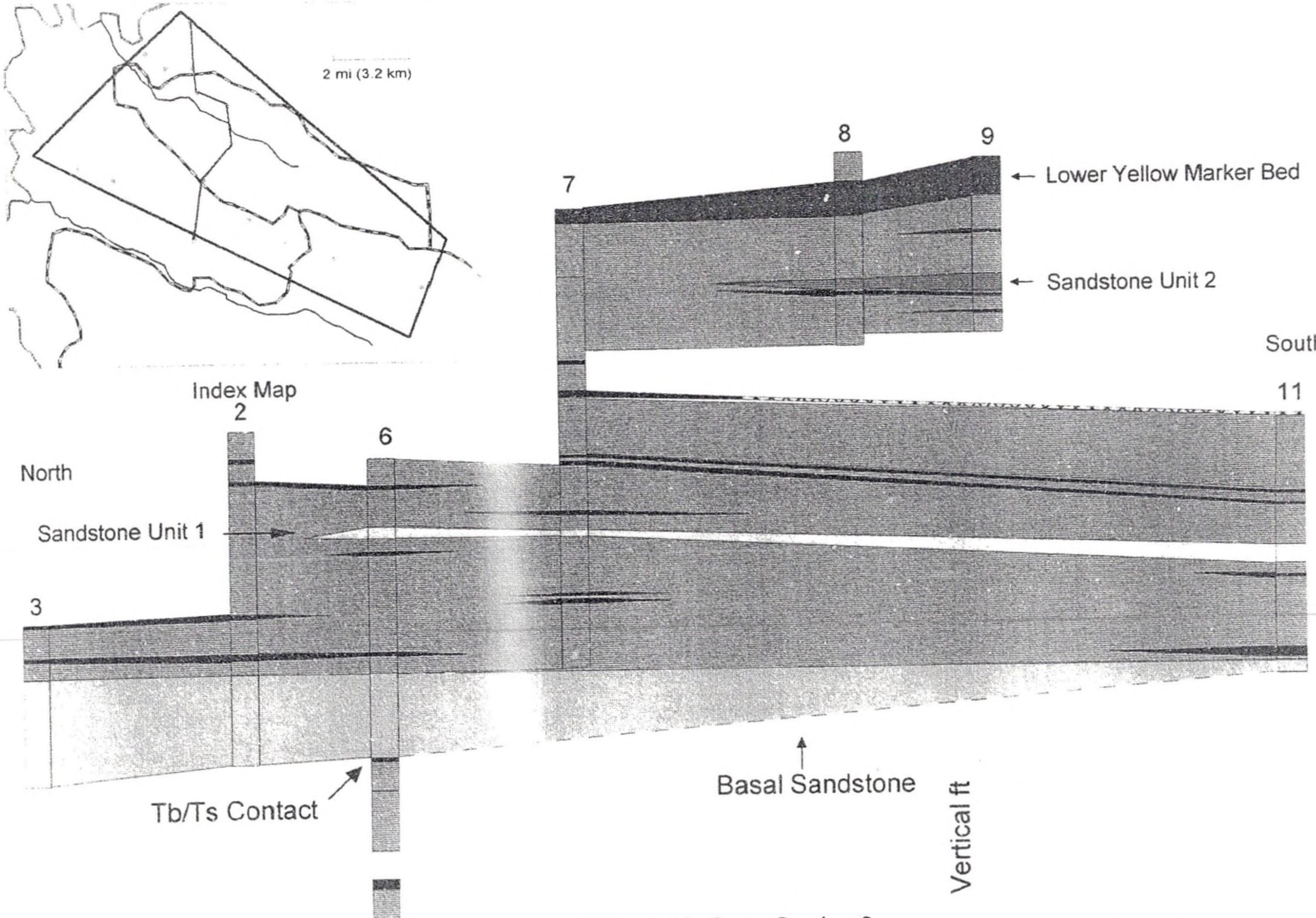


Figure 10. Cross Section 2

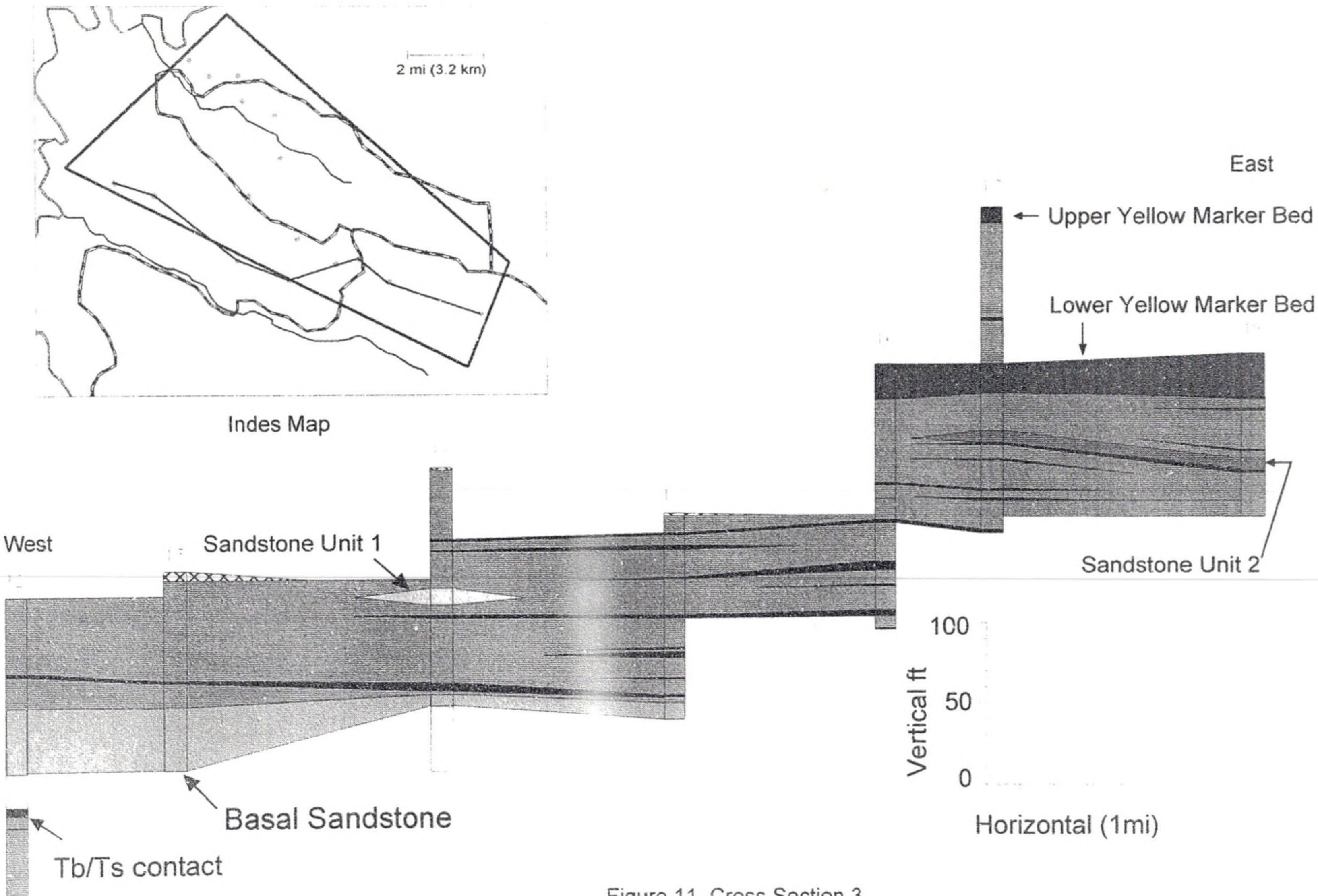


Figure 11. Cross Section 3

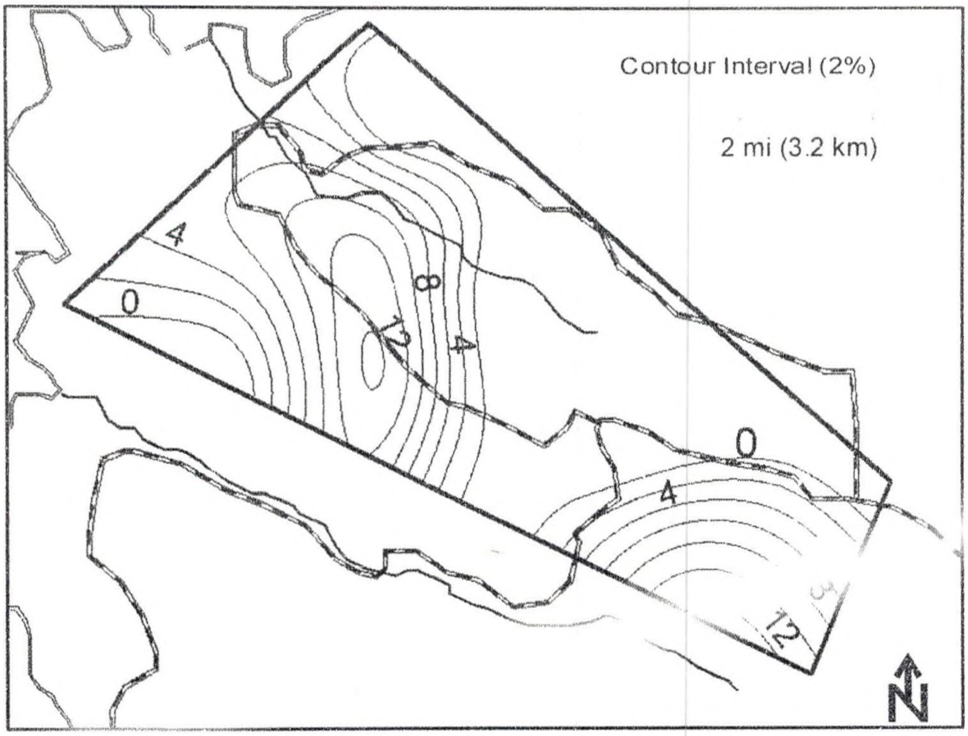


Figure 12. Inferred Sandstone Percentage Map of Sandstone Units 1 and 2.

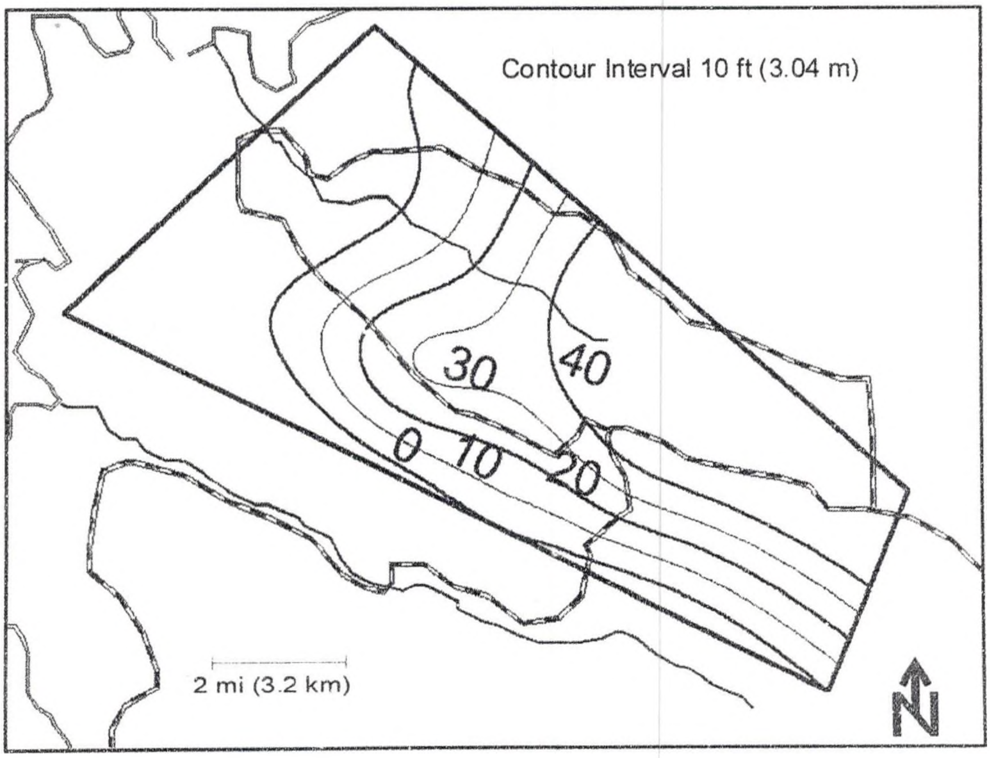


Figure 13. Inferred Isopach Map of the Lower Yellow Marker Bed.

Figure 14. The Upper Sandstone is 37 ft thick in Measured Section 15.

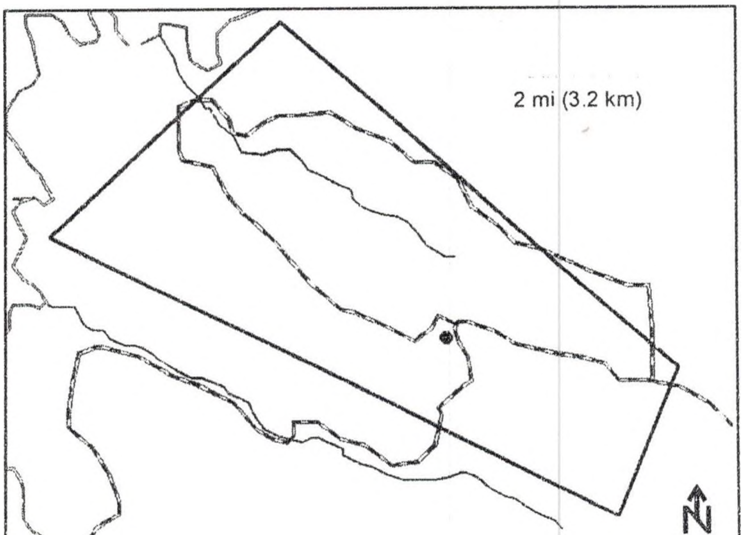


Figure 15. Location of the Upper Sandstone.

CHAPTER 5

SEDIMENTOLOGY OF THE SENTINEL BUTTE FORMATION

In the study area, five different lithotypes were identified within the Sentinel Butte Formation. The vast majority of outcrop was made up of sediments that ranged from clayey mudrock to silty mudrock. Such units will be classified as mudrock and only a brief field description of lithology will be given. Of primary interest to this project is the environmental interpretation of the sandstones. Detailed petrologic data was collected from sandstone units, throughout the study area. The single breccia occurrence was also petrographically analyzed.

Mudrock

Silt and clay-rich sediments made up the majority of exposure within this study area. In general they are very poorly lithified and heavily weathered. Numerous iron-rich zones are evident in outcrop. In some cases these layers simply form a rust-colored horizon within the unit with no apparent change in cementation. However, in other cases, these iron-rich zones form planar concretionary layers that are substantially better lithified than the surrounding sediments. The silt-rich mudrocks tend to be yellowish gray (5Y 7/2), while the clay-rich mudrocks are light olive gray (5Y 6/1). Bedding was very difficult to identify within these units, although in rare instances, planar laminations can be observed. Root traces and other organic material are common. Some layers within the mudrock contain scattered bivalve and gastropod shell fragments, but no complete fossil was found. Petrified fragments and in-place petrified stumps were common within these mudrocks (Fig. 16).

Figure 16. An in Place Petrified Stump within Measured Section14.

Limestone

Numerous limestone bodies occur within the mudrock intervals. These limestones are discontinuous and rarely persist laterally. They can be described as pods and tend to range from a foot to several feet in diameter. The limestone is usually better lithified than the surrounding silts and clays and therefore is a fairly prominent feature within an outcrop. These bodies are usually very fragmented and break with a conchoidal fracture. The limestone ranges from pale yellowish orange (10 YR 8/6) to dark yellowish orange (10 YR 6/6) (Fig. 17). One sample was taken for thin section examination.

Figure. 17 Limestone Pods within Measured Section 14.

In thin section it was evident that this limestone was composed of 100% micrite with no coarse grained calcite visible (Fig. 18).

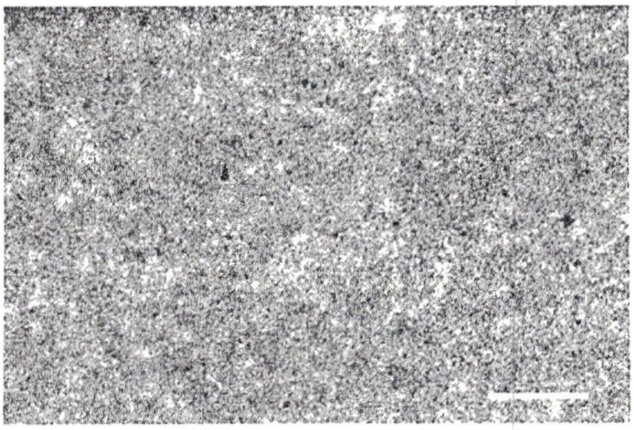


Fig 18. Thin Section Micrographs of a Limestone Sample Showing 100% Micrite. Bar Scale is 0.25 mm.

Lignite

A detailed petrologic analysis was not performed on lignite samples, so only a brief field description will be given. Lignite layers tend to be moderate brown (5 YR 3/4) to black (N1), with a dull pitch-like luster. In some cases, the lignite is very dense and compact, but in other cases is very fragile. Partially decayed woody fibers are commonly imbedded in the finely carbonized material.

Sandstone

Given the abundance of Basal Sandstone exposures, and the presence of an Upper Sandstone within the study area, a petrographic analysis was performed in order to identify possible differences in the mineralogical composition of these two units. Six samples were taken from the Basal Sandstone, two from the base, two from the middle, and two from the upper sections of the unit. Two samples were taken from the Upper Sandstone, one from the base and one from the top of the unit. Only one of these samples, the upper sample of the upper sand, was indurated enough to make into a thin section. The remaining samples were made into grain mounts. All of these were point counted in order to determine the relative percentages of the constituent detrital grains within the sample.

Basal Sandstone

The six grain mounts of the Basal Sandstone were point counted using 200 points per slide. The primary constituent grain types of the Basal Sandstone are quartz (40.4%), feldspar (11.2%), volcanic rock fragments (17.7%), sedimentary rock fragments (22.5%), and lignite (2.3%). Unknown grains (5.7%) were also counted in the total tally. The samples were taken from two localities, with one sample taken at the base of the unit, one in the center and one at the top. The results of this analysis are given in Figure 19. Data for each sample can be found in Appendix B.

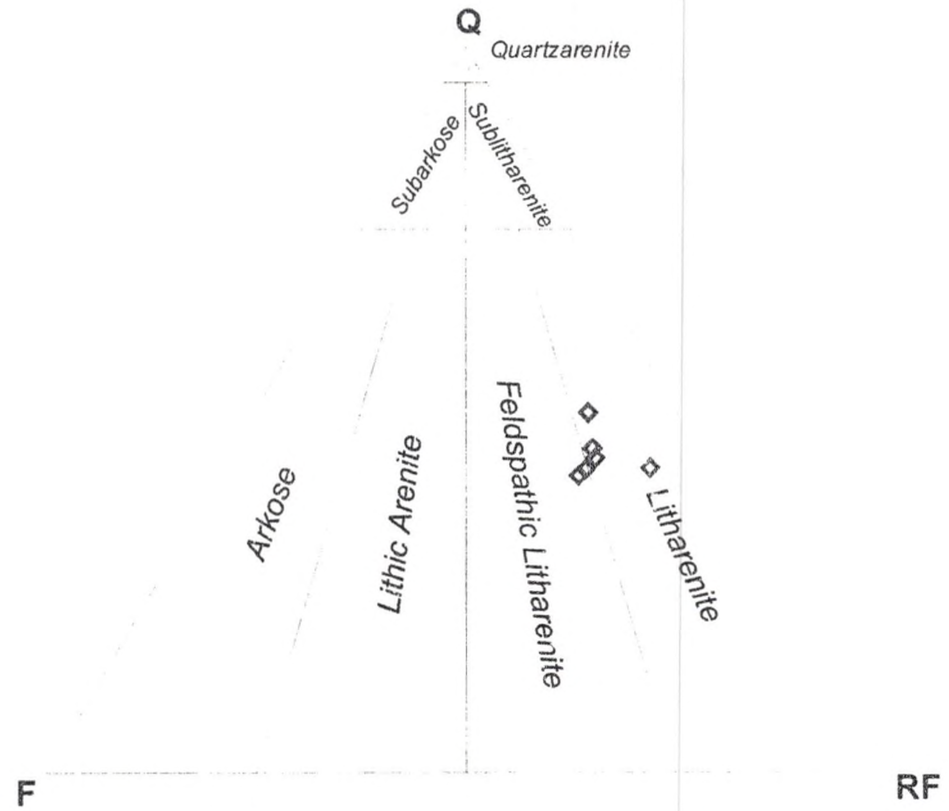
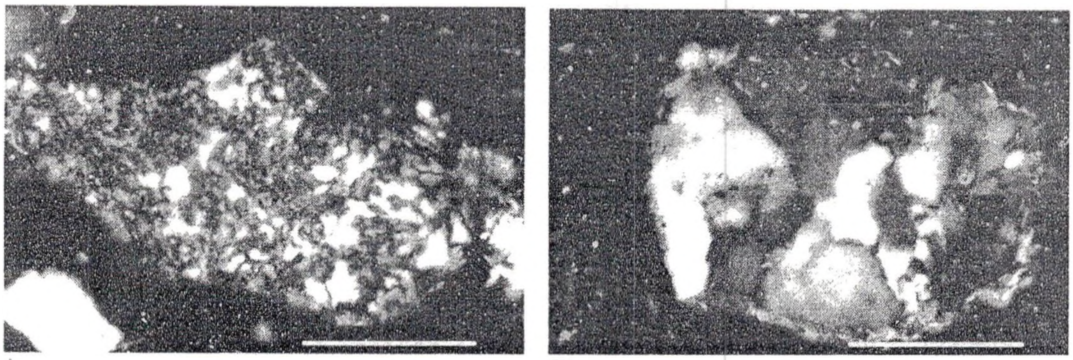


Figure 19. Ternary Plot of Basal Sandstone Samples, B1A, B1B, B1C, B2A, B2B, and B2C (classification based on Folk, 1980); F= feldspar, Q= quartz, RF= rock fragments.

This ternary plot of the Basal Sandstone samples shows that the Sentinel Butte Basal Sandstone can be classified within the compositional range of a feldspathic litharenite or litharenite. This result is in agreement with the analysis completed by Forsman (1985). As is apparent by the above plot, there is little variability of the relative percentages of constituent grains within the Basal Sandstone. However, subtle differences may be present that were not identifiable by this method of analysis, and therefore cannot be completely ruled out.

As stated above, the lithic fragments within the Basal Sandstone were predominantly sedimentary and volcanic grains (Figs. 20 and 21). The sedimentary grains consist primarily of detrital chert fragments (Fig. 20).



A B

Figure 20. Detrital Chert Fragments from the Sentinel Butte Basal Sandstone, A. A grain of More Uniformly Distributed Microcrystalline Quartz, B. A grain composed of a combination of microquartz and megaquartz (sample B2A). Bar scale = 0.1 mm.

Some carbonate grains were present but are believed to be remnant fragments of cement not to represent a significant component of the clastic makeup of the unit. This conclusion is drawn from the existence of pore-wall outlines in some of the carbonate fragments. These outlines provide good evidence for this interpretation. Volcanic grains were easily identified by the observation of numerous randomly oriented mineral laths imbedded in a very fine grained matrix (Fig. 24).

Feldspar fragments within the Basal Sandstone were most easily identified by the presence of polysynthetic twinning. Examples of these grains can be seen in Figure 22. Quartz, the most common mineral grain within the Basal Sandstone, was identified based on its low birefringence, lack of cleavage or twinning, and its low positive relief. An example of a typical Basal Sandstone quartz grain is given in Figure 23.

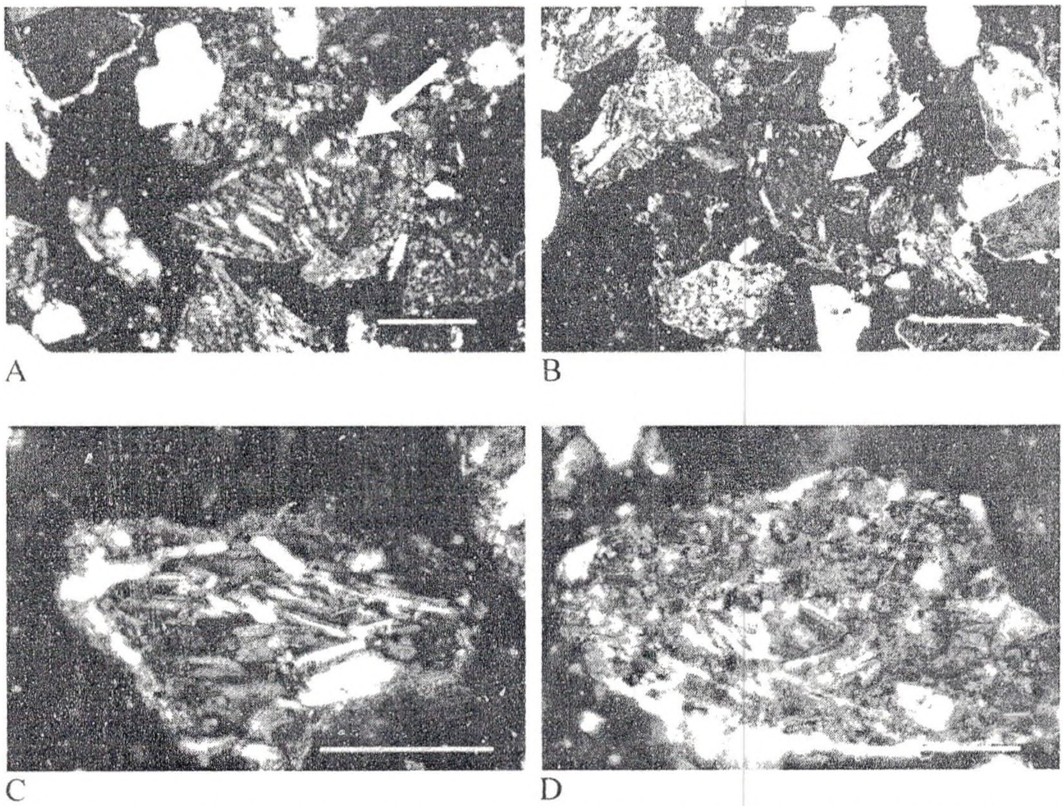
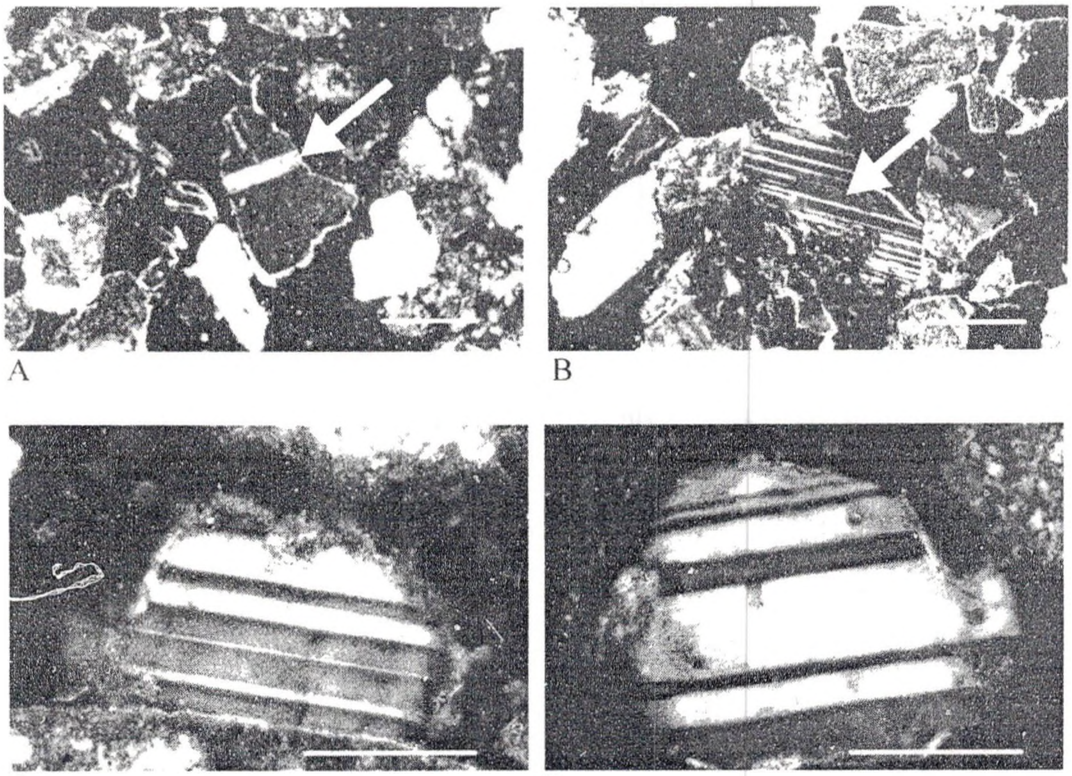


Figure 21. Sentinel Butte Basal Sandstone Volcanic Rock Fragments (arrows). Showing numerous feldspar laths randomly distributed within a microcrystalline matrix (samples B2A and B1C). Bar scales A and B = 0.25 mm bar scales C and D = 0.1 mm.

In order to determine the relative percentage of sand and clay within the Basal Sandstone, an 8.23 g sample of the sand was washed in order to remove the silt/clay fraction. The sample was placed in a 1000 ml beaker and water was added. This mixture was then stirred vigorously and then allowed to settle for several hours. The fine-grained silt and clay still left in suspension was then decanted. This process was repeated several times until no silt or clay could be seen in suspension. The remaining coarse-grained fraction of the sample was then weighed. Of the original 38.23 g sample, 33.02 g remained. Thus, approximately 86.3% of the Basal Sandstone is composed of sand-sized particles, while 13.6% is composed of silt or finer particles.



A B

C D

Figure 22. Micrographs of Feldspar Grains from the Basal Sandstone of the Sentinel Butte Formation, samples B1A and B2B. Note the existence of polysynthetic twinning. Images A, C and D are of plagioclase with characteristic albite twinning. Image B is microcline Bar scales A and B = 0.25 mm, bar scale C and D = 0 .1 mm.

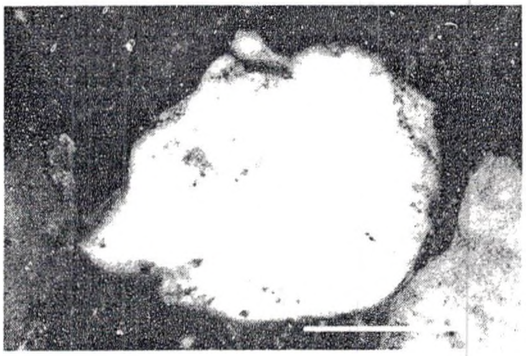


Figure 23. Detrital Quartz Grain from the Basal Sandstone of the Sentinel Butte Formation, Sample B2C. Bar scale = 0.1 mm.

A grain size analysis of the Basal Sandstone was also performed. A 31.5 g sample was sieved and the relative percentages of grain sizes were tabulated. The cumulative percentages of these grain sizes were then graphed and an average phi size for this sample was calculated. This analysis produced an 2.18ϕ average grain size for the Basal Sandstone, or between 0.25 mm to 0.21 mm. Therefore, the Basal Sandstone in this study area is classified as a medium/fine sand (Wentworth size class) (Folk, 1980). The data for this analysis is give in Appendix C.

Upper Sandstone

Two samples from the Upper Sandstone were also analyzed petrographically, using the same methods that were used in the analysis of the Basal Sandstone. One sample was taken from the base of the unit, and a second was taken from the top. Each sample was then point counted, with 400 points each and the results have been plotted in ternary diagrams.

The lower sample consists primarily of quartz (54%) and sedimentary rock fragments (32%). Other grains observed were feldspar (5.5%), volcanic rock fragments (1%), and lignite (1.5%). Unknown grains (5.7%) were also counted in the total tally. On the basis of this mineral composition this sample has been classified as a litharenite (Folk, 1980) (Fig. 24). The point count data for this sample is in Appendix B.

Numerous calcite fragments also occur within this unit. These fragments have been interpreted as being the remains of the original calcite cement that at one time lithified this unit. The calcite grains are angular and are normally broken along cleavage planes. Also portions of intact cement with imbedded detrital material were found preserved within portions of the grain mounts. An example of these calcite fragments is given in Figure 25.

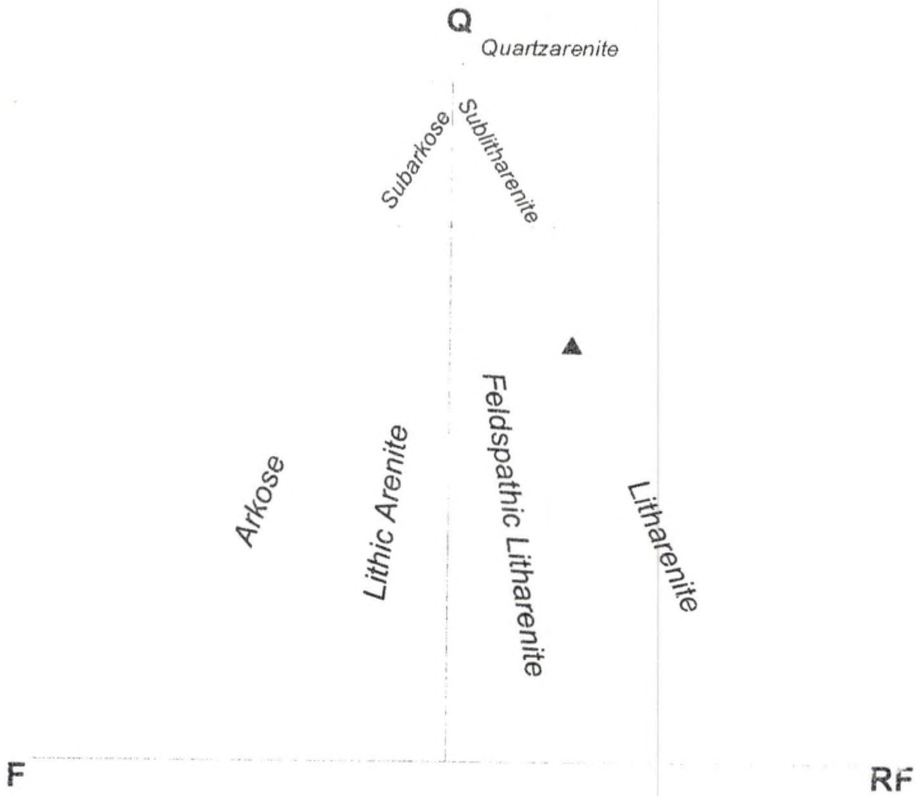


Figure 24. Ternary Plot of the Upper Sandstone Sample, S10.

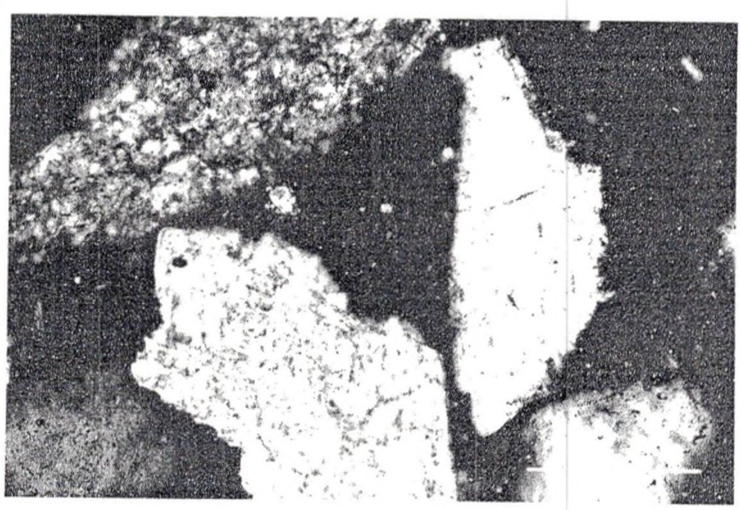


Figure 25. Remnant Calcite Cement Fragments from the Upper Sandstone. Note angular shape. Bar scale = 0.1 mm.

One unique feature of this sand unit is its capping portion. This portion was where the second sample of this unit was taken. This horizon is unlike any lithology observed in the field area. It is very resistant, and thus is a dominant feature of the outcrop. When broken, it breaks in planar sheets and could be referred to as a flagstone (Fig. 26). Petrographic analysis of this layer revealed that it is composed of crystalline calcite (69%), with a significant detrital component made up primarily of quartz grains (24%). The remaining grain types observed were feldspar (1.2%) and sedimentary rock

Fig. 26. Capping Layer of the Upper Sandstone at Measured Section 15.

fragments (3.75%). Unknown grains (2%) were also counted. The crystalline calcite present in this sample is cement and not considered a component of the clastic make-up of the unit. Therefore, this sample has been classified as a sublitharentie (Folk, 1980), (Figs.27 and 28).

The lower sample for the Upper Sandstone was also washed in order to determine the relative percentages of sand and mud within the unit. Methodology was the same as in the Basal Sandstone analysis. A 40.75g sample was used and upon removal of all mud 39.27 g of sand remained. Therefore, the relative percentages of sand and mud within the Upper Sandstone are 96.3% and 3.6%, respectively.

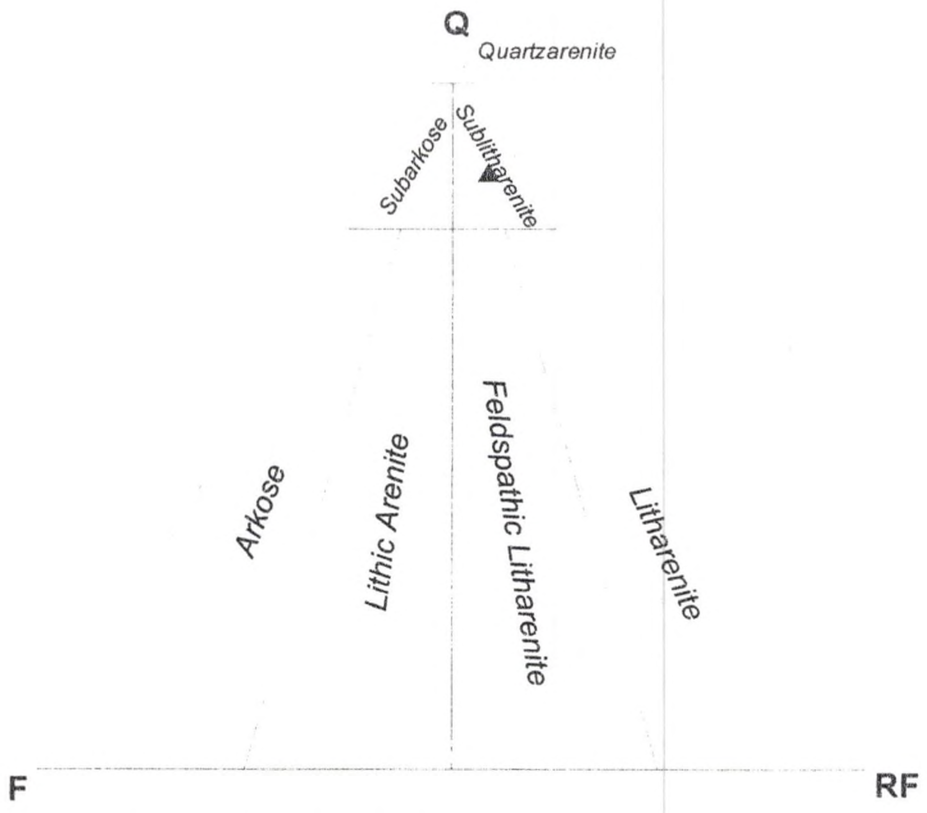


Figure 27. Ternary plot of the Upper Sandstone capping layer, sample S9

The same grain size analysis as used in the Basal Sandstone was also performed on a sample of the upper sand. A 20.0 g sample of this sand was sieved and the relative percentages of grain sizes were tabulated. The results revealed an 3.05ϕ average grain size for the Upper Sandstone, or between 0.125 mm and 0.105 mm. Thus, this sample is classified as a very fine sandstone (Wentworth size class) (Folk, 1980). Data for this analysis are given in Appendix B.

Breccia

Within the Upper Sandstone unit there was one localized occurrence of a breccia (Fig. 29). This sample is characterized by large angular clasts imbedded in a sandy

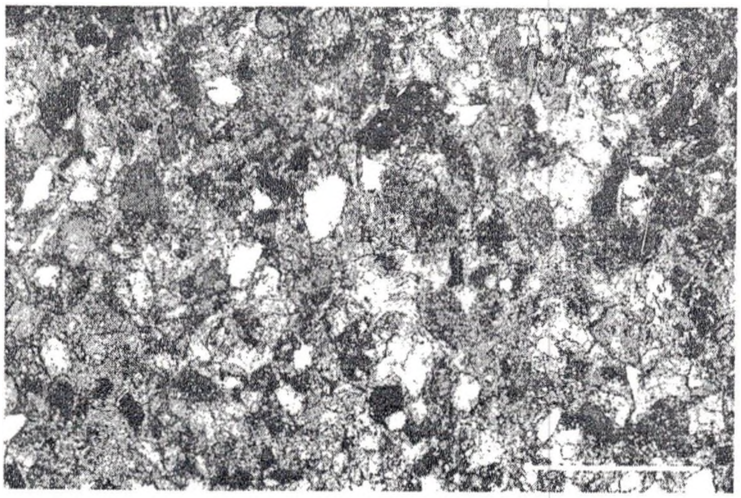
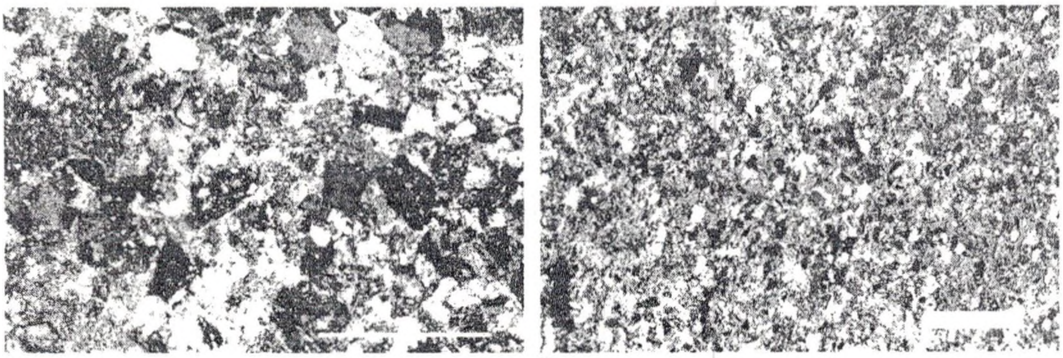


Figure 28. Thin Section Micrograph from the Upper Sandstone Capping Layer. Note the large amount of crystalline calcite cement. Bar scale = 0.1 mm.

Figure 29. In Situ Occurrence of Breccia in the Upper Sandstone at Measured Section 15.

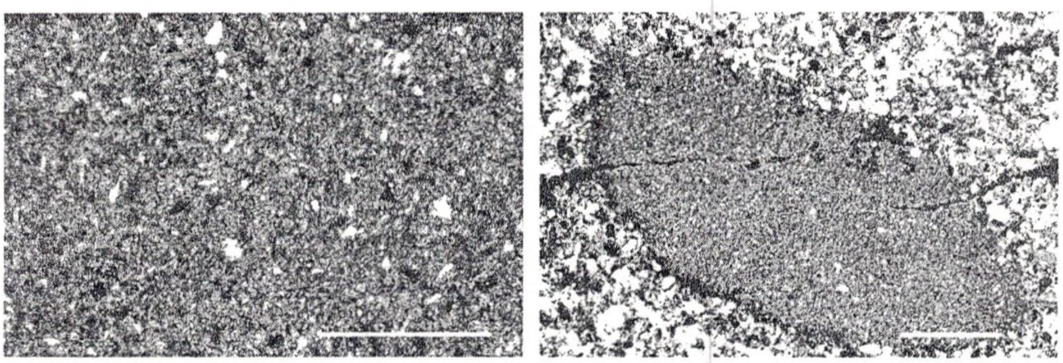
matrix. A thin section was made of this sample and a point count (200 points) analysis was performed for the sandy matrix. This analysis shows that this portion of the sample is composed of 22.4% quartz, 3.5% feldspar, 10% sedimentary rock fragments, and 63.5% calcite cement. Unknown grains (0.5%) were also counted in this analysis. Thin section images of this matrix are given in Figure 30.

The larger clasts within this sample ranged from 0.5 cm to 6.0 cm and were primarily composed of micrite and quartz grains (Fig. 31).



A B

Figure 30. Thin Section Micrographs of the Matrix Portion of the Breccia Sample Taken from the Upper Sand Unit. Bar scale A = 0.1 mm, bar scale B = 0.25 mm.



A B

Figure 31. Thin Section Micrographs of the Large Clasts Within Breccia Sample S8. Bar scale A = 0.1 mm long, bar scale B = 0.25 mm. Image B also shows a portion of the surrounding sandy matrix.

Summary

The primary goal of this sedimentologic analysis was to compare and to possibly identify differences between the Basal Sandstone and upper sands in this study area. The Basal Sandstone contained a relatively high percentage of lithic fragments. Of those lithic fragments a significant percentage was volcanic grains. Almost no volcanic grains were observed in the upper sand unit. In the lower sample of the Upper Sandstone, lithic fragments were identified, but were almost all of sedimentary origin. In the upper sample of the Upper Sandstone very few lithic fragments of any type were identified and the primary detrital component was quartz. The Basal Sandstone is more feldspathic (11.3%) than the Upper Sandstone (3.4%). There is also a marked increase in the amount of secondary carbonate from the Basal Sandstone to the Upper Sandstone. Only scattered occurrences of calcite grains occur in the Basal Sandstone, while in the Upper Sandstone calcite cement is a major component of both samples. These two units also differ in grain size. The Basal Sandstone has an average grain size of 2.18ϕ, while the Upper Sandstone has an average size of 3.05ϕ. Also, within the Upper Sandstone a localized breccia lithology is present.

CHAPTER 6

DISCUSSION

A primary goal of this research was the determination of an overall depositional model for the Sentinel Butte Formation in the study area. Several workers have proposed models for portions of the formation or for the formation as a whole, but no general agreement has been reached (Royse, 1967; Johnson, 1973; Jacob, 1976; Cherven, 1977; Winczewski and Groenewold, 1982; Daly et al, 1985; Cherven and Jacob, 1985; Wallick, 1984; Peck, 1992). The source of the debate certainly stems from the variability of the lithology of the Sentinel Butte Formation across the various areas studied. This factor combined with an overall lack of detailed stratigraphic and temporal data for the formation as a whole has made a broad interpretation very difficult.

The first step in developing a general depositional model for this study area is to identify the individual depositional environments present in the section.

Sandstone

Sandstone units within the Sentinel Butte Formation were described as being the result of fluvial deposition (Royse, 1969; Johnson, 1973; Cherven, 1977; Wallick, 1984; Peck, 1992). Evidence, such as bed morphology, sedimentary structures, and the relationship to surrounding lithotypes, has supported this hypothesis. Four major sandstone bodies have been identified within this study area. The Basal Sandstone, which is the most persistent lithic unit in the area exhibits characteristics of a fluvial origin. Evidence for this interpretation includes numerous examples of cross-bedded intervals. In the lower part of the Basal Sandstone and in sandstone units 1 and 2, several planar and trough cross-bedded intervals were found (Figs. 32, 33, and 34). In most cases, cross-bedded intervals were between several inches to a foot in thickness. Preservation of sedimentary features within the Sentinel Butte Formation sandstones is very poor, except within concretionary layers, where there is very good preservation of cross beds. However, concretions are scattered, and a connective trend between these bodies is impossible to trace.

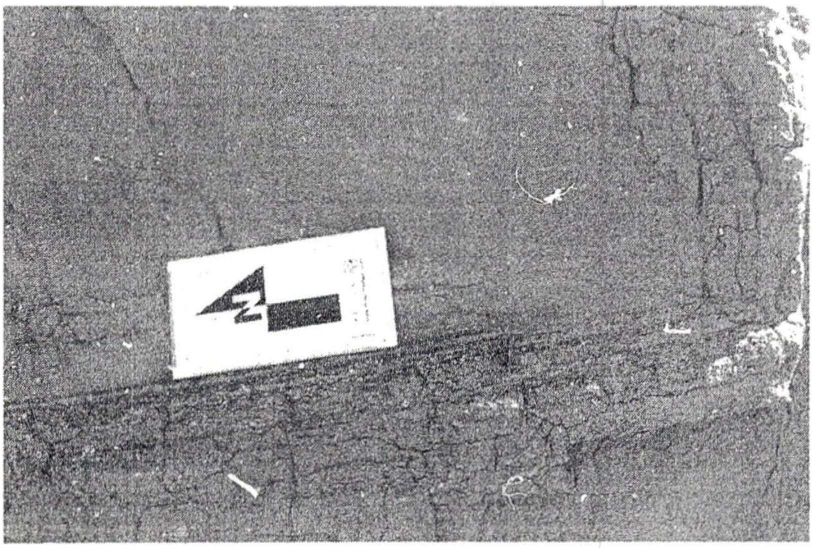


Figure 32. An Example of Planar Crossbedding within the Basal Sandstone. The card is 6 in (15.2 cm).

Using the classification described by Miall (1981), beds displaying planar cross stratification represent deposition along linguoid bars or deltaic foresets extending out from older bar remains. Trough cross stratification is interpreted as deposition in minor channel fills. Both of these observations support a fluvial model for the deposition of the unit, but what type of fluvial system is at work?

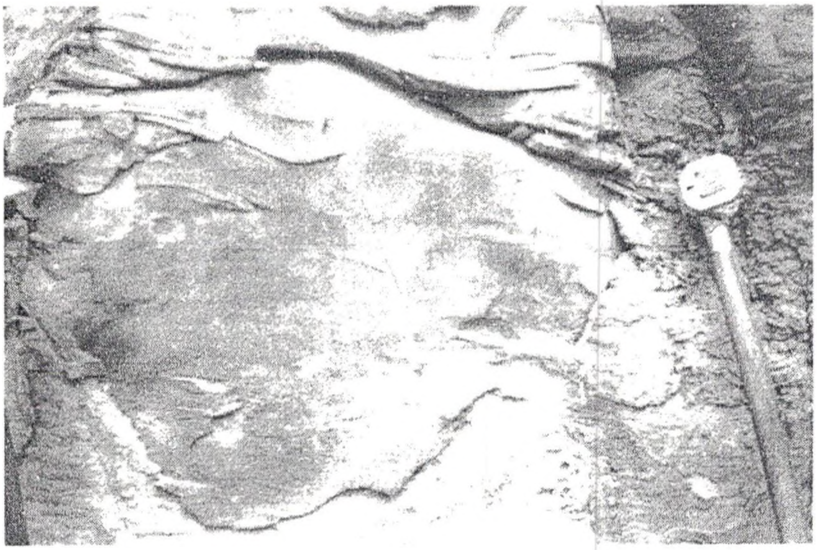


Figure 33. Trough Crossbedding within a Log Concretion in the Basal Sandstone in Measured Section 12. The Brunton Compass is 2.6 in (6.6 cm) long.

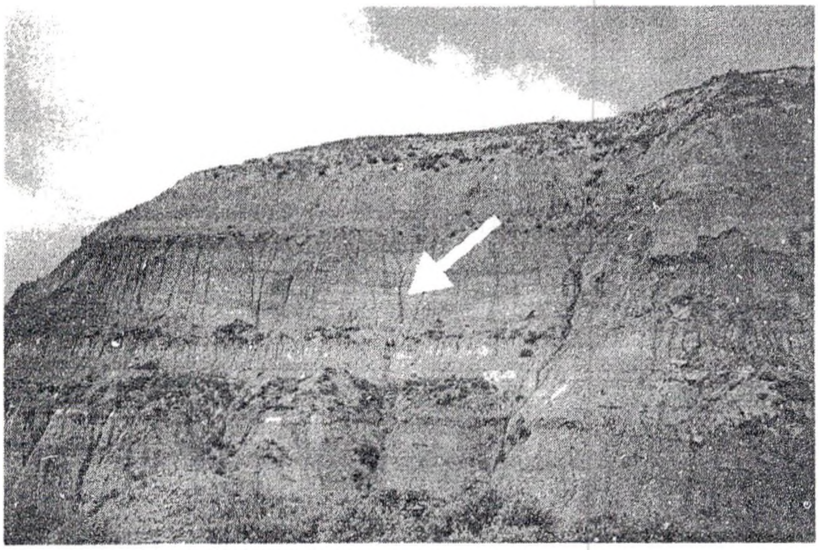


Figure 34. Crossbedding (arrow) within Sandstone Unit 1 in Measured Section 18.

There are three types of fluvial systems that can be considered for answering this question. They are low sinuosity multichannel, anastomosing, and meandering systems (Miall, 1977,1981). Low sinuosity multichannel systems are usually associated with sand-dominated deposition. This is clearly not applicable to the Sentinel Butte Formation, since silt and clay represent the majority of the deposits for the Sentinel Butte

Formation in the study area. Anastomosing river systems are low- energy complexes of several interconnected channels of variable sinuosity (Smith and Smith, 1980). This type of system is typically associated with a humid environment, where peat bogs, wetlands, and floodplain ponds are common. Channel banks are stabilized by vegetation and overbank floods are frequent. In this system there is little channel migration and lateral accretion of sand is limited. This produces the most distinctive feature of anastamosing river systems, a vertical accretion of sandstone (Miall, 1981). When studying deposits from such a system, sandstone units should be very thick, but laterally restricted. This feature was not observed within the study area. Meandering river systems are identified based on several distinct characteristics. Meanders within these systems produce a helical overturn within the flow of the river. Velocities tend to decelerate as water moves up the point bar from the thalweg. This deceleration sorts sediment, producing a classic fining-upward sandstone sequence that accretes laterally as the meander migrates downstream. The accretion of these point bars produces laterally extensive sandstone units that are much more persistent horizontally than they are vertically. This type of fluvial system would tend to produce sandstone units that are relatively thin, but are traceable for some distance. This feature is observed within the study area and can be seen in Figures 9, 10, and 11. Three of the four sand units identified within this area can be traced laterally for several miles. Much of the Upper Sandstone in the study area has been removed by erosion, so its lateral persistence cannot be assessed.

Another line of evidence for a meandering fluvial system is apparent in the sandstone percentage map of sandstone units 1 and 2 (Fig. 12). This map presents the inferred character of these sandstone units. It was developed by interpolating measured section data with a computer and projecting the pre-erosional distribution of these units. The contour patterns of these two units show a definite meandering trend. Since sedimentary structures within these units indicate some type of fluvial deposition and a map of the sandstone percentage shows a meandering accumulation pattern, it can be concluded that these sandstones were deposited as the result of a meandering fluvial system. The meandering pattern exhibited by an inferred isopach map of the Basal Sandstone (Fig. 7) is not quite as evident as the pattern exhibited by the sandstone percentage map of Sandstone Units 1 and 2 (Fig. 12). Again, this is an inferred isopach map produced using the available measured section data. This data was then processed statistically to calculate the probable thickness of the unit prior to erosion. The isopach does not represent the current distribution of the Basal Sandstone as it appears today, but rather interpolates the probable distribution of the Basal Sandstone prior to erosion. The Basal Sandstone is a much thicker unit than the overlying sandstones and therefore I infer that the fluvial system responsible for the deposition of this unit was possibly larger than for Sandstone Units 1 and 2. Therefore, the meandering pattern of the Basal Sandstone fluvial system should also be spread out over a larger area geographically, an area larger than that of the middle sands and thus not as obvious at the scale of the study area.

The classic fining-upward sequence of meandering systems that is mentioned above was not identified in the sandstones in the Sentinel Butte Formation of the study area. There was no apparent upward fining from the base to the top of any of the four observed sandstone units. Structures that occur within the point-bar complexes of meandering fluvial systems, such as epsilon cross stratification (Allen, 1963), were not evident.

Given the poor preservation of sedimentary structures within the sands of this formation, identification of such structures was not possible.

Perhaps, the uppermost sandstone unit described in this area merits a different interpretation than the underlying sandstone units. Unlike the sandstone units below, the Upper Sandstone preserves fairly well sedimentary structures. Large-scale planar cross bedding occurs at the base of this unit (Figs. 35 and 36).

Figure 35. Planar Crossbeds within the Upper Sandstone in Measured Section 15.

These cross-bedded intervals thin upsection to the upper part of the unit, where planar-bedded intervals occur (Fig. 37).

There seems to be a change in flow velocities from the base of the Upper Sandstone to its top. The large-scale crossbeds at the base of the sand body indicate a fluvial origin for this portion of the Upper Sandstone, something similar to that described in the Basal Sandstone. However, the presence of the horizontally bedded intervals indicate a change

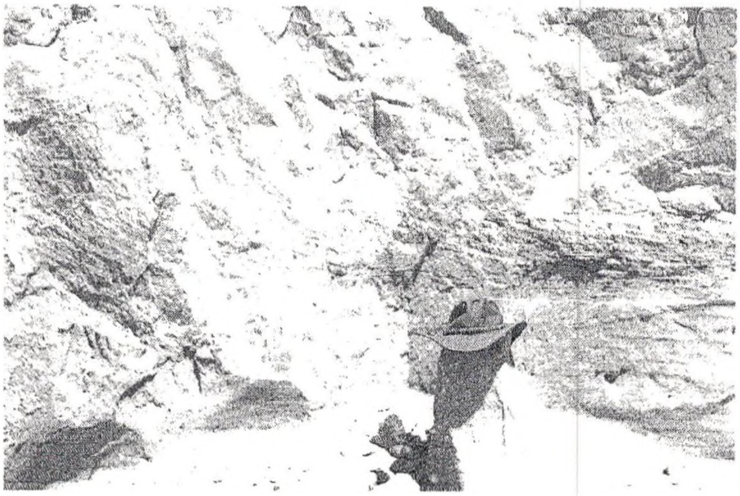


Figure 36. Large Scale Planar Crossbedding (arrow) within the Upper Sandstone in Measured Section 15.

Figure 37. View showing planar bedding in the upper exposures of the Upper Sandstone in Measured Section 15.

in depositional setting. Pettijohn et al. (1987) reported that horizontally laminated sands occur in almost all environments and thus have several origins. Since the mode of formation for this type of sandstone is uncertain, it is difficult to determine a particular paleoenvironment for the deposition of this portion of the Upper Sandstone. Therefore, this sandstone unit is interpreted as representing deposition initially within a meandering-channel system, like the sandstone units below. However, due to some type of change in the flow regime, this channel system did not maintain the same conditions throughout deposition. Pettijohn (1987) described a very similar condition and suggested that horizontally laminated sandstone intervals could represent a transitionary period in accumulation of sand, with fluctuating flow velocities. This change from initial conditions could represent a cutoff meander, a flood event, or possibly deposition within a secondary portion of the channel. Any of these circumstances could be responsible for the deposition of the upper sections of the Upper Sandstone. Since there is no evident fining upwards within the unit, this section does not fit with the channel plug facies of Cherven (1977), where cut-off meanders fill with sand, silt, and finally clay. In this setting, there was still sand supplied, which suggests that this area was not very far from the main channel. Perhaps this interval represents the early stages of a cutoff meander. The absence of overlying strata in the study area prohibits interpreting additional lithologies up-section. Thus, a comparison of the Upper Sandstone and other classic cutoff meander sequences is impossible. Given the ambiguity in the interpretation of laminated sandstones, a depositional model for this section remains unclear.

Mudrock

If the lateral accretion of sandstone units within this portion of the Sentinel Butte Formation resulted from deposition within a meandering channel, then there should be nearby evidence of clastic deposition outside of the channel. In this study area, the mudrock portion of the section is interpreted as representing accumulation of sediment in areas separate from the main channel system. These intervals could possibly represent an accumulation of sediment within environments ranging from levees adjacent to the main channels, to areas farther out upon a floodplain (Miall, 1981). The siltstone-dominated sections could represent overbank flood deposits or deposition within levees. These silty intervals tend to directly overlie the channel sandstones, which would be expected of a levee deposit. However, levee deposits tend to contain sand as well as silt (Miall, 1981). In this area, there were no sandstone intervals within the mudrock. A potential facies classification of this interval is best described by Miall (1985) as element OF, or overbank facies. This lithofacies is characterized by an assemblage of mudstone and siltstone units, directly overlying channel-form sandstones (Miall, 1985). However, the crevasse splay component of Miall's classification is missing within this interval.

The vertical accretion of the silt and clay portions within this interval could simply represent a transition from levee-overbank flood deposits adjacent to the channels, to floodplain deposits distal to the channels. This is similar to the vertical accretion model suggested by Allen (1963, 1970) in which silts and clay directly overlie channel sands. Allen reports that these overbank facies are typically overlain by lignite horizons, which is also the case for this study interval.

Lignite

Lignite beds within the study area represent deposition away from the channel system in densely vegetated backswamps. This environment was far enough away from the stream system to allow for the uninterrupted accumulation of large quantities of organic matter that result in the formation of lignite beds. Deposition continued until the meandering channel migrated over peat forming areas ending organic accumulation due to the influx of sediments.

Limestone

Limestone beds present within the study area indicate a lacustrine environment (Fig. 17). Since these beds are very small the associated lacustrine system responsible for their deposition must also be limited in area. How these units fit into the overall system is unclear. They always occur within the mudrock intervals and are normally associated with the more clay-rich portions of this interval. If these clay portions are interpreted to represent deposition on the floodplain, then the lacustrine deposits must also originate on the floodplain. There are four major sources of calcium carbonate in lacustrine settings (Dean and Fouch, 1983): 1) inorganically precipitated carbon, 2) bioinduced (abiotic) carbonate, 3) biogenic carbon from calcareous plants and animals, and 4) allochthonous (detrital) material. Of these, carbonate in lacustrine environments is inorganic or biogenetically induced carbonate (Dean and Fouch, 1983). In some cases, biogenic precipitation of carbonate plays a key role. Biogenic carbonate is produced in littoral zones of lakes where aquatic vegetation may become encrusted with calcium carbonate. In pelagic or open water portions of a lake, where allochthonous material is at a minimum, biogenically produced carbonate precipitation is similar to that in littoral zones. In this case algae provide the medium by which carbonates form (Dean and Fouch, 1983).

In a system where allochthonous and biogenic carbonate is at a minimum, inorganic and bio-induced precipitation of calcium carbonate becomes the primary modes by which carbonate is precipitated. Through CO_2 respiration, aqueous plants raise the pH to levels of 9 and above. This results in the supersaturation and subsequent precipitation of $CaCO_3$.

Perhaps these environments developed in times between floods when clastic (allochthonous) deposition was at a minimum. Isolated bodies of water could have formed and provided the conditions necessary for calcium carbonate precipitation. This same setting could also have formed within abandoned meanders and oxbow lakes, all of which should be found within a meandering fluvial system. More data are needed to interpret the origins of these limestone beds.

Paleoflow Directions

Flow directions were measured on cross-bedded units (Fig. 41). The average orientation was 181°, indicating flow of the channels was to the south. This result is different from the findings of other workers. Royse (1970) and Peck (1992) reported an average flow direction of 120°, and 203°, respectively. However, given that the channel that produced these crossbeds is interpreted as meandering, a wide range of flow directions should be expected. Only by taking numerous measurements over a large area would an accurate reconstruction of the net flow direction of preserved channels be permitted.

Depositional Models

Two depositional models have been proposed for the Sentinel Butte Formation. Jacob (1976) developed a marine-deltaic model of deposition for both the Bullion Creek and the overlying Sentinel Butte Formation. Jacob thought that a large prograding delta advanced seaward toward the regressing Cannonball Sea. The Bullion Creek Formation represents deposition along a lower delta plain, while the Sentinel Butte Formation is part of an upper delta plain system. Jacob (1976 p. 33 and 34) believed that the laterally

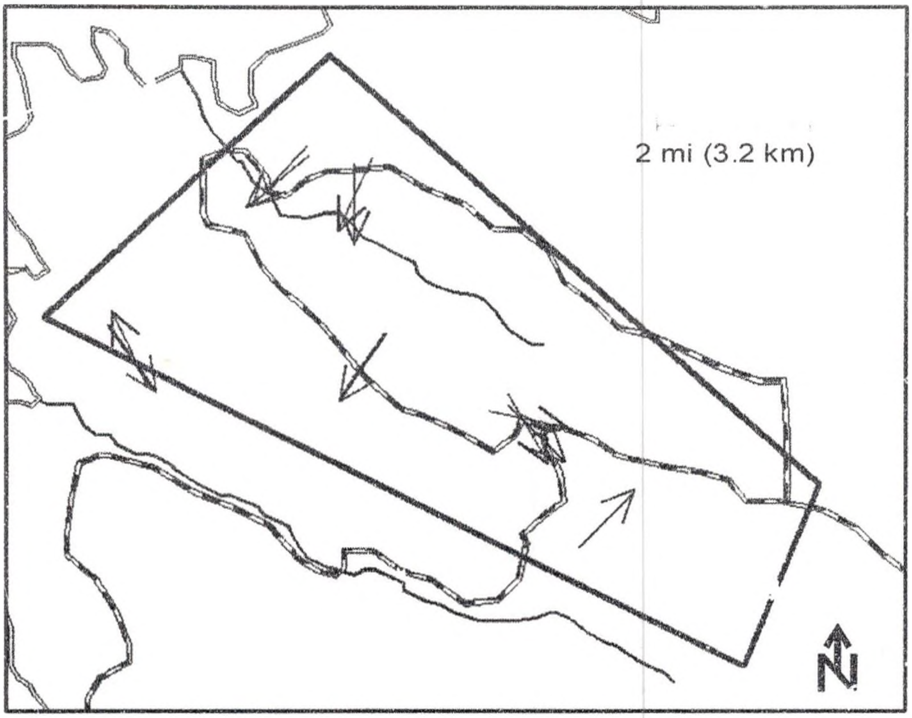


Figure 38. Paleoflow Directions Measured from all the Sandstone Units from the Sentinel Butte Formation in the Study Area.

extensive lignite deposits of the Bullion Creek, along with "trough shaped, non-braided, low sinuosity stream deposits" are characteristic of sediments within a lower delta plain environment, while the nonlaterally extensive lignites and abundant elongate, "high-sinuosity" stream deposits of the Sentinel Butte Formation are more generally associated with upper delta-plain environments. Cherven (1977) supported this hypothesis by providing a fluvial and deltaic facies analysis for the formation. He identified several features within the section that suggest that a combination of meandering channel and deltaic systems were at work during Sentinel Butte deposition. In support of a meandering channel system, Cherven identified meandering-channel, channel-plug, natural levee, flood basin, and swamp facies. Of these, all but the channel-plug facies have been identified in the current study area. Deltaic facies Cherven identified included distributary channel, channel plug, natural levee, marsh, delta front, prodelta, interdistributary, and crevasse splay facies. Of these only the natural levee facies was identified within the study area and it is related to a meandering fluvial system and not to an upper deltaic system.

A "tectonic fluvial" model was proposed by Winczewski (1982) and Winczewski and Groenewold (1982). This study relied on subsurface geophysical data gathered from 225 well sites in western North Dakota. The authors constructed numerous cross sections that resulted in the recognition of repeating intervals of clastic deposition capped by extensive lignites. Their model of the deposition of the Bullion Creek and Sentinel Butte Formations included the diversion eastward of a northward flowing fluvial system that originated in the Powder River Basin of Wyoming. This diversion was initiated by subsidence of the Williston Basin, and was eventually cut off by sediment accumulation, and rediverted back to the north (Winczewski and Groenewold, 1982).

The data gathered in this study do not support the deltaic or the tectonic fluvial models. No evidence was observed that reflects any of the characteristics of the deltaic facies described by Cherven (1977). However, there is evidence to support the meandering channel system portion of the deltaic model proposed by Cherven and Jacob (1985). The cyclic sedimentation described by Winczewski and Groenewold (1982) may be present in the current study area, but is not as simple as they suggested. In their study, seven clastic cycles of sandstone are capped by fine silts, clays and or lignite. Only in a general sense is this type of cycle present in the current study area (Figs. 9, 10, and 11). In the present study sandstone is normally followed by an interval of mudrock, which is followed by a lignite bed. These intervals of fine sediments and lignite are highly variable, with multiple horizons of alternating silt, clay and lignite present between sandstone intervals. This sequence could hardly be referred to as cyclic. Thus the tectonic fluvial model is rejected as a possible model for Sentinel Butte Formation deposition in this study area.

CHAPTER 7

CONCLUSIONS

1) On the basis of the evidence provided in this thesis, the most probable model for deposition of the Sentinel Butte Formation is a meandering channel system flowing over a low gradient alluvial plain. This interpretation best fits into Miall's model 7 (Miall, 1985), that describes a "highly sinuous, suspended load stream." Depositional settings consist of major channel elements with lateral accretion deposits, minor sandy bedforms and abandoned channels. Over bank deposits of mostly silt and clay are also major elements. The overall architecture of these elements is controlled by the migration and stacking of the major channel systems (Miall, 1985).

Several of the above characteristics are identified in the current study. Three lateral accreting sand units are recognized, all of which contain sedimentary structures that indicate a fluvial environment. Thick sequences of vertically accreting silt and clay represent over bank accumulation of sediments, and these are normally capped by lignite deposits. These units indicate deposition within floodplain and back swamp environments respectively. Limestone beds within the unit indicate some type of lacustrine environment that may have developed within abandoned channels or other topographic lows located on floodplains.

2) The deltaic fluvial model of Jacob and Cherven (1985) is rejected as a possible model for the deposition of the Sentinel Butte Formation. The facies characteristics described in their model do not correspond with the observed characteristics of the surficial exposures of the Sentinel Butte Formation in my study area.

3) The tectonic fluvial model of Winczewski and Groenewold (1982) is rejected as a possible model for deposition of the Sentinel Butte Forma[illegible]. The basis of this model was the recognition of cyclic sedimentation within the unit. [illegible] was not possible to identify any type of cyclic pattern within the Sentinel Butte sediments within the current study area

More data are undoubtedly needed to further develop this alluvial plain model into something that can be applied to the entire Sentinel Butte Formation. Currently, there is not enough coverage of the whole formation to provide adequate detailed data regarding the distribution and characteristics of the sediment types within the formation. Until better coverage is achieved, any basin wide interpretation of the Sentinel Butte Formation will remain difficult.

Suggestions for Future Work

1) More stratigraphic data regarding the Basal Sandstone should be gathered basin-wide. This would provide needed data regarding the depositional pattern of this unit and better help to identify the mode by which it accumulated. This would also help to identify the overall drainage pattern of the basin during the deposition of the lower part of this formation.

2) More studies, similar to this, should be done within the Sentinel Butte Formation, gathering a large amount of sedimentologic and stratigraphic data from the entire basin.

This should help in more precisely developing a model for the deposition of the entire formation.

APPENDIX A

Measured Section Data

Measured section 1
Sentinel Butte Formation
Location: 47°30.153 N, 103° 33.376 W

Unit		Unit Thickness (ft)	Cumulative (ft)
16	Limestone gray and brown mudrock, interbedded, very fissile lenses	42	365
15	Gray mudrock	23	323
14	Gray, fine sandstone, numerous very large boulder concretions	9	300
13	Mudrock, gray, iron stained, scattered gastropod fossils	40	291
12	Lignite, woody	1	251
11	Mudrock, gray iron stained, scattered concretions, root traces	37	250
10	Liginite	3	213
9	Mudrock dark gray, laminated, root traces	15	210
8	Fine sandstone, fining upward into mud, petrified stumps (not in place), prominent concretionary and iron rich layers, (Sentinel Butte Basal Sandstone sand)	92	195
7	Lignite (HT bed?)	10	103
6	Mudrock, gray, scattered laminations, petrified tree stumps, bottom of interval is the color change from Bullion Creek to Sentinel Butte	5	93
5	Mudrock, yellow and gray with fossilized tree trunks	15	88
4	Sandstone, buff yellow, fine, iron stained, numerous small pebble/cobble concretions, climbing ripple cross laminations	18	73
3	Mudrock, yellow, iron stained, numerous concretions	20	55
2	Sandstone and silt, yellowish gray interbedded iron stained , concretionary, scattered gastropod fossils	25	35
1	Lignite	10	10

Measured Section 2
Sentinel Butte Formation
Location: 47°29.815 N, 103° 32.927 W

Unit		Unit Thickness (ft)	Cumulative (ft)
10	Mudrock, gray, iron stained, with numerous limestone fragments (on top of butte)	25	278
9	Lignite	3	253
8	Mudrock, dark gray, laminated	15	250
7	Lignite, woody, interbedded organic black shale	4	235
6	Mudrock, dark gray, iron stained with limestone pods	107	231
5	Lignite	3	124
4	Mudrock, dark gray, iron stained, with limestone pods	30	121
3	Lignite with interbedded black organic shale	3	91
2	Mudrock, dark gray, iron stained, gastropod fossils	13	88
1	Sandstone, gray fine, numerous organic rich layers, petrified wood (not in place), small concretions iron stained, boulder sized limestone pods, thin interbedded mudrock	75	75

Measured Section 3
Sentinel Butte Formation
Location: 47° 30.917 N, 103° 32.205 W

Unit		Unit Thickness (ft)	Cumulative (ft)
5	Lignite	2	135
4	Mudrock, gray, swelling, draping	25	133
3	Lignite	3	108
2	Mudrock, gray, finely laminated, root traces	15	105
1	Sandstone, gray medium/fine, fining upward, iron stained, numerous planar orange concretionary layers (6 inches to 2 feet thick), trace amounts of interbedded silt and clay, numerous black organic stringers, trace limestone pods	90	90

Measured Section 4
Sentinel Butte Formation
Location: 47° 29.941 N, 103° 32.543 W

Unit		Unit Thickness (ft)	Cumulative (ft)
5	Lignite, woody with organic shale	i	95
4	Mudrock, gray, iron stained, few concretions	19	94
3	Lignite	5	75
2	Mudrock, gray, finely laminated, root traces, gastropod fossils fragments	20	70
1	Sandstone, fine/medium gray, iron stained, black organic stringers, concretions	50	50

Measured Section 5
Sentinel Butte Formation
Location: 47° 26.412 N, 103° 28.791

Unit		Unit Thickness (ft)	Cumulative (ft)
6	Silt, bright yellow, powdery could be lower SB yellow-bed, sparsely vegetated	20	173
5	Mudrock, dark gray, ironstained, shell fragments, limestone pods	94	153
4	Lignite, thin, woody	1	59
3	Mudrock, gray, iron stained thin limestone layers	25	58
2	Clay, dark gray, draping, white under gray layer, petrified stumps	3	33
1	Mudrock, gray, iron stained, gastropod and bivalve fossils, petrified wood fragments	30	30

Measured Section 6
Sentinel Butte Formation
Location: 47° 29.382 N, 103° 32.363 W

Unit		Unit Thickness (ft)	Cumulative (ft)
16	Mudrock, gray, iron stained, very top of butte is littered with yellowish gray platy limestone	23	390
15	Lignite, woody with black organic shale	2	367
14	Sandstone, fine gray, fining up into dark gray mudrock, iron stained	34	365
13	Sandstone, fine, gray, large concretions and limestone pods	10	331
12	Mudrock, gray, iron stained, orange concretionary chips litter the surface	10	321
11	Shale, very organic purple/gray, very brittle	2	311
10	Mudrock, gray, iron stained with scattered limestone pods	84	309
9	Lignite	1	225
8	Sandstone, fine grained , grading upward into mudrock gray, very iron stained, numerous concretions	15	224
7	Sandstone, medium/fine gray, numerous orange concretionary layers, interbedded siltstone and claystone, large scale crossbedding	70	209
6	Lignite, woody, thin yellow sandstone immediately above	4	139
5	Color change from Bullion Creek to Sentinel Butte Formation, (at 110ft.) changing from yellow mudrock of Bullion Creek Formation to gray (somber) mudrock of Sentinel Butte Formation petrified wood (not in place).	25	135
4	Sandstone, yellow fine grained, grading upward into mudrock, interbedded limestones numerous shell fragments, one thin lignite and organic shale at 105 ft	50	110
3	Sandstone, very fine grained yellow, iron stained, small concretionary bodies, interbedded mudrocks, shell fragments	23	60
2	Lignite, woody, blackish – brown	10	37

	interbedded organic black shale		
1	Mudrock, yellow, iron stained few gastropod shell fragments	27	27

Measured Section 7
Sentinel Butte Formation
Location: 47° 29.140 N, 103° 31.641 W

Unit		Unit Thickness (ft)	Cumulative (ft)
21	Very soft powdery silt, bright yellow, (lower yellow bed)	10	368
20	Mudrock, iron- stained, gray	45	358
19	Mudrock, gray, iron stained, numerous limestone pods	45	313
18	Mudrock, gray, ironstained, numerous petrified stumps in place, numerous occurances or very platy yellowish gray limestone	10	268
17	Mudrock, gray, iron stained, rare laminations and root traces	13	258
16	Lignite and organic shale	2	245
15	Mudrock, gray, iron stained, petrified wood fragments, large boulder concretions	20	243
14	Clinker	5	223
13	Mudrock, gray, iron stained, root traces	46	218
12	Lignite and organic shale	2	172
11	Mudrock, gray, iron stained, trace laminations	5	170
10	Lgnite, woody	3	165
9	Mudrock, gray, concretionary, limestone pods	35	162
8	Lignite, woody and organic shale	4	127
7	Mudrock, gray, iron stained, planar concretions	12	123
6	Sandstone, silty, gray, iron stained, numerous concretions	6	111
5	Mudrock, gray, iron stained, few concretionary bodies, petrified stumps and limestone pods	45	105

4	Lignite and shale	1	60
3	Mudrock, gray, trace laminations	2	59
2	Lignite, woody black and organic shale	5	57
1	Mudrock, gray, numerous petrified stumps, small shell fragments, limestone pods, and orange concretionary layers	52	52

Measured Section 8
Sentinel Butte Formation
Location: 47° 27.437 N, 103° 31.107 W

Unit		Unit Thickness (ft)	Cumulative (ft)
9	Mudrock, gray, iron stained, limestone pods	25	156
8	Mostly covered, but very yellow silt, (lower yellow bed)	25	131
7	Mudrock, gray, root traces, laminated, shell fragments	35	106
6	Clay, dark gray swelling with thin interbedded, lignite, organic shale	8	71
5	Sandstone, gray, grading upward into mudrock, iron stained, limestone pods	10	63
4	Sandstone, gray fine, iron stained	10	53
3	Mudrock, gray, iron stained, petrified wood, orange concretionary bodies	2	43
2	Lignite	1	41
1	Mudrock, gray, iron stained, petrified wood fragments, some concretionary bodies	40	40

Measured Section 9
Sentinel Butte Formation
Location: 47° 27.428 N, 103° 31.523 W

Unit		Unit Thickness (ft)	Cumulative (ft)
11	Silt, bright yellow powdery, few bivalve fossils, (lower yellow marker bed)	30	135
10	Mudrock, gray, iron stained, few gastropod shell fragments	27	105
9	Lignite, thin, with organic shale	2	78
8	Mudrock, gray, iron stained, concretionary, gastropod fossils	30	76
7	Sandstone, fine gray, large concretions, cross-bedded, fining upward	14	46
6	Mudrock, gray, iron stained root traces	2	32
5	Lignite, shale	4	30
4	Mudrock, gray, iron stained, gastropod fossils and in place petrified stumps	10	26
3	Lignite, organic shale	1	16
2	Clay, dark gray swelling	2	15
1	Mudrock, gray, iron stained, gastropod shells	13	13

Measured Section 10
Sentinel Butte Formation
Location: 47° 25.722 N, 103° 31.063 W

Unit		Unit Thickness (ft)	Cumulative (ft)
17	Clay, gray swelling, very soft, top of butte is littered with clinker	15	166
16	Lignite, woody with shale	1	151
15	Clay, brown and gray, very soft	9	150
14	Lignite, woody, shale	3	141
13	Mudrock, gray, iron stained, numerous limestone pods, one thin (4 in) lignite	24	139
12	Mudrock, gray, iron stained, concretionary	31	115
11	Lignite, very woody, shale	3	84
10	Mudrock dark gray, iron stained, root traces, laminated	12	81
9	Sandstone, gray silt, scattered concretions	13	69
8	Lignite, woody with organic shale	1	56
7	Mudrock, gray, numerous root traces, laminated	2	55
6	Shale, some lignite, in place petrified stump	3	53
5	Clay, dark gray swelling, petrified wood fragments, white clay under weathered layer, one interbedded 6 inch lignite at 32 ft	17	50
4	Clay, dark gray swelling	12	32
3	Lignite, woody	3	20
2	Mudrock, gray, ironstained scattered gastropod fossil fragments	5	17
1	Sandstone, fine grained, gray, fining upward, few iron stains and small concretions	12	12

Measured Section 11
Sentinel Butte Formation
Location: 47° 26.235 N, 103° 32.764 W

Unit		Unit Thickness (ft)	Cumulative (ft)
11	Mudrock, gray, two thin interbedded lignites and shale, top of butte is littered with clinker	96	245
10	Sandstone, fine grained gray, interbedded mudrock iron stained, few concretions, finning upward	15	149
9	Mudrock, gray, iron stained, numerous shell fragments	5	134
8	Lignite, woody	2	129
7	mudrock, gray, iron stained, numerous shell fragments, organic rich laminations	55	127
6	lignite, interbedded with dark gray clay and organic shale, woody	7	72
5	Clay, dark gray, swelling, petrified wood fragments	3	65
4	Color change from Bullion Creek Formation to Sentinel Butte Formation (54 ft), yellow silty sandstone overlain by gray silty sandstone, fining upward into mudrock, iron stained, cobble sized concretions	8	62
3	Covered, but looks like yellow silty sandstone, scattered limestone pods	10	54
2	Sandstone, yellow, well indurated, silty	4	44
1	Sandstone, yellow, silty, very soft, some limestone pods	40	40

Measured Section 12
Sentinel Butte Formation
Location: 47° 27.723 N, 103° 35.665 W

Unit		UnitThickness (ft)	Cumulative (ft)
8	Mudrock, sparsely covered gray, scattered limestone pods	32	240
7	Mudrock, gray, iron stained, limestone pods with plant impressions	30	208
6	Lignite, covered	2	178
5	Sandstone, silty, grading upward into laminated clay, root traces	25	176
4	Sandstone, fine grained, gray, fining upwards, iron stained interbedded mudrock and organic rich layers	80	151
3	Lignite	6	71
2	Mudrock, gray, iron stained scattered limestone pods, color change at 65 feet from yellow mudrock of Bullion Creek Formation to gray mudrock of Sentinel Butte Formation.	10	65
1	Mudrock, yellow, numerous shell and gastropod fragments	55	55

Measured Section 13
Sentinel Butte Formation
Location: 47° 27.577 N, 103° 35.126 W

Unit		Unit Thickness (ft)	Cumulative (ft)
7	Covered, however ground surface is littered with clinker chips	15	168
6	Mudrock, gray, sparsely covered iron stained	50	153
5	Mudrock, gray, numerous boulder concretions, interbedded highly organic rich layers	31	103
4	Lignite and organic shale, woody	2	72
3	Clay, dark gray, laminated, in place petrified stump	5	70
2	Mudrock, gray, iron stained	15	65
1	Sandstone, gray medium/fine, finning upwards, cross bedded (epsilon?), large concretions, interbedded mudrock, overlying covered section of bright yellow mudrock of Bullion Creek Formation,	50	50

Measured Section 14
Sentinel Butte Formation
47° 26.674 N, 103° 31.183 W

Unit		Unit Thickness (ft)	Cumulative (ft)
15	Clinker	3.5	150.5
14	Clay, gray, laminated root traces	31.5	147
13	Silt, bright yellow, powdery (lower yellow marker bed)	21.5	115.5
12	Lignite	.5	94
11	Mostly covered, looks the same as unit 10	.5	93.5
10	Mudrock, yellowish gray fining up ward into claystone	11	88
9	Mudrock, fining upward into claystone	11	77
8	Lignite, very woody, shale	1	66
7	Mudrock, fining upward to clay yellowish gray, iron stained, petrified wood fragments, small concretionary bodies,	12	65
6	Shale, two thin layers seperated by claystone	1	53
5	Mudrock, yellowish gray iron stained, petrified wood fragments, small concretionary bodies, fining upward to clay	19.5	52
4	Lignite, very woody, in-place petrified stump	1	32.5
3	Mudrock, yellowish gray, iron stained, petrified wood fragments, small concretionary bodies, fining upward to clay	14.5	31.5
2	Clay, gray, white where unweathered, in place petrified stumps, numerous limestone pods	2.5	17
1	Mudrock, yellowish gray	14.5	14.5

Measured Section 15
Sentinel Butte Formation
Location: 47° 26.504 N, 103° 28.298 W

Unit		Unit Thickness (ft)	Cumulative (ft)
1	sandstone, medium fine, gray planar cross bedded at base horizontally bedded at top cross beds thin up section, numerous discontinuous surfaces, possibly old channel structures, upper portions show fine horizontal laminations, numerous concretionary or burrow structures, unit is capped by a very resistant flagstone, one sedimentary breccia is associated with this unit, it is a small lens approximately 2 ft thick and not laterally continuous, entire unit is trough shaped	37	37

Measured Section 16
Sentinel Butte Formation
Location: 47° 26.272 N, 103° 28.531 W

Unit		Unit Thickness (ft)	Cumulative (ft)
19	Silt,yellow powdery, numerous shell fragments	32.5	218.5
18	Mudrock,yellowish gray iron stained, interbedded claystone, numerous shell fragments	32	186
17	Clay, gray, interbedded thin lignite lens and organic shale	12.5	154
16	Clay, gray, trace shell fragments	5.5	141.5
15	Mudrock, yellow gray concretionary, finely laminated in places finning up into claystone	16.5	136
14	Shale and lignite, rooty	2.5	119.5
13	Mudrock, yellow gray concretionary	27.5	117
12	Lignite, woody and shale	2.5	89.5
11	Mudrock, yellowish gray concretionary	31	87
10	Lignite and organic shale	9	56
9	Mudrock, yellow-gray concretionary	11.5	47
8	Shale and lignite woody, numerous root traces	1.5	35.5
7	Clay, gray	1	34
6	Mudrock, yellowish gray, iron stained, small cobble concretions, some large log concretions	18	33
5	Lignite	1.5	15

	woody, numerous petrified fragments		
4	Mudrock, yellowish gray fining upward into claystone	1.5	10.5
3	Mudrock, grayish yellow numerous concretions, some log concretions	4	9
2	Claystone, gray in place petrified wood stump	4.5	5
1	lignite	.5	.5

Measured Section 17
Sentinel Butte Formation
Location: 47° 26.119 N, 103° 27.544 W

Unit		Unit Thickness (ft)	Cumulative (ft)
18	Covered but looks the same as unit 17	23	253
17	Mudrock, grayish yellow laminated in places	40	230
16	Mudrock, fining upward into siltstone and then claystone, few small concretions	16	190
15	Lignite and shale, very woody	2	174
14	Mudrock, yellowish gray iron stained, root traces trace planar laminations shell fragments	33	171
13	Siltstone, yellow lower yellow bed	24	138
12	Mudrock, yellowish gray iron stained, root traces laminated, shell fragments	31	114
11	Sandstone, light gray fine grained, N7	12	83
10	Lignite	1	71
9	Clay, gray, 5y 7/2 light olive gray	5.5	70
8	Mudrock, yellowish gray 5y 7/2, shell fragments,iron stained	5.5	64.5
7	Shale,lignite mostly covered, in place petrified stumps, scattered limestone pods on ledge	1	59
6	Claystone, light olive gray 5y 6/1	9	58
5	Mudrock, concretionary iron stained, fining upward into claystone	19.5	47

4	Lignite, shale very woody	1.5	27.5
3	Clay, light olive gray woody fragments	6	26
2	Mudrock, yellowish gray 5y 7/2 iron stained fining upward into claystone, concretionary	19	20
1	Lignite	1	1

Measured Section 18
Sentinel Butte Formation
Location 47° 25.705 N, 103° 26.786 W

Unit		Unit Thickness (ft)	Cumulative (ft)
12	Silt, bright yellow powdery, shell fragments lower yellow bed	36	131
11	Shale, very organic woody	1	95
10	Mudrock, yellow gray 5y 7/2, fining up into claystone	9	94
9	Shale, very organic trace amounts of lignite	1	85
8	Mudrock, yellowish gray 5y 7/2, shell fragments concretions, climbing ripple laminations	32	84
7	Lignite, woody mostly covered	1	52
6	Mudrock, light olive gray 5y 6/1	5	51
5	Sandstone,fine gray interbedded silts planar crossbeds numerous concretions	7	46
4	Mudrock,light olive gray 5y 6/1	2	39
3	Lignite, shale	2	37
2	Clay, draping light olive gray 5y 6/1 numerous limestone pods interbedded silty layers	17	35
1	Mudrock,yellow gray 5y 7/2, fining upward into claystone	18	18

APPENDIX B

Point Count Data

<u>Basal Sandstone Point Count Data</u>

200 points counted per sample

<u>Sample B1A</u>	<u>Count</u>	<u>Percentage</u>
Quartz	74	37
Feldspar	26	13
Volcanic fragments.	37	18.5
Sedimentary fragments	39	19.5
Lignite	13	6.5
Unknown	11	5.5
<u>Sample B1B</u>		
Quartz	79	39.5
Feldspar	13	6.5
Volcanic fragments.	37	18.5
Sedimentary fragments	58	29
Lignite	1	0.5
Unknown	12	6
<u>Sample B1C</u>		
Quartz	79	39.5
Feldspar	22	11
Volcanic fragments.	33	16.5
Sedimentary fragments	42	21
Lignite	6	3
Unknown	18	9
<u>Sample B2A</u>		
Quartz	82	41
Feldspar	24	12
Volcanic fragments	32	16
Sedimentary fragments	50	25
Lignite	5	2.5
Unknown	7	3.5
<u>Sample B2B</u>		
Quartz	77	38.5
Feldspar	30	15
Volcanic fragments	42	
Sedimentary fragments	38	19
Lignite	3	1.5
Unknown	10	5
<u>Sample B2C</u>		
Quartz	94	47
Feldspar	20	10
Volcanic fragments	31	15.5
Sedimentary fragments	44	22
Lignite	0	0

Unknown	11	5.5

Upper Sandstone Point Count Data

Sample S10 (lower sample)	Count	Percentage
Quartz	217	54.25
Feldspar	22	5.5
Volcanic fragments	4	1
Sedimentary fragments	128	32
Lignite	3	1.5
Unknown	23	5.75

Sample S9 (upper sample)		
Quartz	96	24
Feldspar	5	1.25
Volcanic fragments	0	0
Sedimentary fragments	15	3.75
Lignite	0	0
Unknown	8	2
Calcite Cement	276	69

APPENDIX C

Grain Analysis Data

Basal Sandstone

US Sieve Number	Opening (mm)	Opening (phi)	Weight (gr)	Weight %	Cumulative %
25	0.707	0.5	0	0	0
40	0.354	1.25	0.1	0.3	0.3
60	0.25	2	13.3	42.2	42.5
80	0.177	2.5	11.2	35.6	78.1
100	0.125	2.75	2.5	7.9	86
170	0.088	3.5	2.6	8.3	94.3
230	0.062	4	1.1	3.5	97.8
Pan			0.6	1.9	99.7
Total			31.4	99.7	99.7

initial wt. (gr)	31.5
final wt. (gr)	31.4
wt. Loss (gr)	0.1
wt. Loss (gr)	0.1

Upper Sand

US Sieve Number	Opening (mm)	Opening (phi)	Weight (gr)	Weight %	Cumulative %
25	0.707	0.5	0	0	0
40	0.354	1.25	0.1	0.5	0.5
60	0.25	2	0.5	2.5	3
80	0.177	2.5	4.4	22	25
100	0.125	2.75	3.83	19	44
170	0.088	3.5	7.3	36.5	80.5
230	0.062	4	1.8	9	89.5
	0				
Pan			1.9	9.5	99
Total			19.8	99	99

initial wt. (gr)	20
final wt. (gr)	19.8
wt. loss (gr)	0.2

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