# INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

**The quality of this reproduction is dependent upon the quality of the copy submitted.** Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# STRATIGRAPHY OF THE UPPER PIERRE SHALE AND FOX HILLS FORMATION (CAMPANIAN AND MAASTRICHTIAN; LATE CRETACEOUS) IN THE BADLANDS NATIONAL PARK REGION, SOUTH DAKOTA: IMPLICATIONS FOR EUSTATIC CHANGES IN SEA LEVEL, TECTONISM, AND MARINE PALEOECOLOGY OF THE WESTERN INTERIOR SEAWAY

by

Philip Ward Stoffer

A dissertation submitted to the Graduate Faculty in Earth and Environmental Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, the City University of New York

1998

UMI Number: 9830765

---

---

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

This manuscript has been read and accepted for the Graduate Faculty in Earth and Environmental Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

2-4-98 John A. Chamberlain Jr.
Date Chair of Examining Committee

2/4/98
Date Executive Officer

Neil H. Landman
Robert W. McWilliams
Frederick C. Shaw
Supervisory Committee

THE CITY UNIVERSITY OF NEW YORK

## Abstract

# STRATIGRAPHY OF THE UPPER PIERRE SHALE AND FOX HILLS FORMATION (CAMPANIAN AND MAASTRICHTIAN; LATE CRETACEOUS), THE BADLANDS NATIONAL PARK REGION, SOUTH DAKOTA: IMPLICATIONS FOR EUSTATIC CHANGES IN SEA LEVEL, TECTONISM, AND MARINE PALEOECOLOGY OF THE WESTERN INTERIOR SEAWAY

by

Philip Ward Stoffer

This research focuses on the upper Pierre Shale and Fox Hills Formation (Late Cretaceous, Late Campanian and Maastrichtian) in a study area extending from eastern Wyoming to the Missouri River valley in South Dakota, with an emphasis is on the region encompassing Badlands National Park. Named stratigraphic units in eastern Wyoming include the Lower Unnamed Shale Member, the Kara Bentonitic Member, and the Upper Unnamed Shale Member of the Pierre Shale, and the Fox Hills Formation (oldest to youngest). The equivalent lithostratigraphic sequence in the Missouri River Valley is the Verendrye, Virgin Creek, Mobridge, and Elk Butte members of the Pierre Shale, and the Trail City and Timber Lake members of the Fox Hills Formation (oldest to youngest).

Evaluation of the sequence stratigraphy indicates that both eustatic changes in sea level and tectonism influenced depositional patterns in the Badlands National Park region. A fall in sea level during latest Campanian time (*Baculites reesidei*) resulted in the development of an unconformity encompassing the Campanian/Maastrichtian boundary in the park area. Sea level rose in early Maastrichtian time with a highstand during *Baculites grandis* time. Regression followed in *Baculites clinolobatus* time. Sea level also rose and fell during deposition of the Fox Hills Fm.

Evaluations of sediment charactericstics, outcrop features, and the general distribution of shell fauna and trace fossil assemblages provide insight into the paleoenvironmental conditions of the seaway. The generally uniform composition the sediment throughout the section and across the region suggests that marine circulation patterns thoroughly mixed the sediment. The characteristics of sedimentary facies are a function of water depth. The influence of episodic storms on sedimentation is suggested by storm-generated bedforms and the record of rapid kill events of marine fauna. Progradation of clinoform mudbanks from the south during Campanian time, and from the north during Maastrichtian time, suggest that early Laramide uplift in the Black Hills region influenced marine circulation and sediment transport in the seaway. Equivalent stratigraphic units in the Badlands National Park region are thinner by more than half by comparison to the Wyoming and Missouri River sections.

## ACKNOWLEDGEMENTS

I extend special gratitude to Paula Messina (my wife, friend, fellow student, and traveling research partner), and to my advisor, Dr. John A. Chamberlain, Jr. (Brooklyn College), for both his guidance and support. Thanks are also extended to Dr. Neil Landman, Susan Klofak, and other staff of the American Museum of Natural History Invertebrates Department, and to many faculty, students, librarians, and staff at both Brooklyn College and CUNY Graduate School, Department of Earth & Environmental Sciences, Ph. D. Program. Special thanks are extended to Dr. Frederick Shaw, Chair or the CUNY Earth and Environmental Sciences PhD Program, and Dr. Robert McWilliams (Professor of Geology Emeritus, Miami University, for their support and criticisms.

This research was supported by funds provided by CUNY grants through the City University Research Foundation, by a Lerner-Gray Foundation Grant (AMNH), and a U.S. Geological Survey EDMAP Grant. Research facilities and equipment were provided by Brooklyn College and AMNH.

In the field many people were very gracious to extend a hand or to grant permission to allow me to collect fossils on private or public managed lands. Thanks are extended to Rachel Benton, the park paleontologist at Badlands National Park; the South Dakota ranch owners: Alan Johnson, Ray Johnson, Paul Jensen, and Tom Trask. People who contributed discussion and help for this research include. William A. Cobban (USGS Senior Researcher Emeritus), Jim Hoffman (Univ. Tulsa), Frank Ettensohn (Univsity of Kentucky), Victor

Goldsmith (Hunter College), Gerald M. Friedman (Brooklyn College), Dave Hahn (Mayor of Wall, South Dakota), and two fellow students at Brooklyn College: Roland Scal and Marty Becker.

To my parents, Ruth & Lewis Stoffer, I owe sincere thanks for motivating me towards a science career! Finally, I am extremely grateful to all my brothers, friends, teachers, and research associates that have contributed to my knowledge and experiences of my life and career.

## TABLE OF CONTENTS

Chapter

Appendix

## LIST OF TABLES

# LIST OF ILLUSTRATIONS

Figure

# CHAPTER 1

## INTRODUCTION

This dissertation is a study of the stratigraphy of the upper Pierre Shale and Fox Hills Formations (Campanian and Maastrichtian; Late Cretaceous) within a study area extending from the Missouri River in central South Dakota to the Powder River Basin in northeastern Wyoming. Emphasis was placed on the area encompassing the Badlands National Park region of western South Dakota, and in placing the stratigraphy in and around the park in its proper regional setting. During Late Cretaceous time the study area occuppied the central portion of the Western Interior Seaway (Fig. 1). The Western Interior Seaway was a broad, shallow, epeiric sea that covered much of central North America during the Cretaceous and extended across the continent from the Gulf region of Texas northward to the Arctic Ocean. The seaway was bounded on the west by structural and volcanic mountains of the Cordillera and on the east by low, rolling topography of the Canadian Shield and the gently uplifted region of the east-central lowlands west of the Appalachians. Crustal thickening resulting from active margin-style tectonism and sediment loading on the western margin of North America caused the isostatic downwarping responsible for

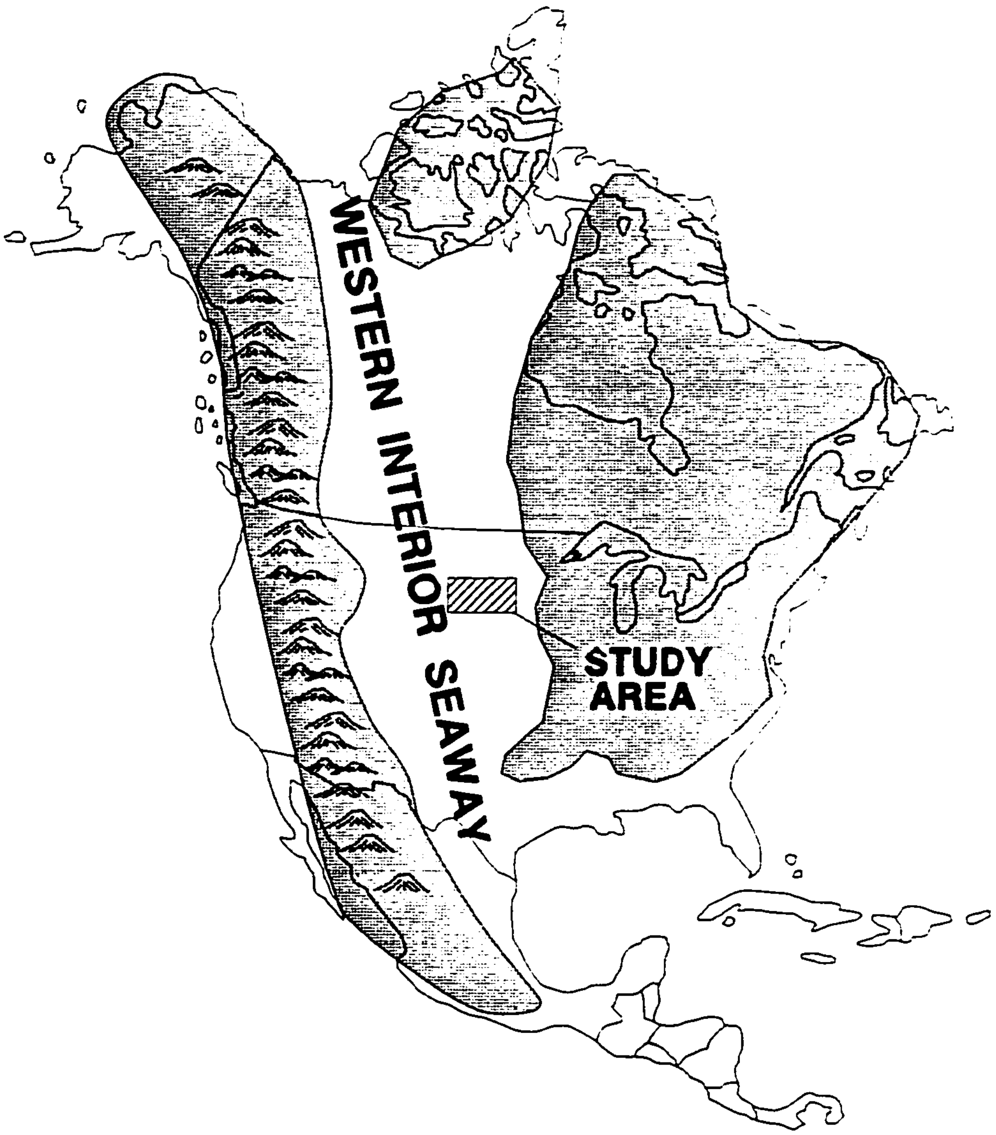


Fig. 1. The study area in relation to the Western Interior Seaway during Late Campanian time; shoreline geometries are after Williams (1975) and Wright (1987).

excursions of the seaway into the Western Interior throughout late Mesozoic and early Cenozoic time (McGookey, *et al.*, 1972; Williams & Stelck, 1975; Dyman, *et al.*, 1994). The Sevier Orogeny was responsible for the uplift of the Cordilleran ranges and the development of several volcanic centers along the western margin of the seaway, both of which provided vast quantities of clastic material to the Western Interior Basin. In contrast, the low-lying land bordering the eastern margin of the seaway probably contributed comparatively little sediment to the basin (Gill & Cobban, 1973; Wright, 1987). Starting in late Campanian time tectonism and regional uplift associated with the earliest stages of the Laramide Orogeny began to influence sedimentation patterns throughout the seaway (Keefer, 1965; Winn, Bishop, & Gardner, 1987).

This dissertation focuses on sedimentation patterns during the deposition of seaway sediments in the late Campanian and early Maastrichtian, and it interprets eustatic changes on sea level and the influence of local and regional tectonism. Research emphasis is on outcrop exposures along the Cheyenne River and its tributaries in Badlands National Park where the study interval is well exposed along several branches of Sage Creek in the North Unit, and along Cedar Creek in the South (Stronghold) Unit of the park. Supplemental reference sections from localities along the Cheyenne River Valley between Wasta, SD and the Missouri River are included to resolve detail of stratigraphic relationships between the Badlands area and the Missouri River section. The emphasis on the study of Cretaceous strata in Badlands National Park is based on a fortuitous opportunity to gain access to study and collect samples from highly restricted areas in designated wilderness within the national park. Consultation with numerous individuals, particularly W. A. Cobban (a senior Cretaceous biostragraphy researcher of the U.S. Geological Survey), and a review of the literature revealed that very little detail on the Cretaceous stratigraphy of the region east of the Black Hills has been published.

The primary goals of this research are to:

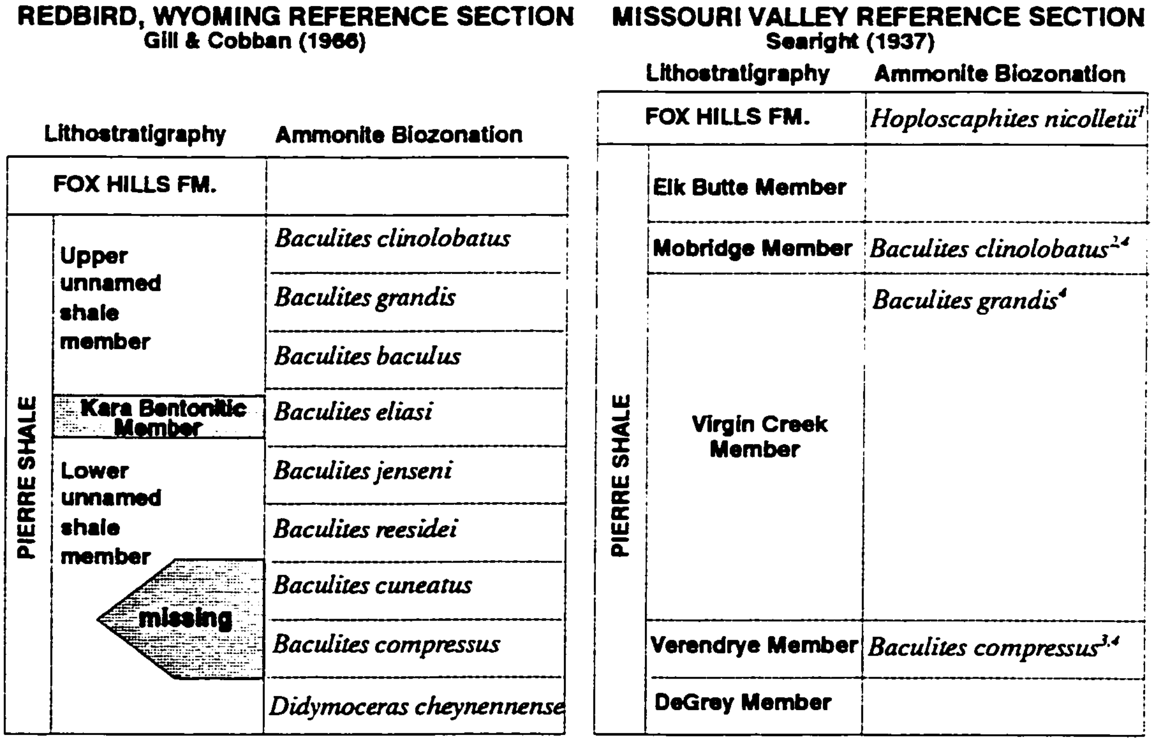
1. Resolve the lithostratigraphic and biostratigraphic relationships of Cretaceous beds in the Badlands National Park area in relation to established reference sections along the Missouri River in South Dakota and near Redbird, Wyoming;
2. Refine understanding of the sequence stratigraphy in the study area (that is, determine the influence of both eustatic changes and tectonism on sedimentation patterns in the seaway); and thereby,
3. Determine details about the paleoenvironmental conditions affecting sedimentation patterns and processes in the seaway. (This includes evaluation of diagenetic features in the sediments, such as bedforms, concretion horizons, bentonites, etc., and an interpretation of the influences of sedimentation on the occurrence and distribution of shelled fauna preserved in the study interval.);
4. Construct a logical, consistent model for the geologic history of the Late

Cretaceous in the Badlands National Park region.

These goals are accomplished by combining traditional field observations throughout the region with laboratory sedimentological and geochemical analyses and fossil identification outlined in Chapter 4 - *Research Methods*.

The lithostratigraphy of the Pierre Shale is clearly established along the Missouri River in South Dakota, first by Searight (1937) with revisions by Gries (1942), Crandell (1950), and Crandell (1958). The Fox Hills lithostratigraphy and biostratigraphy in the upper Missouri River Valley was also established by Waage (1964) and Waage (1968), with detail presented by Daly (1991), Landman & Waage (1993). The establishment of the type section for the Pierre Shale in Redbird, Wyoming by Gill & Cobban (1966) linked ammonite biozonation to named and unnamed stratigraphic units on the western flank of the Black Hills. The disparity between the biostratigraphy in the Redbird, Wyoming area and the lithostratigraphy of the Missouri River section is a source of a variety of problems for identifying stratigraphic terminology in the Badlands region. For instance, in the Redbird section stratigraphic assignment to the Lower Unnamed Shale Member, the Kara Bentonitic Member, and the Upper Unnamed Shale Members is based on the range occurrence of baculitid ammonite index fossils. (The Kara Bentonitic Member is also a prominent marker horizon between the two unnamed members.) Along the Missouri River and in the Badlands National Park region the Kara Bentonitic Member is unrecognized or missing. Lithostratigraphic units named by Searight (1937) (and others that followed) did not use ammonite index fossils to define lithostratigraphic members, with certain exceptions: Searight (1937) established *Baculites compressus* to be an index fossil of the Verendrye Member. Searight (1937) also recognized *Baculites grandis* as an index fossil for the Virgin Creek Member. Searight (1937), Gill & Cobban (1966) and Cobban (personal communication, 1996) described *Baculites clinolobatus* as an index fossil of the Mobridge Member. A summary of the lithostratigraphic and established biostratigraphic descriptions of the two type areas is presented in Fig. 2. Definition of the stratigraphy in the Badlands National Park area is compounded by problems associated with variations in sedimentary facies relationships, the occurrence and nature of unconformities, the disparity in the occurrence and preservation of fossils in some zones, and the influence of post-depositional weathering of the upper Pierre Shale and overlying Fox Hills Formation. Previous investigations in the park area have also introduced nomenclature of stratigraphic features in the park (particularly a prominent weathering profile affecting the study interval called the "Interior Zone" or "Yellow Mounds Weathering Profile") that are not consistent with either the Redbird section or the Missouri River section (Ward, 1922; Wanless, 1923; Ward, 1926; Raymond & King, 1976; Retallak, 1983; and Retallak, 1985).

Investigation of the original reference sections of the upper Pierre Shale could



[1] Landman & Waage (1993)
[2] Gill & Cobban (1966) and Cobban (pers. comm., 1996)
[3] Crandall (1958)
[4] Searight (1937)

Fig. 2. Comparison of lithostratigraphy and ammonite biostratigraphy of the Pierre Shale from the Redbird, Wyoming type reference section by Gill & Cobban (1966) with established lithostratigraphic and biostratigraphic information for reference sections along the Missouri River Valley region.

not be accomplished during the course of this investigation. We were denied access to the private land containing Gill & Cobban's (1966) Pierre Shale reference section in the Redbird, Wyoming area. In addition, the original reference sections for the Pierre Shale and Fox Hills (Searight, 1937) along the Missouri River no longer exist. The development of the Lake Oahe Resevoir on the Missouri River flooded the lower members of the section, and resulted in the abandonment and overgrowth of a highway that provided roadcuts for inspection of the upper members. These problems were resolved, in part, by establishing new reference sections on public lands in the regions of both original reference sections. In Wyoming, useful exposures were found on public land in the Mush Creek and Osage Oil Fields in Weston County (between 60 and 80 kilometers northwest of Redbird). Study and sampling of the Pierre Shale/Fox Hills interval in the Mobridge, South Dakota region was conducted along roadcuts of SD Highway 12 with supplemental data from private ranches owned by Ray Johnson and Alan Johnson (between 20 and 40 kilometers west of Mobridge).

All paleontological specimens relating to this study have been reposited in collections of the American Museum of Natural History, Department of Invertebrates. Supplemental specimens have been donated to the research collection at Badlands National Park.

# CHAPTER 2

## BACKGROUND

Extensive research has been conducted on the Western Interior Basin and the seaway that flooded it for most of its geologic history, particularly in reference to economically important petroleum reserves, coal, and other mineral resources. Significant summaries about the overall geologic history of the basin are presented by McGookey et al., (1972), Williams & Stelck (1975), Kauffman (1977), and Dyman et al., (1994). Stratigraphic patterns in rocks of Late Cretaceous age in the Western Interior region indicate that at least seven major transgressive-regressive episodes occurred during this interval (Dyman et al., 1994). Table I illustrates these cycles in relation to named stratigraphic units in the Black Hills region. This research focuses on aspects of the last great cycle, the Bearpaw, which represented the final great transgressive episode before the drastic changes that affected the region at the close of the Mesozoic Era. In the study area, the combination of the upper Pierre Shale and Fox Hills interval represents the marine portion the Bearpaw Cycle, which was named after an equivalent shale formation exposed on the eastern flanks of the Canadian Rockies.

## TABLE I

Cretaceous cyclothem stratigraphy in the Black Hills region (youngest on top) (after McGookey et al., 1972; Kauffman, 1977; Dyman et al., 1994)

| CYCLOTHEM | STRATIGRAPHIC UNITS | GEOLOGIC AGE |
|---|---|---|
| Bearpaw | Hell Creek Fm. | late Maastrichtian/Paleocene |
| | Fox Hills Fm. | early Maastrichtian |
| | upper Pierre Shale Fm. | late Campanian/early Maastrichtian |
| Claggett | lower Pierre Shale Fm. | early to late Campanian |
| Niobrara | Niobrara Fm. | early Coniacian to early Campanian |
| Carlile | Sage Breaks Mbr. (Carlile) | late Turonian to early Coniacian |
| Greenhorn | Poole Creek Mbr. (Carlile) | early Turonian |
| | Greenhorn Fm. | late Cenomanian to early Turonian |
| | Belle Fourche Fm. | middle Cenomanian |
| | Mowry Shale Fm | late Albian to early Cenomanian |
| | Newcastle Sandstone Fm. | late Albian |
| Kiowa-Skull Creek | Skull Creek Fm. | late Albian |
| | Fall River Fm. | middle Albian |
| Lakota | Lakota Fm. | late Aptian to early Albian |

Previous work has raised many questions about the paleoenvironmental conditions of the Western Interior during the Cretaceous. Depositional cycles have been described throughout the Cretaceous section. Large cycles are thought to reflect major transgression/regression couplets bounded by unconformities, with each cycle lasting many millions of years. Cycles within cycles are reflected on the scales of formation, members, units, and beds, and may be interpreted on various orders of magnitude within the hierarchy of sequence stratigraphy. Cycles are expressed in terms of oscillating patterns in clastic and carbonate sedimentology (King & Skotnicki, 1994); organic and inorganic content (Dean, 1988; Arthur & Pratt, 1986; Arthur & Dean, 1991); isotopic signatures (Tourtelot & Rye, 1969; Wright, 1987; Kyser et al., 1993; Barrera, 1994; McArthur et al., 1994); abundance of fossil calcareous nannoplankton (Eicher & Diner, 1989); and abundance of trace fossils (Savrda & Bottjer, 1989; Mieras et al., 1993). Cycles have been interpreted as resulting from oscillating changes in sea level (Haq et al., 1987; Hancock, 1993; King & Skotnicki, 1994); wet-to-dry climate cycles (Wright, 1987; Jerzykiewicz & Sweet, 1989); global temperature variations (Spicer & Corfield, 1992; Barrera, 1994); global paleogeography (Barren & Washington, 1984); variations in anoxia and sedimentation rates (Hallam, 1977; Weissert, McKenzie & Hochuli, 1979; Savrda & Bottjer, 1989; Jewell, 1993); upwelling (Parrish & Gautier, 1988; Eicher & Diner, 1989); turbidites (Einsele, 1991); ocean circulation and density stratification patterns

(Wright, 1987; Roth, 1989; Jewell, 1993; Barrera et al., 1997); regional paleotectonism (Gill & Cobban, 1973; Elder, 1994; Shurr, Hammond & Bretz, 1994); and orbital effects (e.g., Milankovitch cycles)(Einsele & Ricken, 1991; Fischer, 1991); and extraterrestrial impacts (Lunar and Planetary Institute, 1994; Anderson & Witzke, 1994). Although, in detail, the causes of sedimentary cycles may vary, cyclic sedimentation in general must in general reflect regional climatic conditions, water circulation patterns, sediment supply, changes in sea level, or the influences of regional tectonism. Infrequent major storm events probably were an important factor in moving large quantities of sediment into the central basin region of the seaway (discussed in Chapter 9).

On a global scale, Campanian through Maastrichtian time was characterized by rapidly changing continental arrangements and mountain building around the globe; and by eustatic changes in sea level (Barrera et al., 1997; Haq et al., 1987). In North America, the Western Interior Seaway (which initially connected to both the Gulf of Mexico and the Arctic Ocean) became very restricted or isolated from the Gulf via the combined effects of regression, sea level fall, and/or regional uplift (Fig. 3). It follows that this isolation must have had a significant effect on both the climate and the organisms that inhabited the seaway (discussed below in section 2.2.).

The shallowing and isolation of the Western Interior Seaway increased its susceptibility to regional climatic variation, particularly in regard to the diversity and

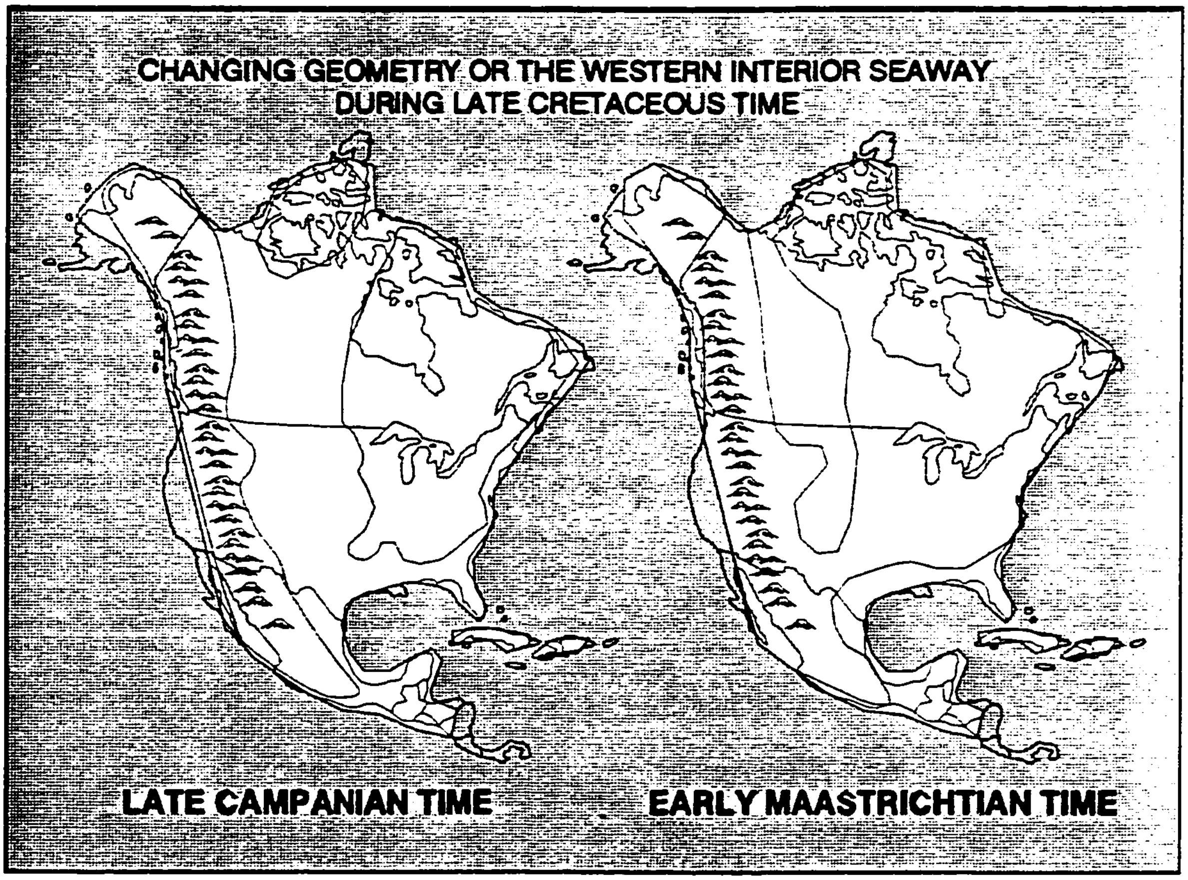


Fig. 3. Paleogeography of North America during latest Cretaceous time (after McGookey et al., 1972; Gill & Cobban, 1973; Williams, 1975; and Wright, 1987).

distribution of marine fauna. Epeiric seas also existed on the continents of Europe, central and southeast Asia, Africa, and in the Middle East (Fig. 4). Through the late Cretaceous time, mountain building activity was increasing worldwide. The equatorial oceanic circulation pattern of the Supertethys realm was gradually disrupted by mountain building activity in Southeast Asia, the Himalayan region, the greater Middle East, southern Europe, and along the southern extension of the North American Cordilleran ranges (Scott, 1990). Late Cretaceous global tectonic activity is probably responsible from the shift of strontium isotope values ($^{87}Sr/^{86}Sr$) towards heavier values starting in late Turonian time through the end of the Cretaceous (McArthur et al., 1994). Increasing $^{87}Sr/^{86}Sr$ values may indicate an increase in terrestrial weathering activity of uplifted granitic ranges worldwide during the late Cretaceous (McArthur et al., 1994; Bryant et al., 1995).

As the width of the Atlantic Ocean increased through the Cretaceous Period it must have significantly influenced the global ocean/atmosphere heat exchange patterns. The combination of high standing seas and a widening Atlantic Ocean may have allowed the passage of strong tropical storms northward into the Western Interior region. Cyclic variability in regional climate may have influenced sedimentation both in the short-term (seasons to years as illustrated in alternating bedding rhythms) as well as in the long-term (in the ranges of hundreds of years to hundreds of thousands of years). For instance, Jerzykiewicz & Sweet (1989)

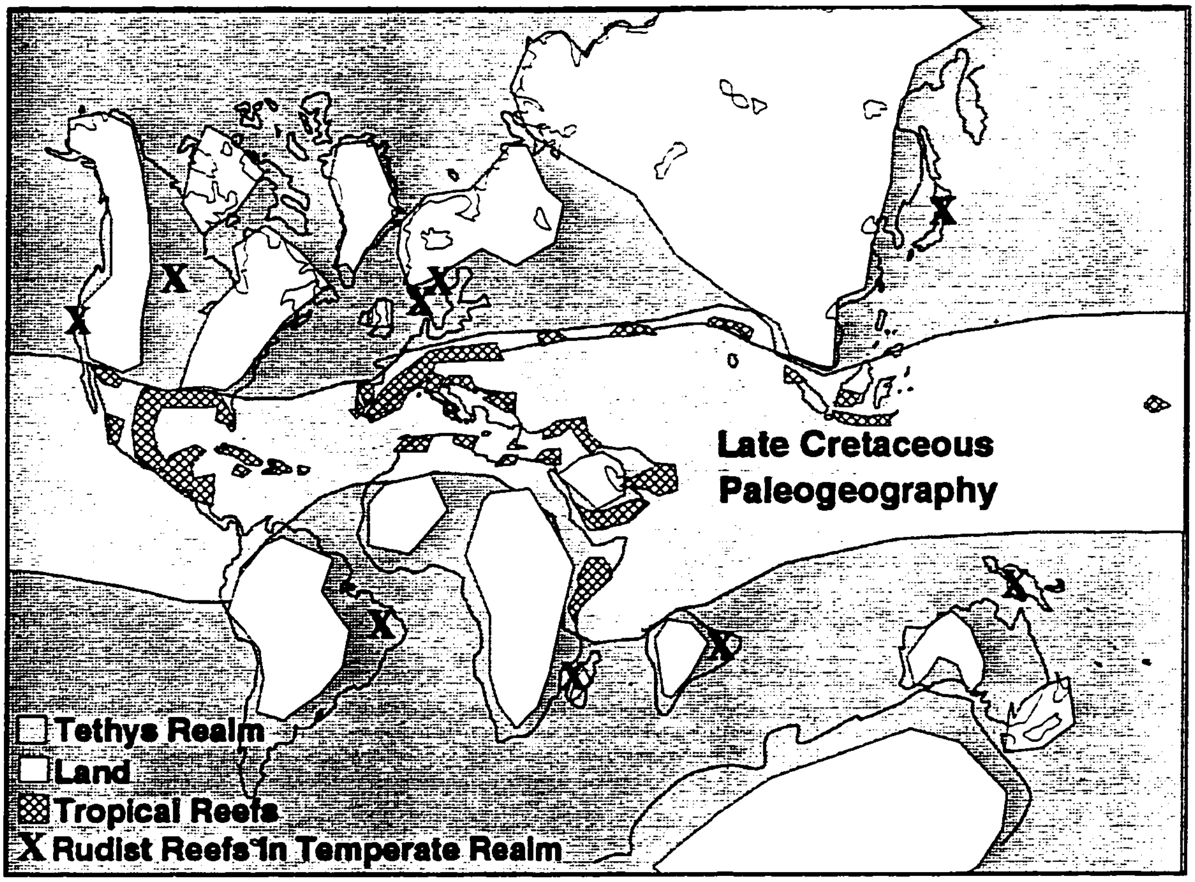


Fig. 4. Late Cretaceous Paleogeography (after Scott, 1990).

demonstrated that coastal flood plain climates alternated between coal-forming swamps (wet) to caliche-bearing paleosols (dry) during Campanian to Maastrichtian time in cycles reminiscent of Pleistocene glacial cycles.

## 2.1 PREVIOUS STUDIES OF STRATIGRAPHY

The upper Pierre Shale/lower Fox Hills interval has been the focus of many investigations outside of the study area, particularly in relation to the occurrence of marine fossils and economic aspects of the shale's soil-forming characteristics, and to the geochemical characteristics of the shale in relation to petroleum source rocks, clays (particularly bentonite), and trace elements including selenium, manganese, and uranium. Selected previous studies of biostratigraphy and lithostratigraphy are discussed below.

The Pierre Shale was first described by Meek & Hayden (1862). Lithologic descriptions for upper Cretaceous units (including type-sections for named stratigraphic units) are given along the Missouri River in South Dakota by Searight (1937) with revisions by Gries (1942), Crandell (1950) and Crandell (1958). These early reports are generally descriptive, focusing on the variations in thickness of units, lithologic appearances, and characteristic fossils. Robinson, Mapel, & Cobban (1959) provided a description of the Pierre Shale along the northern and western flanks of the Black Hills in Wyoming and Montana. Gill & Cobban (1966) described a type reference section for the Pierre Shale based on ammonite biozonation and lithology from outcrops near Redbird, Wyoming (on the southwestern side of the Black Hills). Gill and Cobban's report includes the first extensive correlation of Pierre-equivalent units throughout the region and established the first regional macrofossil biozonation for the Cretaceous in the Western Interior using selected ammonite index fossils (see Fig. 2, p. 7). Further refinement of the regional stratigraphic correlation of the Pierre Shale, particularly in relation to the progradation of the Sheridan Delta (across the northern portion of the study area during late Pierre and Fox Hills time) is described by Gill & Cobban (1973). Cobban (1993) summarizes ammonite biozonation for the Western Interior region and provides an interpretation of ammonite paleoecology through time. Lithostratigraphic investigations of strata of Campanian and Maastrichtian age have been published for the surrounding regions including the work of Roehler (1993) for the Rock Springs Uplift region of central Wyoming, by Winn, Bishop, & Gardner (1987), Perman (1988) in south-central Wyoming, and Daly (1991) in North Dakota.

Descriptions of the Pierre Shale microfossils include a study of foraminifera by Mello (1969) within the upper members of the Pierre Shale in the Missouri River region near Mobridge, South Dakota. Mello (1971) and Bergstresser (1981) described both foraminifera and radiolarians from the Pierre Shale at the type locality at Redbird, Wyoming and elsewhere. Additional works related to the study of stratigraphy and invertebrate paleontology of the upper Pierre Shale and the overlying Fox Hills Formation related to this study include descriptions of the Fox Hills Formation by Waage (1964), Waage (1968), Feldman (1972), Reskind (1975); Carpenter et al., (1988), Daly (1991), Landman & Waage (1993).

Larson et al., (1997) provide the most detailed correlation of stratigraphic units and ammonite range zones for the greater Western Interior region. This publication presents illustrations for the ammonite genera preserved in the Pierre Shale with many representative specimens from the study area region. Their correlation diagram illustrates the complexity of stratigraphic nomenclature attributed to Late Campanian and Early Maastrichtian lithostratigraphy. Details regarding the names and correlation of lithostratigraphic units related to the study area are presented in detail in the Chapter 8.

## 2.2 PALEONTOLOGICAL APPLICATION TO SEQUENCE STRATIGRAPHY

Previous investigations into lithostratigraphic and biostratigraphic correlation serve as a foundation for interpretation of sequence stratigraphy of the study interval. This discussion is an overview of selected lines of evidence which provide support for interpretation of eustatic changes in sea level during Late Campanian and Maastrichtian time. Once the sequence of eustatic changes are clearly resolved it might be possible to differentiate these effects from the influences of local tectonism on sedimentation patterns. Sequence stratigraphy integrates biostratigraphic and sedimentological information and divides a stratigraphic succession on the basis of *key surfaces* into "systems tracts", defined as a linkage of contemporaneous depositional systems, deposited during a specific part of a cycle of relative sea-level change [i.e., lowstand (LST), transgressive (TST), highstand (HST) systems tracts, etc. (Tucker, 1995)]. The method may be applied to a single stratigraphic section, but is of greatest value when applied to many sections or when applied to the study of a whole basin. This report is an attempt to construct the sequence stratigraphy of the Badlands National Park region, but relies on data from previously published work done throughout the Western Interior region.

Once Gill & Cobban (1966) established ammonite biozonation for the Western Interior region they were able to map the occurrence of *Baculites* species in relation to nearshore facies to record the advancement and retreat of shorelines during Campanian and Maastrichtian time (McGookey et al., 1972; Gill & Cobban, 1973) (Fig. 5). Gill & Cobban's research demonstrate that sedimentary facies boundaries in the Western Interior region appear to be *diachronous*, that is, time-transgressive from one location to the next, whereas their Western Interior ammonite biozones are possibly *synchronous* and independent of facies. Bentonite marker beds, where they can be correlated, are also synchronous. These early chronology models were

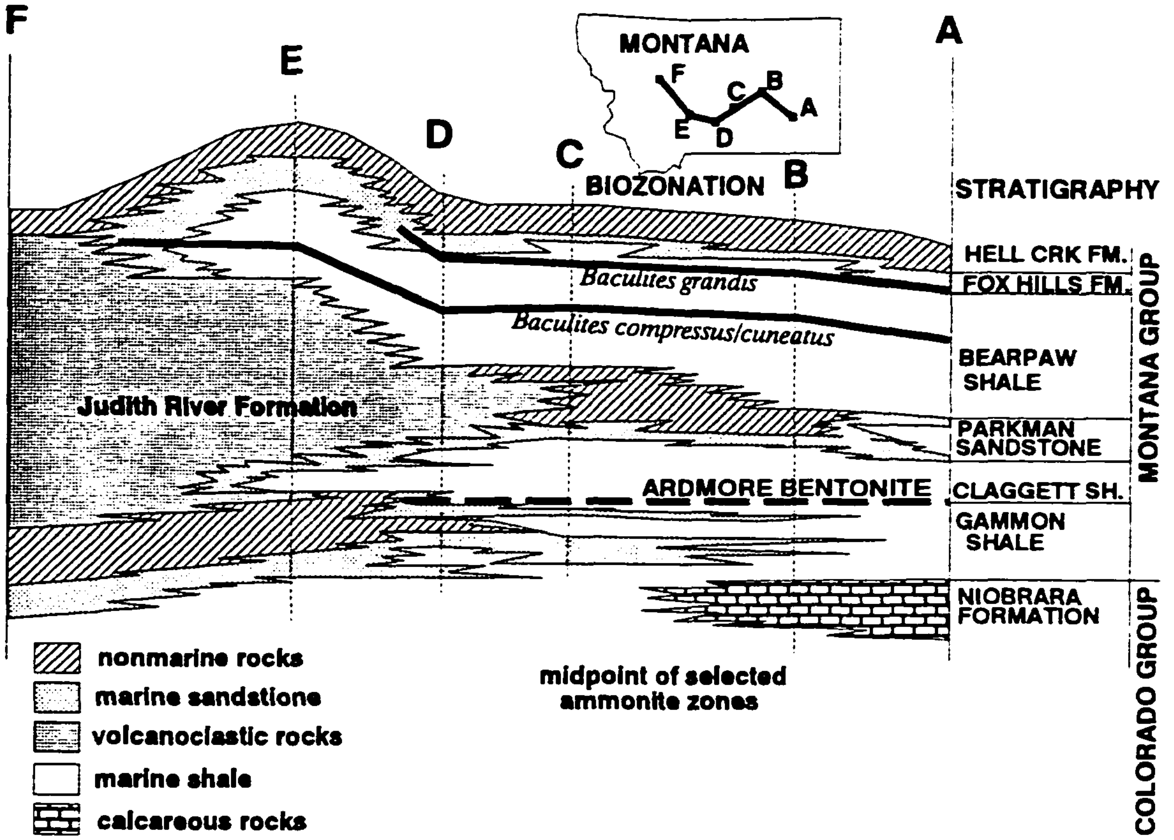


Fig. 5. A cross-section showing Late Cretaceous units through eastern and central Montana showing facies relationships sb3T

integrated into interpretations of global eustatic changes in sea level (sequence stratigraphy) by Haq et al., (1987) and specifically for the Campanian/Maastrichtian interval in Europe and North America by Hancock (1993) (discussed in Chapter 10). Similar interpretations of sedimentary facies and their preserved fauna (biofacies) have been used to define models for transgression and regression in the Western Interior by Kauffman (1977), Sageman (1989), and Sageman et al., (1991). Batt (1987) used the distribution of ammonite fauna to map the transgression and regresssion of the Greenhorn Cycle in the Western Interior Seaway.

Cobban (1993) reviewed evidence for the general changes in ammonite populations in the seaway during Late Campanian through Early Maastrichtian time and demonstrates the value of integrating paleoecological reconstructions into basin history models. Cobban suggested that the evidence for global eustacy is supported by the patterns and distributions of ammonites in the seaway; his discussion is summarized as follows.

Both ammonites and inoceramids flourished in the seaway, with one lineage being replaced by another with each passing transgressive-regressive cycle. According to Cobban (1993) during high stands in sea level Tethyan species were able to migrate northward into the central portion of the seaway from the Gulf region. These species competed with and/or replaced endemic species; through time many of these migrants would, in turn, become endemic. Endemic stocks of heteromorphic ammonites, particularly baculites and scaphites, dominate a majority of Cobban's zones. During lowstanding seas these communities would be stressed by declining habitat space and destabilizing climatic conditions as a result of the reduced volume of water in the seaway. Falls in sea level probably reduced marine circulation, changed and isolated habitats, and possibly increased the effects of catastrophic climatic and weather events. Those species that survived would become the endemic host of the next transgression.

Cobban (1993) stated that during the Middle Campanian migrants from the north, including *Hoploscaphites*, migrated into in the seaway and thrived in the study area for the remainder of the Campanian into the Maastrichtian. He suggested that there was a break in lineage continuity in baculites populations when the lineage ending with *Baculites eliasi* vanished and was replaced by a lineage starting with *Baculites baculus*. This break corresponds closely with models for a major lowstand in sea level near the end of Campanian time reported by Haq et al., (1987), with additional confirmation by Hancock (1993). Using Gill & Cobban's (1973) data for Montana, Hancock concluded that the peak transgressions associated with highstanding seas occurred in Late Campanian time within the Zone of *Baculites cuneatus*, and again in Early Maastrichtian time within the Zone of *Baculites clinolobatus*.

Cobban (1993) described a Campanian endemic center encompassing the region surrounding north-central Colorado. He described this endemic center as a region of greatest diversity and abundance of ammonite genera, and that this endemic center persisted throughout Campanian time with the greatest regional extent occurring during *Baculites compressus* time - probably during a period of high seas. He reported that the greatest diversity of ammonites occurred during *Baculites reesidei* time, and that the endemic center vanished before *Baculites jenseni* time; probably during progressive regression concurrent to a fall in sea level.

Winn, Bishop & Gardner (1987) suggested that sea level rose again during *Baculites eliasi* time to progressively higher levels culminating during *Baculites grandis* time, after which the seas began to progressively recede from their central Wyoming study area region during *Baculites clinolobatus* time. Cobban (1993) suggested that during this Early Maastrichtian interval ammonite genera diversity did not recover to Campanian levels probably because southern migration pathways were blocked by regional regression in the northern and western Texas region. He reported that three genera of ammonites, *Baculites*, *Hoploscaphites*, and *Sphenodiscus* persisted in the study area through the zones of *Baculites baculus* to *Baculites clinolobatus*. Gill & Cobban (1973) interpreted that a regression at the end *Baculites clinolobatus* time was rapid across Wyoming and Montana in association with the progradation of the Sheridan Delta into northwestern South Dakota.

# CHAPTER 3

## GEOLOGIC SETTING

Soil and alluvium formed from the weathering of Pierre Shale and Fox Hills formations represent the surface cover for most of the study area in the Western Interior region surrounding the Black Hills. Fig. 6 is a digital elevation model (DEM) of the study area that depicts the general geography of the region and shows the location of major field localities. The Black Hills uplift stands out in the lower left; vertical exaggeration of the topography on the DEM highlights the valleys of the Missouri River and its eastward flowing tributaries: the Grand, Moreau, Belle Fourche, Cheyenne, and White rivers (north to south, respectively). Beyond the immediate vicinity of the Black Hills the strata are generally flat-lying. Numerous faults and anticlinal structures in the region are not apparent in the image.

Fig. 7 is a generalized geologic map of the study area that emphasizes the outcrop region of the Pierre Shale and Fox Hills formations; on the map the interval of specific interest follows the boundary between the two formations. Fresh exposures of the study interval are scarce. Generally, exposures occur along cut banks of streams, gullies along steep hill slopes, landslide escarpments, and fresh

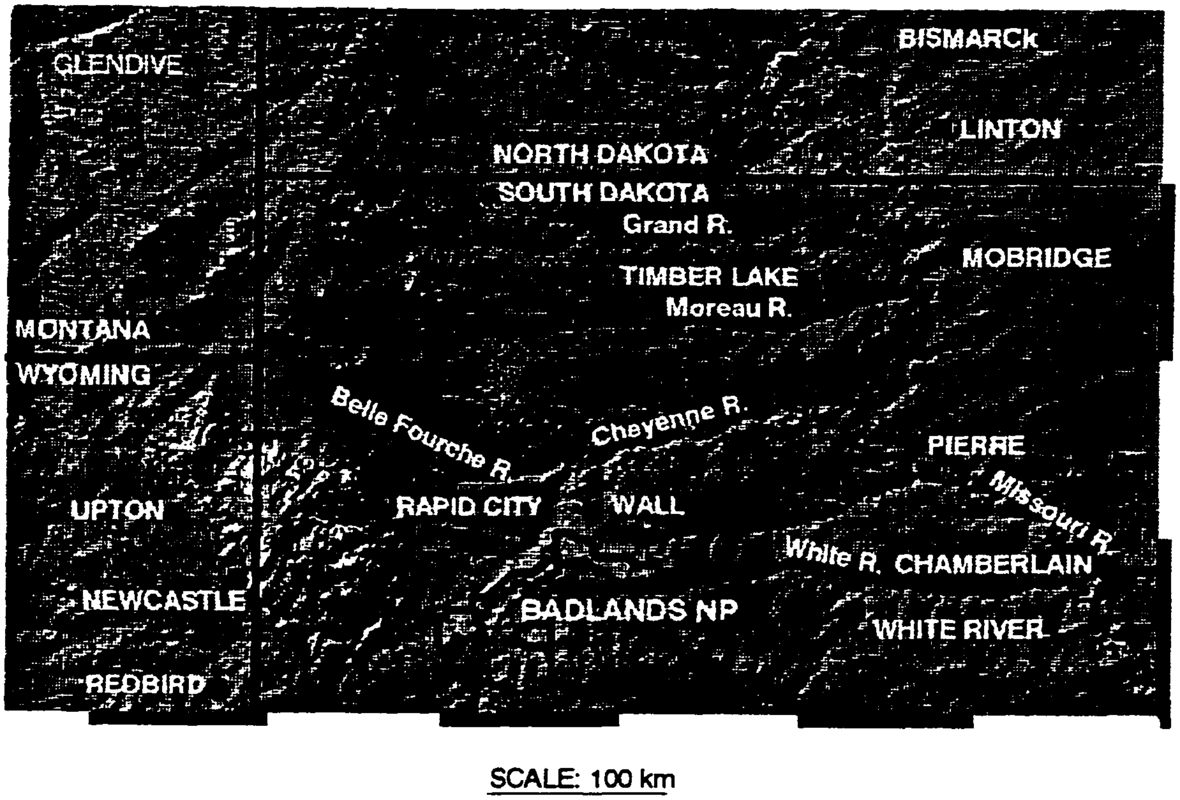


Fig. 6. Digital elevation model of the study area region including the location of important field localities. (DEM was generated using AGI, 1995, *Portrait USA*, CD-ROM).

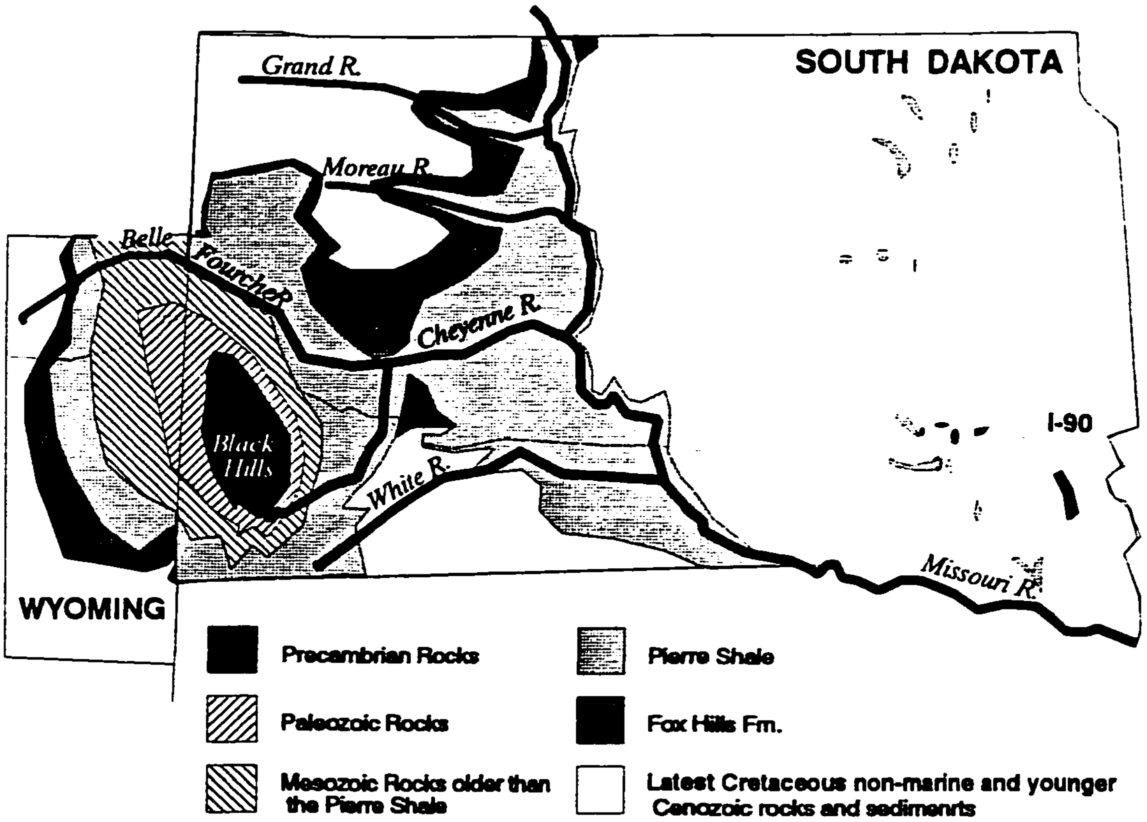
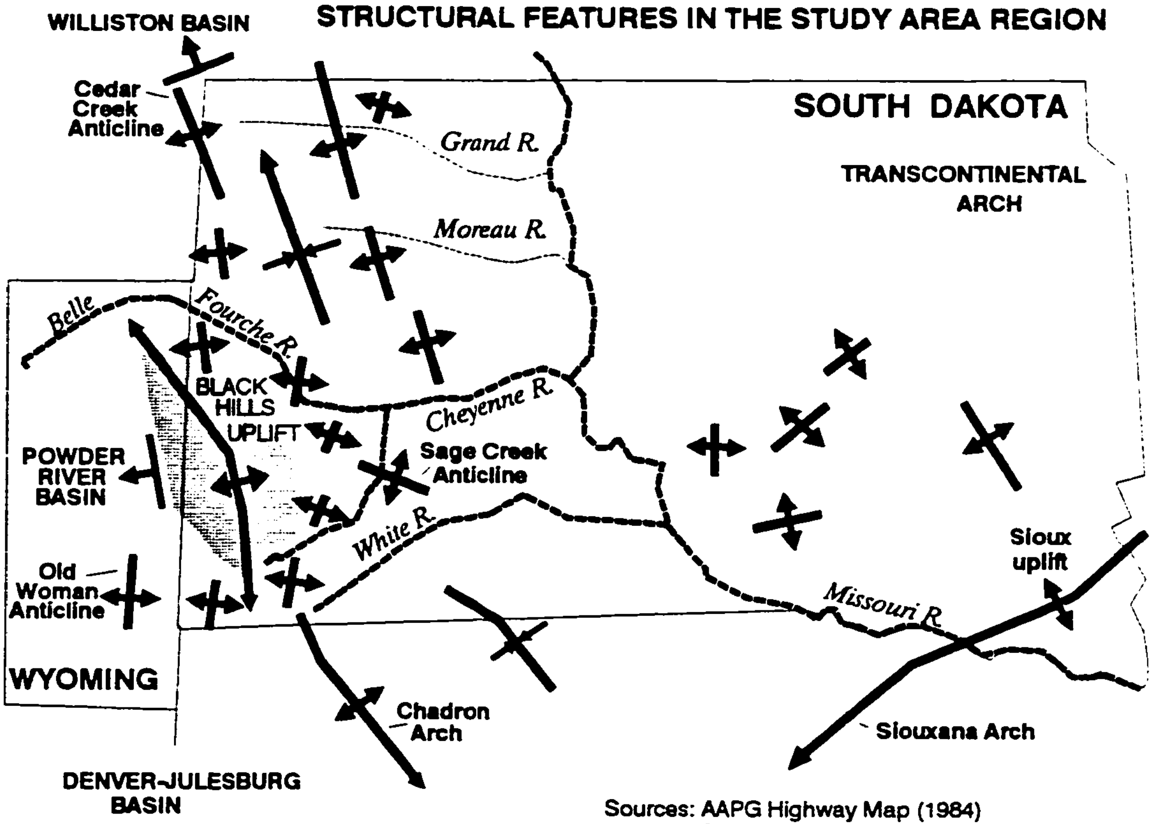


Fig. 7. Generalized geologic map of the study area.

road cuts. Field work is hindered by the great distances between exposures, the lack of access roads, weather extremes during the summer, and by private land ownership. The 1952 *Geologic Map of South Dakota* shows several large northwest-trending anticlines and synclines on the north and east side of the Black Hills in the region around the confluence of the Cheyenne and Belle Fourche rivers. These structures plunge northward into the Williston Basin. A generalized map showing the occurrence of major anticlines, synclines, uplifts, and basins in the region is illustrated in Fig. 8. These structures were not investigated in the course of this field work. However, small east-to-west trending faults and folds were noted throughout the Badlands field area. This includes the complex fault and anticline system long associated with the Badlands Escarpment throughout the North Unit of Badlands National Park, and referred to by Raymond & King (1976) as the Sage Creek anticline/fault system. Structures in the region have been interpreted as being associated with basement blocks and structures which probably initially formed during Precambrian time and have been reactivated episodically throughout Phanerozoic time to the present (Shurr, Hammond & Bretz, 1994).

The formation of Western Interior Basin is attributed to the compressional thrust sheet-loading of the western continental foreland margin associated with the Sevier Orogeny throughout Early and Late Cretaceous time (McGookey et al., 1972). Basin subsidence is attributed to isostatic adjustment related to both the uplift of the



Sources: AAPG Highway Map (1984)
Geologic Map of South Dakota (1952)

Fig. 8. Generalized map of the location of anticlines, synclines, uplifts, and basins in the study area region.

Western Cordilleran ranges and to the sediment and marine water loading, especially along the western margin of the seaway (McGookey et al., 1972; Shurr et al., 1994). This accounts for the asymmetric geometry of the sedimentary sequences across the basin (Gill & Cobban, 1973) (Fig. 9). Whereas the seaway extended eastward from the Cordilleran region to a generally unknown shoreline area in the western Mississippi Valley region, the depositional axis of the basin extended generally north to south in the vicinity of central Wyoming. This lopsided geometry is significant to the influences of both eustatic changes in sea level and regional tectonism on sedimentation in the basin. Whereas the study area in eastern Wyoming and western South Dakota may have been in the geographic central portion of the seaway, stratigraphically it should be considered on the eastern margin of the seaway because it lies in the region of relatively thin sediment accumulation (Shurr, Ludvigson, & Hammond, 1994). Within the central and eastern portion of the basin, sedimentation was perhaps influenced by proximity to, and contemporaneous activity of, local faults and folds.

The location of the deepest water in the seaway constantly shifted as tectonism and eustacy influenced sedimentation in the seaway probably for each of the great sedimentation cycles (Greenhorn, Claggett, Bearpaw, etc.). On a large scale, sedimentation patterns in the basin depended on the geometric characteristics of the seaway (particularly the maximum extent of transgression and the extent of restriction

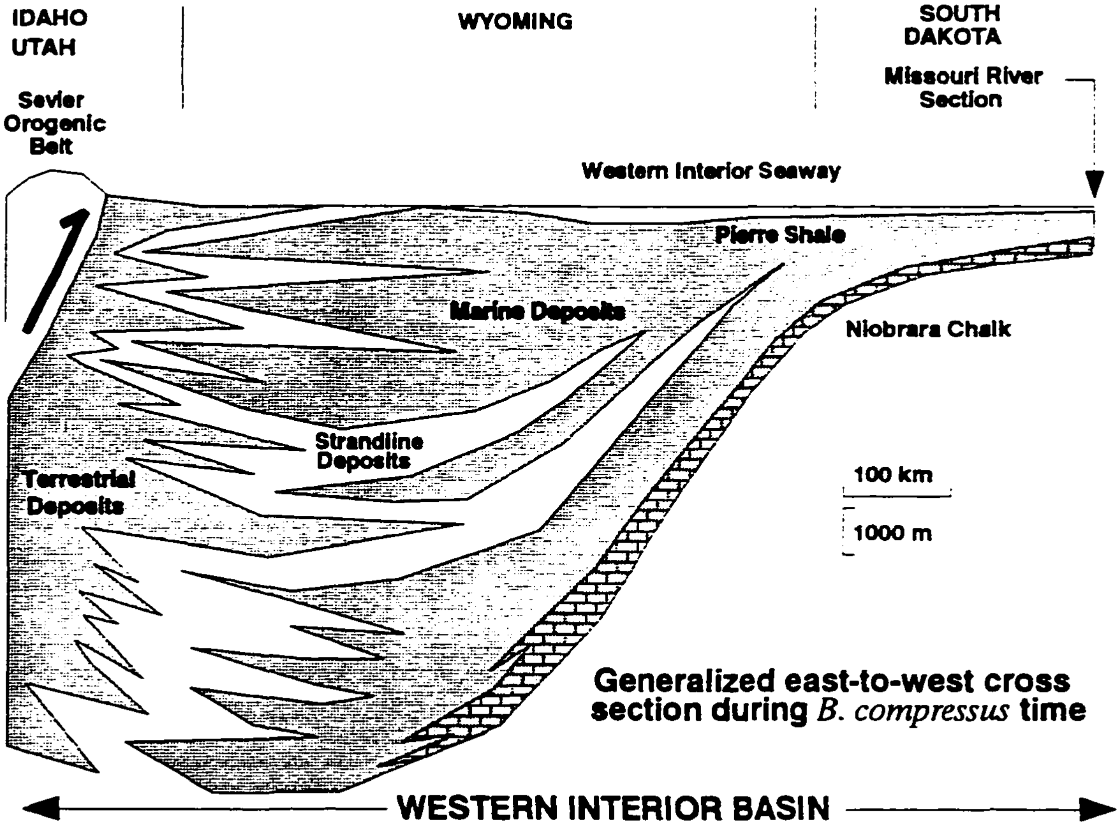


Fig. 9. East-west cross section across the Western Interior region illustrating the general geometry of the Western Interior Basin during the Late Cretaceous (after Gill & Cobban, 1973).

of marine circulation from both the Arctic Ocean and Gulf of Mexico), the location of river sediment sources (with prograding deltaic clinoforms) along the western margin of the seaway, and on the general counter-clockwise circulation patterns within the seaway (Wright, 1987; Roehler, 1990; Roehler, 1993). Turbidity current-style sedimentation is quite apparent in the Cretaceous shales deposited in deeper water settings in the western portion of the basin (Winn, Bishop, & Gardiner, 1987).

The relationship of different water depths to sedimentological characteristics of depositional environments is apparent in the stratigraphy of the eastern basin. For instance, deeper water facies are represented by black, organic-rich shales lacking benthic fauna. Examples are the Gammon Shale and the Sharon Springs Member of the Pierre Shale (Gill & Cobban, 1966). Intermediate depths are represented by gray silty shales displaying a restricted benthic fauna and bioturbation. Examples are portions of the Degrey and Verendrye members of the Pierre Shale along the Missouri River (Crandall, 1958). Sediments deposited in shallow water characteristically preserve a more diverse benthic fauna because of higher oxygenation conditions and nutrient availability; they also may display sedimentological characteristics of nearshore depositional environments. Examples of shallow water facies (by comparison with the units mentioned above) include the Trail City and Timber Lake members of the Fox Hills near Timber Lake, South Dakota (Waage, 1968; Carpenter et al., 1988).

The relationships between transgression and regression and the occurrence of unconformities and sedimentary facies are well defined within the framework of sequence stratigraphy (Haq, 1987; Vail, 1987; Friedman et al., 1992). Oil and gas exploration efforts in the Gulf and Atlantic coastal plain and continental shelf have provided a generous volume of literature describing the influence of eustatic changes in sea level and local and regional tectonism on the occurrence of unconformities and sedimentary facies (Grow & Sheridan, 1986; Klitgord & Hutchinson, 1986; Olsson et al., 1986). However, details of the sequence stratigraphy of the Pierre Shale and Fox Hills formations east of the Black Hills are unclear. Gill & Cobban (1973) mapped the shoreline transgression along the western margin of the seaway as having begun in Late Campanian time (during *Baculites compressus* time); it reached its maximum westward transgression in Early Maastrichtian time (during *Baculites baculus* time). Regression followed until the seaway possibly vanished from the region following the deposition of the Fox Hills Formation during Middle Maastrichtian time. However, the occurrence of unconformities within the section have been postulated; the Pierre Shale section has been described as thinner in the Badlands region compared to sections on the western flank of the Black Hills or along the Missouri River (W. A. Cobban, personal communication, 1995). The influence of tectonism associated with the Late Cretaceous Laramide Orogeny on sedimentation patterns in the Western Interior basin is fairly well known for regions west of the Black Hills (Keefer, 1965;

Gill & Cobban, 1973; Winn, Gardner, & Bishop, 1987; Roehler, 1993), but is unclear for the region east of the Black Hills.

Paleoecological consideration of relatively abundant preserved molluskan faunas and trace fossils is critical to deciphering facies relationships in the Western Interior Seaway. Kauffman (1977) and Kauffman & Sageman (1990) provide interpretations of sedimentary facies relationships with respect to shelled macrofauna for the Greenhorn and Niobrara cycles in the seaway. They demonstrated that benthic and pelagic organisms tolerated specific ranges of a variety of ecological factors within the seaway, including oxygen availability, water depth, turbidity, and sedimentation rates. They suggested that the occurrence of communities of shelled fauna could be used in conjunction with sedimentological analyses for more detailed paleoenvironmental interpretation. Following Kauffman's biofacies model, Batt (1987) used ammonite and planktonic foraminifera to interpret pelagic biofacies during transgression and regression in the Greenhorn Cycle of the Western Interior Seaway. Savrda & Bottjer (1989) demonstrated that trace fossil assemblages could provide detail in relation to oxygen availability and sedimentation rates on the scale of individual beds or horizons.

Perhaps a significant factor for moving sediments onto the eastern margin of the seaway might have been the episodic occurrence of giant storms in the seaway region. Studies of the aftermath of Hurricane Camille in the Gulf (Morton, 1988), and the dramatic effects of Hurricane Hugo, Hurricane Andrew, and numerous "Nor'easters" on the Atlantic Coast on the nearshore and shallow shelf demonstrate the magnitude of sediment transport processes involved in tropical and extratropical storms. The occurrence of fossiliferous horizons in the Trail City Member of the Fox Hills Formation have been interpreted as having formed when storm currents moved vast quantities of sediments from the margins of the seaway and smothered biological communities inhabiting both the water column and the substrate (Waage, 1964; Waage, 1968; Carpenter et al., 1988). They suggest that the occurrence of fossiliferous shell beds (preserved in laterally continuous concretion horizons) were a result of rapid kill events associated with episodic floods during the accumulation of sediments of the Fox Hills Formation. Biological communities that inhabited the study area portion of the seaway were subjected to rapidly-changing conditions during storms and, possibly, to restrictive hypoxic conditions related to thermohaline-style stratification in the seaway during periods of drought (Hallam, 1977; Wright, 1987; Savrda & Bottjer, 1989; Jewell, 1993).

Long-term climatic conditions (in the order of thousands, hundreds of thousands, or millions of years) must have also controlled sediment accumulation rates and dispersion patterns in the seaway. The link between the rise and fall of sea level and the change from wet to dry, or from warm to cold climate conditions in the greater Western Interior region during Campanian to Maastrichtian time may eventually be established. For instance, Jerzykiewicz & Sweet (1988) interpreted cycles of transgression and regression from outcrops of Campanian and Maastrichtian formations along the eastern Canadian Rockies. Their interpretations suggest that regional climate influenced sedimentation along the western margin of the seaway, resulting in the accumulation of coal swamps during wet periods, and caliche-bearing alluvial coastal plain deposits during dry periods. Interpretations of long-term climatic patterns might also be applied to the upper Pierre Shale in the South Dakota region. Mello (1969) demonstrated that calcareous foraminifera are abundant in the calcareous Mobridge Member of the Pierre Shale, yet are rare or replaced by siliceous forms (in greatly reduced abundance) in the overlying non-calcareous Elk Butte Member. Whether the transition between the Mobridge and Elk Butte members is a reflection of regional climate change or a taphonomic artifact remains unclear, but may be better resolved by further investigation. The relationship of sea level change to long-term regional climate patterns in the seaway region during the Late Cretaceous will probably be demonstrated. It is evident that when the seas finally completely withdrew from the region in mid-Tertiary time that the climate became drastically drier.

# CHAPTER 4

## RESEARCH METHODS

The spectrum of paleontological, sedimentological and geochemical procedures detailed in this section were used at different stages of this research. This section presents a short chronological record of the progress of this study. In addition, laboratory procedures used for sample preparation and measurement are outlined.

### 4.1 FIELD INVESTIGATIONS

Field work was conducted over the course of three summers. During the summer of 1994 a month of field reconnaissance was accomplished involving examination of numerous exposures of Late Cretaceous sedimentary strata in New Mexico, Utah, Colorado, Wyoming, South Dakota, and Montana. The focus of this field season was to gather information about the occurrence of fossiliferous concretions throughout the Western Interior region, to collect representative ammonite specimens for addition to the collections of the American Museum of Natural History, and to take photographs and make qualitative descriptions of each field locality. It was at the end of this field season that the upper Pierre Shale in central western South

Dakota was chosen as the topic of dissertation research for several reasons. The interval yields abundant fossils in most locations visited; numerous exposures of the interval existed on public lands; and preliminary literature review demonstrated that, unlike other regions in the Western Interior and Rocky Mountains, there are not any detailed, previously-published investigations for the upper Pierre Shale in central-western South Dakota.

Preparation for the second field season involved first conducting an extensive literature review on the Pierre Shale, the Western Interior Basin and Seaway, on Late Cretaceous paleontology and paleogeography, and on the sedimentology and geochemistry of shale and concretions. Preliminary isotope geochemical analyses were conducted on selected shell and concretion matrix samples collected in the previous year.

The second field season (conducted during the summer of 1995) involved six weeks of travel throughout the field area. Fieldwork was conducted with the following agenda:

1. To locate outcrops on public land (or private land where permitted) where "fresh" shale was exposed;
2. To scour the outcrops for fossils, particularly those in-situ;
3. To establish reference locations using both topographic map (township,

range, and section) and geographic longitude and latitude using a hand-operated global positioning system (GPS);

4. To collect core samples, noting details of the lithology in a field notebook;
5. To photograph outcrop exposures;
6. To trace outcrop exposures from one stream valley to the next.

Field observations began in Niobrara State Park in northern Nebraska. Stratigraphic observations were made along river bank exposures and roadside outcrops along the Missouri River northward to the vicinity of Pierre, South Dakota. Near Pierre exposures described by Crandall (1958) representing the middle and upper Pierre Shale were examined. Afterward, these stratigraphic exposures were traced northward along the Missouri River and along the shores of Lake Oahe Reservoir to the Mobridge, South Dakota area. Core sampling began in the Mobridge area in accessible locations close to the original localities used by Searight (1937). As noted earlier, Searight's exposures no longer exist due to the abandonment of road and railroad cuts, and overgrowth of the original localities. One of the type localities for the Pierre Shale/Fox Hills Formation boundary near Linton, North Dakota (Daly, 1991) was also examined.

After sections were measured and sampled in the Mobridge and Timber Lake, South Dakota areas, the stratigraphy was followed across the Cheyenne River Indian

Reservation (where sampling and fossil collecting were not permitted). Sampling and collection of fossils resumed to the south of the reservation in the Cheyenne River Valley and the Badlands National Park region where four weeks were spent for this purpose. Sampling and field collecting focused on exceptional stream cut exposures in the Sage Creek Campground area (Badlands National Park, North Unit), the Cedar Creek area (Badlands National Park, South [Stronghold] Unit), and along the Cheyenne River north of Wasta, South Dakota on the land of Tom Trask Ranch. Two weeks were spent collecting and coring the study interval on public lands in the Osage Oil Field and the Mush Creek Oil Field in Weston County, Wyoming.

During the fall and spring semesters fossils were catalogued, and sediment core samples were processed and analyzed for sedimentological and geochemical data using in-house and commercial services outlined below.

Field work conducted during the summer of 1996 involved a return to the Badlands National Park region to gather more detailed field data and to collect more fossils from field localities throughout the Sage Creek Wilderness Area. Additional sites were investigated in the national park and on the Buffalo Gap National Grasslands. In addition, permission to examine outcrops on private ranch property along the Cheyenne River valley between Wall and Cherry Creek, South Dakota was granted. Field investigations focused on making detailed descriptions of outcrop exposures in relation to ammonite biozones and to lithological variations using data from the previous year's investigation as reference. Field study involved collecting fossils; measuring sections with a Jacob Staff, a Global Positioning System unit, and hand-operated altimeter; and recording images with both photographic and digital cameras.

Parameters of interest in field work include the location of bentonite beds, concretion-bearing horizons, changes in color, texture, grain-size, mineralogical properties, bedding structures, unconformities, structural features, fossils, and trace fossils. The specific location data for shale samples, concretion samples, and fossil specimens were recorded. Additional detail regarding field locality descriptions is presented in Field Investigations section (Chapter 6).

Field work during the summer of 1997 involved a return to Badlands National Park on a field mapping expedition supported by a U.S. Geological Survey EDMAP Grant with the mission to generate a revised map of the Sage Creek Wilderness Area with detailed stratigraphic revisions. Three weeks of field work were conducted in cooperation with a Dennis Terry, a graduate student from the University of Nebraska who is a specialist on the White River Group. Field investigations yielded new data about the structures associated with the Sage Creek anticline/fault system and added confirmation and revisions to previously investigated areas of the park area.

## 4.2 PALEONTOLOGICAL ASSESSMENT

Stratigraphic positioning in the field was conducted primarily using William Cobban's ammonite biozonation (Gill & Cobban, 1966; Scott & Cobban, 1986) in conjunction with the field experiences of Neil Landman of the American Museum of Natural History, New York, and John Chamberlain of Brooklyn College, City University of New York. Bulk samples of ammonite fossils were collected from localities where sections were measured primarily for reference purposes. When possible, fossils were gathered for later identification. Assessment of the abundance and diversity of fossils and trace fossils were limited to qualitative judgements (i.e., absent, scarce, common, very abundant) after Savrda & Bottger (1989). Representative specimens are described in the Paleontology section (Chapter 5) of this dissertation. Ammonite zones are charted on stratigraphic columnar sections in the Regional Correlation section (Chapter 8).

## 4.3 GEOCHEMICAL AND SEDIMENTOLOGICAL ANALYSES

Petrographic and geochemical analyses were conducted to evaluate the changing conditions of the substrate associated with concretion-bearing horizons, as well as to help evaluate compositional changes through each section. Cored shale samples were collected and processed as follows:

I. Cores were collected using a portable hand-operated sediment coring device (Forestry Suppliers, Inc., Model #78324). This mechanism captures a ±500g sample in a six-inch long butyrate plastic tube. A summary of the proceedure follows:

a. For every chosen field location, a reference spot was located using a map and GPS receiver (limited to 50 meter resolution). Sites were chosen near landmarks so that they could be found easily again later. Landmarks included such features as the axis of a stream meander, or a USGS benchmark, both which are useful as elevation references.

b. Elevation above (or below) reference was measured using a "Jacob staff" (painted on a shovel handle); elevations were compared with readings from a hand-held altimeter and topographic maps.

c. Sample locations were selected on the basis of visual inspection of the outcrop. One to two feet of soil and weathered shale overburden were removed until a "fresh-appearing" exposure was encountered. If "fresh" shale was not encountered the hole was abandoned.

d. A clean plastic tube was inserted into the coring barrel and hammered into the outcrop. The hammering of the core proceeded until progress stopped, indicating that shale had come in contact with the end of the core barrel. One or two firm reverse jerks removed the core tool from the ground.

e. The tubes were removed from the coring tool, sealed, and oriented stratigraphically using with color-coded caps. The coring tool was then wiped clean to prepare for the next sample.

f. Labels were fixed to each tube and were provided with a sample identification numbers. Notes regarding each sample were written on each label and in a field notebook. Notes included observations of the placement of a core in relation to observed lithologic boundaries (i.e., bentonite beds, concretion horizons, etc.); distance from the previous core and the base of the section; relation to fossil sample bags collected; ammonite zone; locality; date; GPS coordinates; and township & range location information from topographic maps. This information is recorded in Appendix A.

II. In the lab, each core was examined before being processed. Visual examination of sediment through the clear butyrate plastic core tube allowed for qualitative judgements of:

a. bedding lamination character and thickness (i.e., no lamination, 1mm thick/even lamination, 2 mm thick/uneven lamination, etc.), and;

b. degree of bioturbation (i.e., none, trace, abundant, very abundant).

This information is recorded in Appendix B. A portion of each sample was placed in a small glass beaker and dried for step III. The remainder of the sample was placed in a washed coffee can and oven dried for step IV.

III. Whole rock and trace element analyses:

a. A ±15 gram sample of dried shale was crushed in a ceramic mortar and pestle. (Mortars and pestles were washed and oven dried after grinding each sample.)

b. The crushed sample was dry sieved through a 125$\mu$m mesh. (Sieve was washed and oven dried after grinding each sample.)

c. Powdered sample was assigned a numeric code for color (intensity, hue, and saturation) compared to a GSA standard color chart.

d. 10 grams of powder from each sample was sent to XRAL Laboratories (Toronto, Canada) for whole rock analysis. X-ray fluorescence techniques were used to determine the standard elemental composition for the following:

> Major elements: $SiO_2$, $Al_2O_3$, CaO, MgO, $Na_2O$, $K_2O$, $Fe_2O_3$, MnO, $Cr_2O_3$, $P_2O_5$, $TiO_2$, loss on ignition (lower reporting limit: 0.01%),
>
> Trace elements: Ba, Nb, Rb, Sr, Y, Zr (detection limit: 10 ppm; Ba - 50 ppm).

Eighty-three out of one hundred and twenty cores collected were chosen for geochemical analyses based on visual inspection judgement; if a core appeared weathered, or if it contained roots or fracture fillings that could not be removed from the sample, then it was rejected for geochemical analysis. Elements of primary interest were silicon, aluminum, iron, calcium, and carbon due to their significance as major rock-forming elements. Loss on ignition (LOI) was substituted for carbon in dried samples because carbon cannot be measured with X-ray diffraction method used by XRAL Laboratories. Summaries of geochemical data are graphically presented in the Sedimentary Geology section (Chapter 9). Tabulation of full results of geochemical analyses reported in standard whole rock percentages ($SiO_2$,

$Al_2O_3$, $Fe_2O_3$, CaO, etc.) and parts-per-million for selected trace elements are included in Appendix E.

IV. Sedimentological analyses:

All core samples collected were prepared for sedimentological analyses. The methods used in the laboratory were as follows:

a. 250 grams of dried shale was soaked in a solution containing washing soda for three days to allow the sample to unconsolidate.

b. The wet sample was then washed through a stack of sieves containing 1000$\mu$m, 500$\mu$m, 250$\mu$m, and 63$\mu$m mesh (sieve numbers 18, 35, 60, and 230, respectively). Water washing of each sample proceeded until no visible fine fractions were noted in the wash.

c. Sieved fractions were placed in individual petri dishes and allow to air dry for 3 days.

d. Each petri dish sample was weighed and placed in sample envelope for later inspection (step V).

e. Weight percent of each sieve fraction was calculated against original 250g weight.

V. Fractions were inspected for general characteristics of each of the sieve fractions (1000$\mu$m, 500$\mu$m, 250$\mu$m, and 63$\mu$m). Three-hundred point counts were conducted on each 250mm sample for mineralogical content (i.e., quartz grains, feldspar, mica, chert, phosphate, glauconite, organic matter, calcite grains, fossil fragments, microfossils, pelloids, etc.). Tabulation of data from sieve analyses is included in the Appendix C. Data from point count tabulations are presented in Appendix D. A summary of sieve fraction data and sand content characteristics of the 250$\mu$m fraction are presented in the Sedimentary Geology section (Chapter 9).

VII. Samples of ammonite shells were tested for strontium isotope ratios for geochronology evaluation. Information from selected samples are included in the Geochronology section (Chapter 7). Samples of concretions, baculite shells, and bivalve shells from the *Baculites eliasi, Baculites grandis,* and *Baculites clinolobatus* zones were analyzed for stable isotopes of carbon and oxygen. This data is presented in the Sedimentary Geology section (Chapter 9). All samples tested for isotopic information were analyzed by Krueger Enterprises, Inc., in Boston, Massachusetts.

# CHAPTER 5

## BIOZONATION

Regional stratigraphic correlation of the Pierre Shale and Fox Hills formations was accomplished primarily through the application of established ammonite range zone fossils. During the course of field mapping, when an ammonite fossil was found in place on an outcrop (and identified), observations were made about lithological characteristics (such as sediment color, texture, bentonite beds, concretions, other shelled fauna, etc.). With experience, ammonite ranges could be established in relation to the physical appearance of the encasing sediment on reference outcrops. This helped establish visual recognition for gross stratigraphic correlation throughout a greater area (and from one study area to the next).

Baculitid and scaphatid ammonites are by far the most abundant and easily recognizable (on a species level) of all fossils in the study interval. During the course of field investigations, however, other fossils also became important for correlation, particularly inoceramids and other bivalves, as well as chondricthyan teeth, arthropods, belemnites, coprolites, and trace fossils. All important fossils used for correlation are discussed and illustrated below.

### 5.1 Ammonite Biozonation

Ammonite fossils used in this investigation for biostratigraphic correlation within the upper Pierre Shale and Fox Hills formations are illustrated in Figs. 10-12. These fossils correspond to the established ammonite biozonation for the Western Interior (Cobban, 1993) with the two following exceptions. First, *Baculites corregatus*, shown in Fig. 11 occurs below the *Baculites compressus* Zone, and is therefore equivalent to the *Didymoceras cheyennense* Zone. Second, the smooth, compressed variant form of *Baculites clinolobatus* may possibly represent a different species from the larger, ribbed variant of *Baculites clinolobatus*. Ammonite biozonation of the Cretaceous sediment in the Western Interior is primarily due to the work of William A. Cobban, paleontologist emeritus of the U.S. Geological Survey. Gill & Cobban (1966) established ammonite biozonation for the upper Pierre Shale in the Redbird, Wyoming type section. Their selection of baculitid ammonites as primary fossils for the Western Interior region was strengthened with the publication of a series of U.S. Geological Survey maps, reports, and journal articles about the Rocky Mountains and Western Interior region [the most important for this discussion being: Gill & Cobban (1973); Scott & Cobban (1986); and Cobban (1993)]. Many additional studies of sedimentary formations of Campanian and Maastrichtian age and the geochronology of the Western Interior region are based on Cobban's ammonite biozonation including Bishop (1977); Perman (1988); Reiskind (1975); Roehler

**Western Interior ammonite zonation (Kennedy, Johnson, & Cobban, 1995).**

**Maastrichtian**

*Jeletzkeytes nebrascensis*
*Hoploscaphites nicolletii*
*Hoploscaphites birkelundi*
*Baculites clinolobatus*
*Baculites grandis*
*Baculites baculus*
*Baculites eliasi*

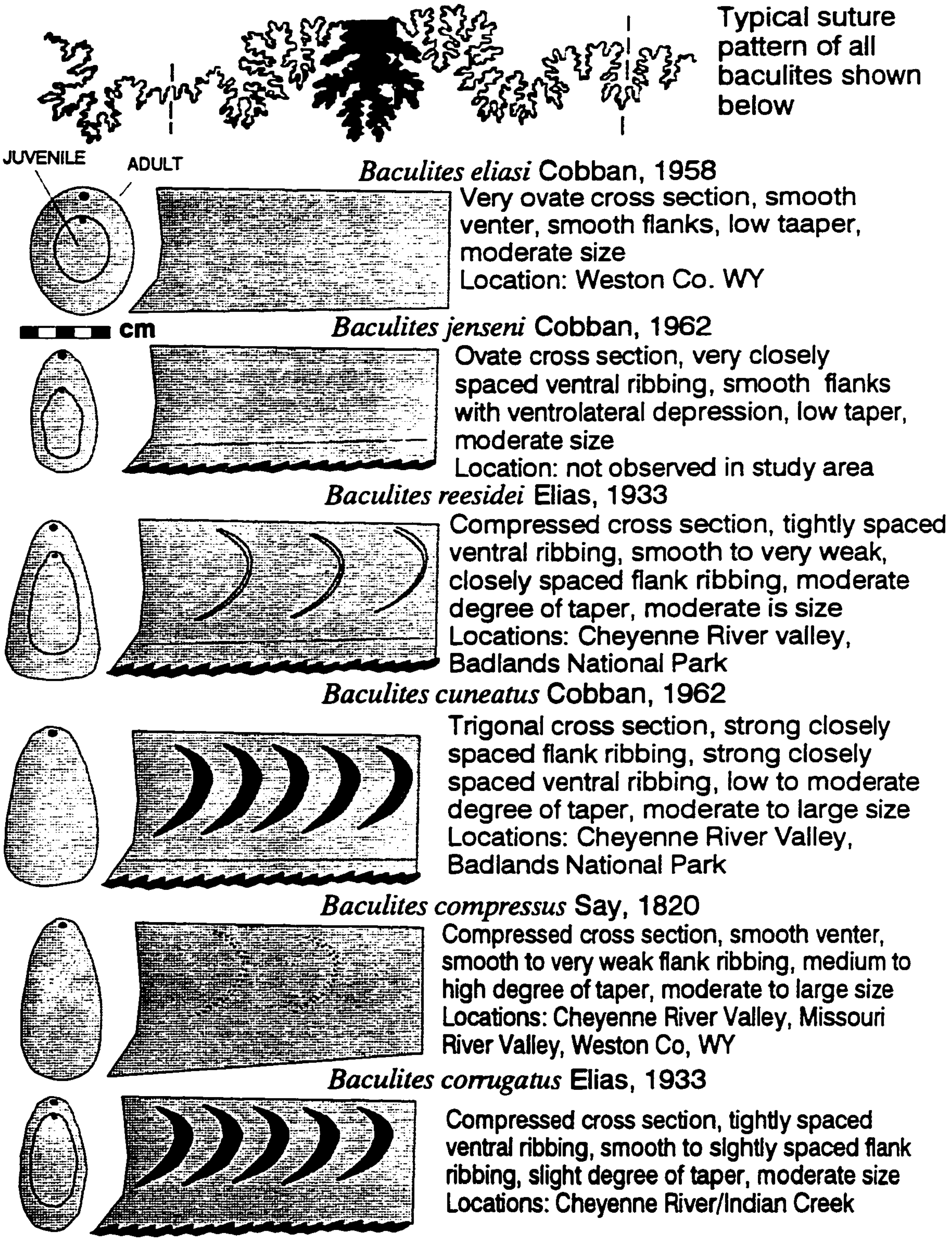
**Upper Campanian**

*Baculites jenseni*
*Baculites reesidei*
*Baculites cuneatus*
*Baculites compressus*
*Didymoceras cheyennense*
*Exiteloceras jenneyi*
*Didymoceras stevensoni*
*Didymoceras nebrascense*

*Didymoceras cheyennense* Meek & Hayden, 1854

Loosely coiled, spiraled phragmacone with a large J-shaped body chamber. Surface is covered with strong oblique ribbing displaying two sets of parallel ventrolateral tubercles on the outside edge of the whirl. Body chambers are round to slightly ovate in cross section, up to 10 cm in diameter. Locations observed: Indian Creek/Cheyenne River Valley

Fig. 10. Western Interior ammonite zonation (Kennedy, Johnson, & Cobban, 1995); and an illustration of *Didymoceras cheyennense* from the Pierre Shale (Late Campanian) (modified from Scott & Cobban, 1986).



Typical suture pattern of all baculites shown below

*Baculites eliasi* Cobban, 1958
Very ovate cross section, smooth venter, smooth flanks, low taaper, moderate size
Location: Weston Co. WY

*Baculites jenseni* Cobban, 1962
Ovate cross section, very closely spaced ventral ribbing, smooth flanks with ventrolateral depression, low taper, moderate size
Location: not observed in study area

*Baculites reesidei* Elias, 1933
Compressed cross section, tightly spaced ventral ribbing, smooth to very weak, closely spaced flank ribbing, moderate degree of taper, moderate is size
Locations: Cheyenne River valley, Badlands National Park

*Baculites cuneatus* Cobban, 1962
Trigonal cross section, strong closely spaced flank ribbing, strong closely spaced ventral ribbing, low to moderate degree of taper, moderate to large size
Locations: Cheyenne River Valley, Badlands National Park

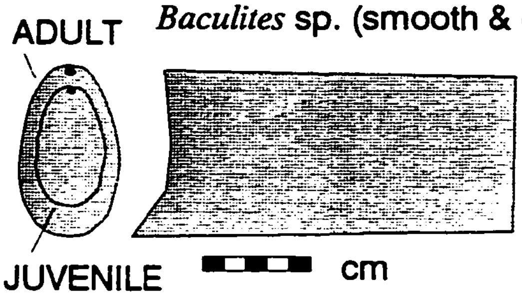
*Baculites compressus* Say, 1820
Compressed cross section, smooth venter, smooth to very weak flank ribbing, medium to high degree of taper, moderate to large size
Locations: Cheyenne River Valley, Missouri River Valley, Weston Co, WY

*Baculites corrugatus* Elias, 1933
Compressed cross section, tightly spaced ventral ribbing, smooth to slghtly spaced flank ribbing, slight degree of taper, moderate size
Locations: Cheyenne River/Indian Creek

Fig. 11. Baculitid ammonites from the Pierre Shale (Late Campanian to Earliest Maastrichtian) from the Western Interior (after Gill & Cobban, 1966; Scott & Cobban, 1986; and Larson et al., 1997). Location in the above descriptions refers to localities within the study area.

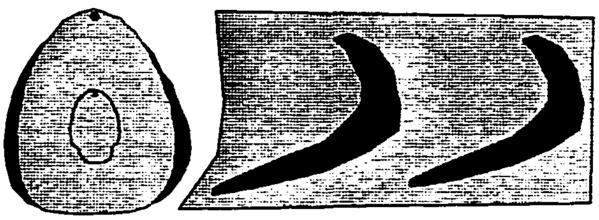
Typical suture pattern of the baculites shown below.

*Baculites* sp. (smooth & compressed variant of *B. clinobatus*)



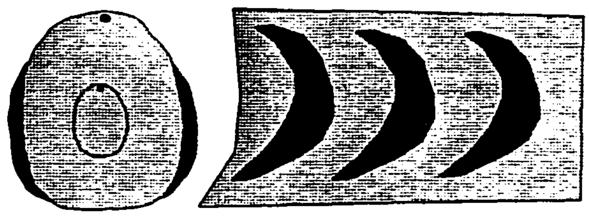
Compressed, eliptical cross section, smooth ventral side, smooth flanks, small to moderate size, found at top of *B. clinolobatus zone*
*Locations: Badlands National Park, Cheyenne River Valley*

*Baculites clinolobatus* Elias, 1933



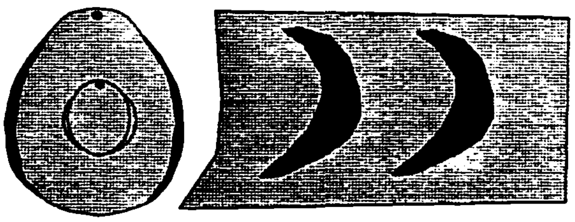
Eliptical to trigonal cross section, smooth to gently undulating ventral ribbing, smooth to deep undulating flank ribbing on large individuals, exaggerated arcuate cusps of flank ribbing, moderate to very large size
Locations: Weston Co., WY, Cheyenne River Valley, Badlands National Park, Missouri River Valley

*Baculites grandis* Hall & Meek, 1854



Ovate to trigonal cross section, smooth the broad ventral ribbing, smooth to highly developed flank ribbing on large individuals, low to moderate taper, large size
Locations: Weston Co., WY, Cheyenne River Valley, Badlands National Park, White River Valley, Missouri River Valley

*Baculites baculus* Meek & Hayden, 1861



Eliptical to circular cross section, smooth to bold venter ribbing, smooth to undulated flanks on large specimens, low taper, large size
Locations: Weston County, WY, Cheyenne River Valley, Badlands National Park, Missouri Valley

Fig. 12. Baculitid ammonites from the upper Pierre Shale (Early to Middle Maastrichtian) from the Western Interior (after Gill & Cobban, 1966; Scott & Cobban, 1986; and Larson et al., 1997). Location in the above descriptions refers to localities within the study area.

(1990); Roehler (1993); Baardsgaard et al., (1993); Hancock (1993); McArthur et al., (1993); and McArthur et al., (1994).

Identification of ammonites collected for this study was based on comparison with specimens from Gill & Cobban (1966); Scott & Cobban (1986); and, Landman & Waage (1993), and illustrations from the original published reports describing their species including Elias (1993); Cobban (1958); and, Cobban (1962). Larson et al., (1997) provided both descriptive illustrations and exceptional examples of baculites from the Western Interior region. Our study of ammonites began with the examination of identified specimens in collections at the Black Hill Institute of Geological Research, Inc. and the South Dakota School of Mines and Technology, Museum of Geology. This initial training in the identification of ammonite specimens was conducted during preliminary field investigations which included the company of Dr. Neil Landman (American Museum of Natural History) and Peter Larson (Black Hills Institute of Geologic Research).

Fossil identification on a species level required considerable trial and error during both field investigation and laboratory study of specimens. Species of baculites are identified by using gross observation of shell cross-section, the occurrence and character of ventral and/or flank ribbing on the surface of shells or casts, the general size of the shell, the suture pattern of the interval septa against the side of the phragmocone, and the taper angle of the shell. In general, large (adult) specimens are readily identifiable to the species level. Shell profile and external ribbing patterns tend to be most useful for purposes of identification and their characteristics are best developed in adult forms. Size, taper angle, and suture patterns are least useful because they tend to vary considerably from one specimen to the next, and nearly all specimens found tend to be incomplete or poorly preserved. William A. Cobban (personal communication, 1996) demonstrated the difficulty of identifying baculites. His method was to examine as many specimens as possible from a particular locality before establishing a species name. This is because most specimens are usually weathered fragments, body chamber casts, or immature specimens, and a large sample in size increases confidence in species designations. However, easy to identify, high quality specimens were abundant in certain horizons, particularly *Baculites compressus* and *Baculites cuneatus* in the Badlands National Park area, *Baculites eliasi* in the Osage Oil Field, Wyoming area, and *Baculites grandis* and *Baculites clinolobatus* practically everywhere in the region.

No fossils were found in the Fox Hills Formation in the Wyoming localities. Several specimens of the genus *Hoploscaphites* were found in Badlands National Park and in sections along the Cheyenne River. These scaphites are very similar in appearance to the Pierre/Fox Hills-type species *Hoploscaphites birkelundi* and were collected from the top or above the *Baculites clinolobatus* Zone. Many partial body chambers and phragmocones were observed in this interval, and probably represent several different species. The Fox Hills Formation and its fauna in the type area of Corson County, South Dakota are described by Waage (1964); Waage (1968), Carpenter et al., (1988); and perhaps most thoroughly described by Landman & Waage (1993).

In several localities zone fossils appeared to be mixed, raising questions about definitions of ammonite range zones (biozones). For example, in the Sage Creek area of Badlands National Park, specimens representing both *Baculites compressus* and *Baculites cuneatus* were found together, sometimes in the same concretion. In most field sections described in the next section of this report, these zones are shown to be overlapping. This was the case for most biozone boundaries. In addition, specimens of *Baculites grandis* are virtually indistinguishable from *Baculites baculus (*the zone below) or *Baculites clinolobatus* (the zone above). In these cases, the zones are shown to encompass the interval where specimens were located that had greatest affinity towards one species. The greatest problem, however, came form identifying species that were completely out of place. These include specimens in "float," specimens in slumps, and specimens that were probably reworked from older deposits. This is best demonstrated by the occurrence of a specimen most resembling *Didymoceras cheyennense* from an interval above an unconformable surface amongst baculites that resembled immature *Baculites baculus* in the Cedar Creek locality in the South Unit of Badlands National Park. Our conclusion about this fossil was that the concretion that encased it had been reworked. The concretion was found partially broken with pieces already missing when it was dug out of the shale outcrop. Other concretions around the specimen also appeared to be reworked, having unusual orientations, and scattered throughout the outcrop rather than in laterally continuous beds more typical of concretion horizons.

Overlapping ranges of fossil species on the eastern flank of the Black Hills presents a problem of definition of ammonite range zones in the Western Interior. Methodology for the assignments of range zones by Gill & Cobban (1966) in the type area near Redbird, Wyoming was not described. However, the method used apparently involved the assignment of a stratigraphic interval to a particular range zone at the first occurrence of the species when to stratigraphic interval is measured from the bottom upward. Intervals that are barren of observed fossils above where an interval where species were noted were included in range zone upward to the first occurrence of the next species. This method of range assignment apparently works well in the type area near Redbird, however, where ranges of fossils overlap definition of a single range zone becomes unclear. In addition, inclusion of barren intervals is problematic where gross changes in lithology occur, possibly representing unconformable surfaces. The occurrence of reworked fossils is perhaps the greatest challenge to definition of zonal ranges on the eastern flank of the Black Hills. The discussion of the *Didymoceras* specimen above is one illustration. Baculites are commonly preserved as fragments of shells, possibly broken by predation, broken by current transport along the sea bottom, or broken by bioturbation. The possibility that shells were reworked by submarine or subaerial erosion is significant, particularly within intervals immediately above and including omission surfaces and unconformities.

The method of defining range zones used for biostratigraphic interpretation in this report is as follows. Measured stratigraphic sections (presented in Chapter 6) show the locations were fossils were noted in outcrop. With experience, it became evident which stratigraphic intervals would yield particular fossils. Interpretations about the ranges of fossils in relation to named lithologic units and boundaries are presented in the Regional Correlation section (Chapter 8). The assignment of the base of a range zone reflects a qualitative judgement of the probable lowest stratigraphic layer in which a fossil is likely to occur in a study locality. The top of the range zone reflects a qualitative judgement of the probable highest stratigraphic layer in which a fossil is likely to occur in a study locality. Prominent changes in lithology (possible unconformities or omission surfaces) above the last occurrence of a species in an area were used to indicate the top of a range zone. In this manner, barren intervals at the top of the section were not assigned biozonation, reflecting the possibility of a hiatus in deposition (an unconformity), and the problem that, without fossils, judgement about the age of the upper barren interval was at best conjectural.

## 5.2 Selected Fossils Illustrated

Figs. 13 to 26 are photographs of selected representative specimens that illustrate typical and important fossils collected during field reconnaissance in the Osage Oil Field area, Weston County, Wyoming, localities in Badlands National Park, and from other localities in South Dakota. Figs. 13-22 illustrate ammonite biozonation fossils (after Cobban, 1993, illustrated in chronological order on Fig. 10 and 11). Figs. 23-26 are supplementary illustrations which include important fossils and trace fossil also used for correlation and paleoenvironmental interpretation in this research. Information regarding the occurrence of fossils are noted within the descriptions of field localities in Chapter 6. Fossils beside ammonites were identified using Shimer & Shrock (1944) - *Index Fossils of North America*, Gill & Cobban (1966), Crandall (1958), Larson et al., (1997), and other popular fossil guides. Trace fossils were identified after Savrda & Bottjer (1989) and Maples & West (1992). Selected additional illustrations of fossils and trace fossils are included with descriptions of study localities in Chapter 6. Specimens with tagged identification numbers that were donated to the collections of the American Museum of Natural History are listed in Appendix F.

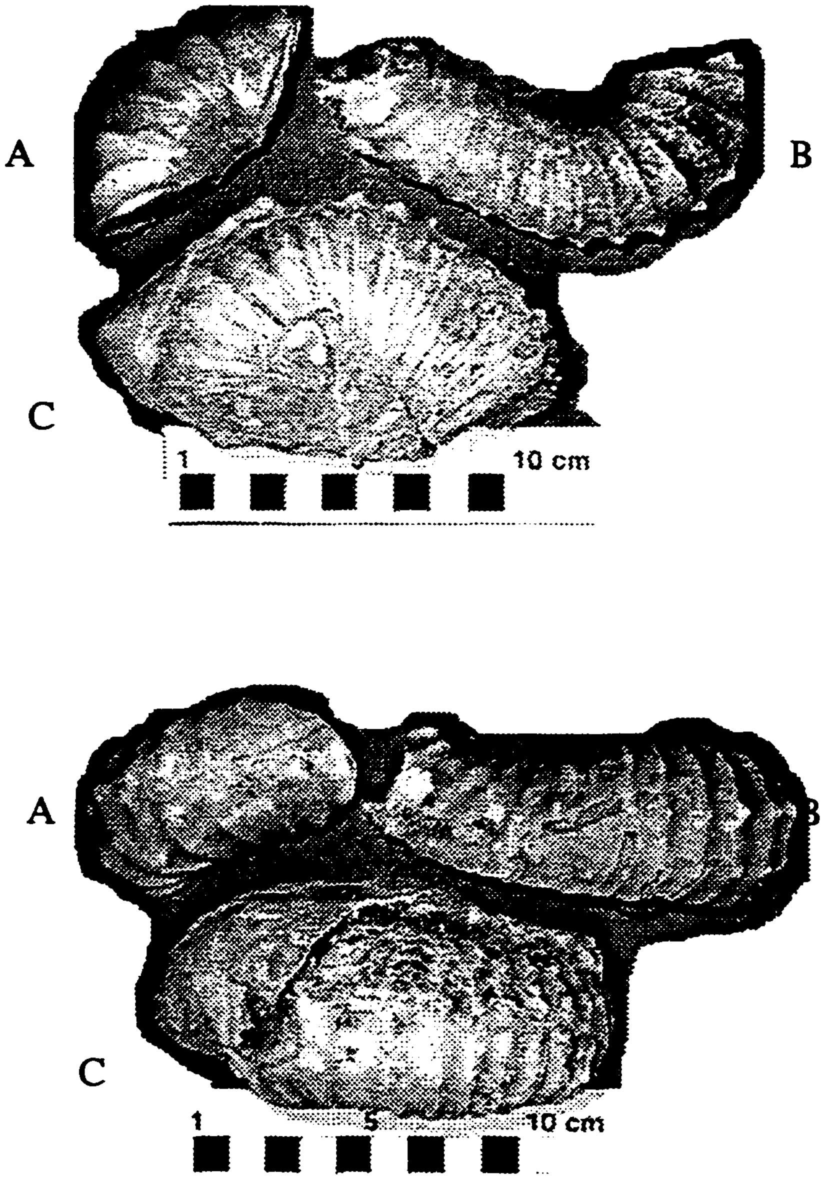


Fig. 13. *Didymoceras cheyennense* (Meek and Hayden, 1856). Flank view of body chambers (top) and ventral view of body chambers (bottom). Specimens A & B are from a roadcut along SD Route 44, about .3 kilometers south of the Cheyenne River bridge, SE, sec. 12, T2S, R12E. The large *Didymoceras* body chamber (C) is from a reworked concretion found in the *Baculites baculus* Zone. It was discovered in the cutbank along Cedar Creek near Redshirt Episcopal Church in Badlands National Park, South Unit (AMNH 3212).

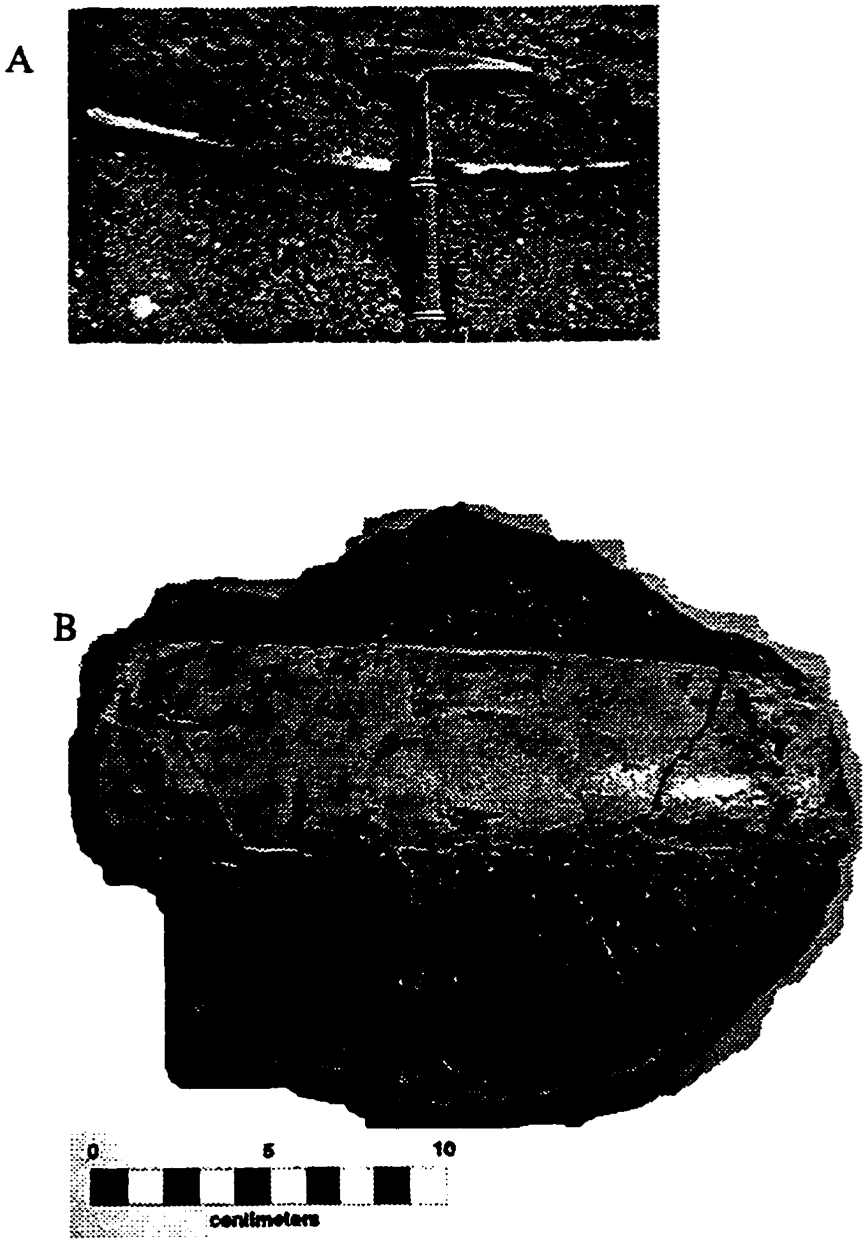


Fig. 14. Baculites: A. *Baculites corrugatus* (Elias, 1933) in cutbank along Indian Creek in NW, Section 27, T3S, R12E; AMNH Locality 3225. The specimen was too weathered to collect. B. *Baculites compressus* (Say, 1820). Fossiliferous concretions bearing *Baculites compressus* Zone fauna are abundant below cutbanks along Sage Creek in Badlands National Park, North Unit. This specimen is preserved in a limestone concretion, collected near the Sage Creek bridge in SW, sec. 35, T1S, R14E (AMNH 3207).

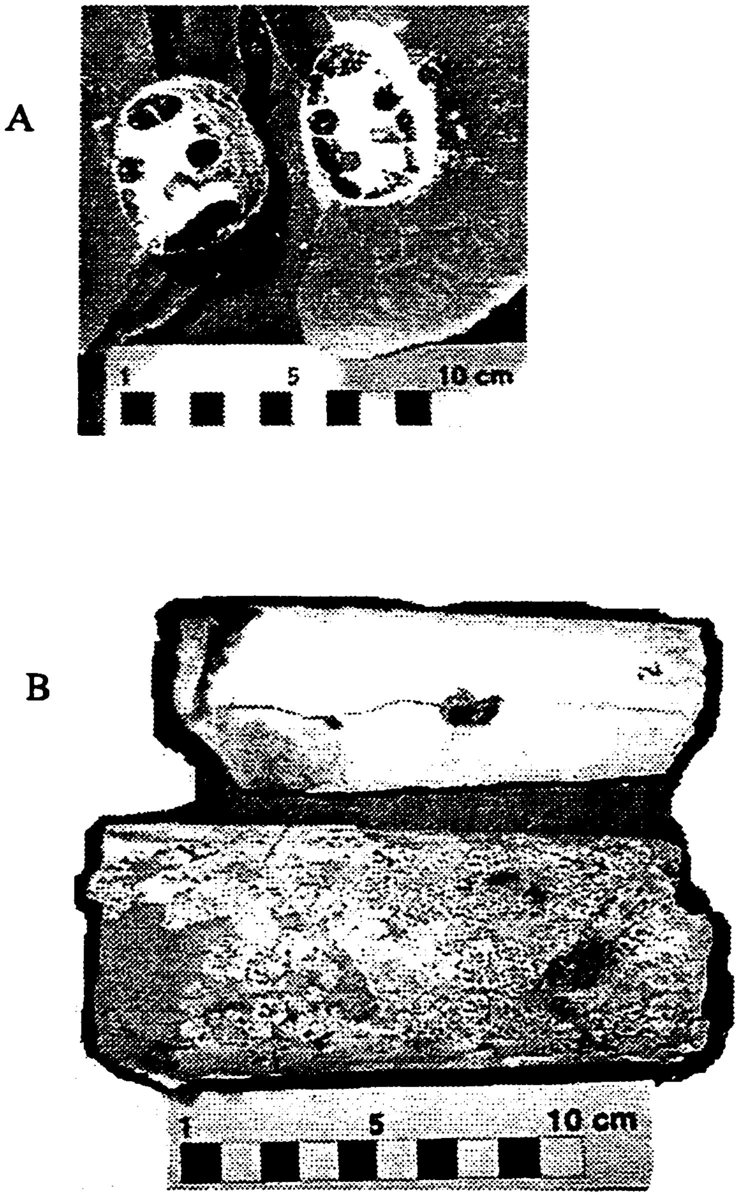


Fig. 15. ***Baculites compressus*** (Say, 1820). Fossiliferous concretions bearing ***Baculites compressus*** Zone fauna are abundant below cutbanks along Sage Creek in Badlands National Park, North Unit, in SW, sec. 35, T1S, R14E (AMNH 3207). Specimens A are a cross section views of a baculite broken at the first septa below the body chamber. Specimens B are flank views showing a body chamber (above) and a phragmacone without shell (below).

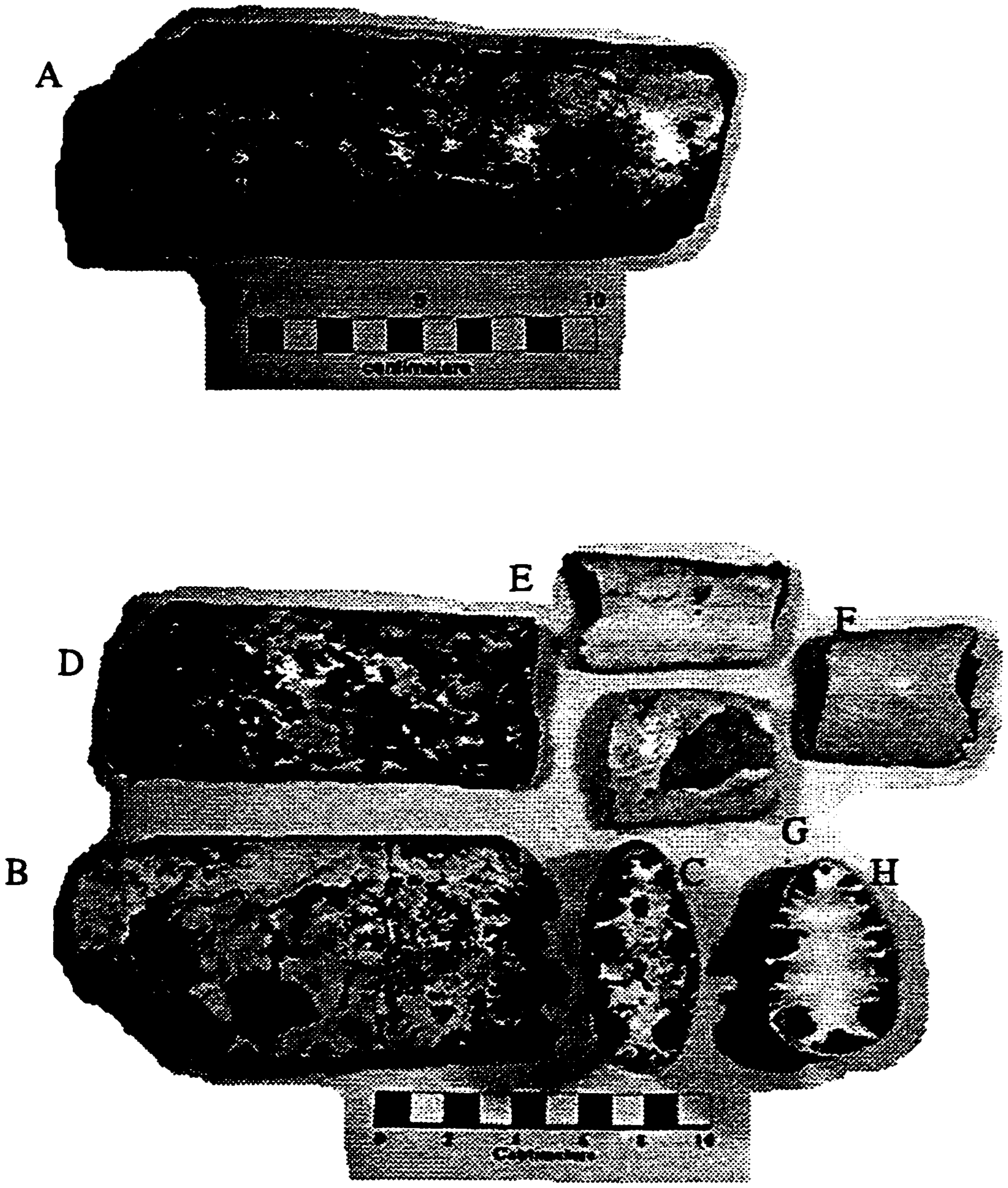


Fig. 16. Baculites. A: *Baculites cuneatus* (Cobban, 1962) from a concretion found near the Sage Creek Bridge in Badlands National Park, North Unit, in SW, sec. 35, T1S, R14E (AMNH 3207). Lower illustration represents a mixed baculite fauna from the Cedar Creek cutbank locality, South Unit, Badlands National Park, (SW, SE Section 11, T42N, R47W)(AMNH locality 3212). Specimens C & D: *Baculites cuneatus*. Specimens E-H: *Baculites reesidei* (Elias, 1933).

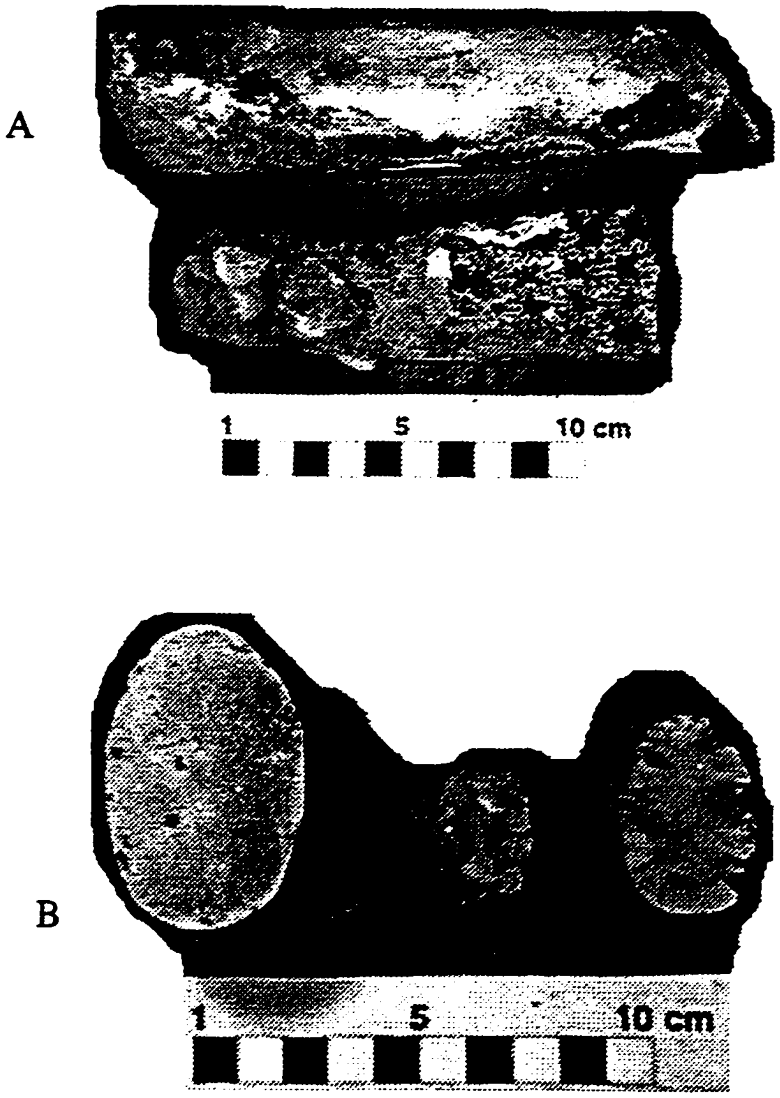


Fig. 17. *Baculites eliasi* (Cobban, 1958). These specimens were collected from the base of the Upper unnamed shale member (just above the Kara Bentonitic Member) in the Osage Oil Field area, Weston County, WY (NW, Sec. 16, T46N, R64W), (AMNH 3194). Specimens A: body chamber (top) and phragmacone (bottom). Specimens B: cross section of a body chamber (left) and cross sections of phragmacones (two on right).

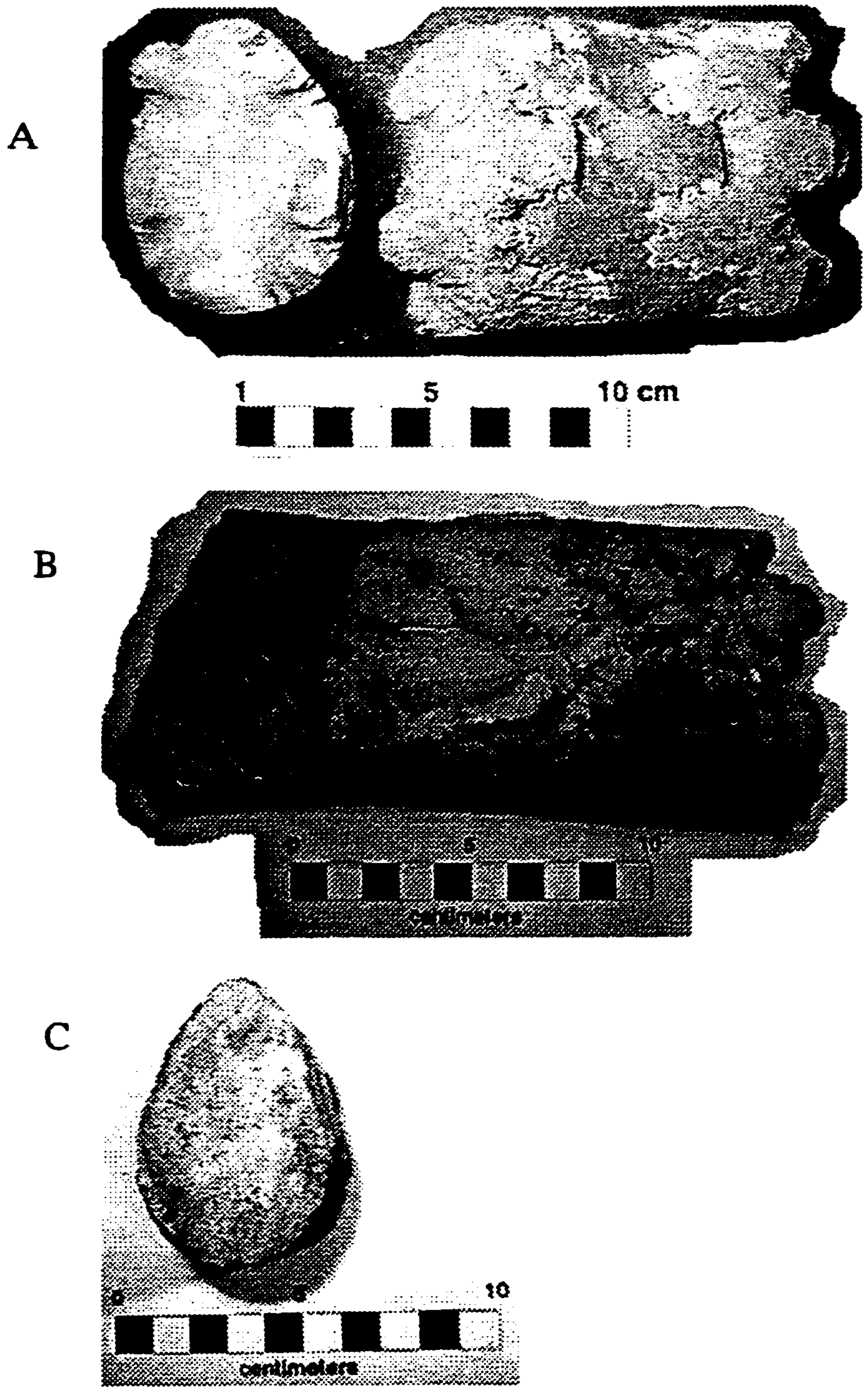


Fig. 18. *Baculites baculus* (Meek & Hayden, 1861). Specimens A: phragmacone cross section (left) and flank view (right) from Osage Oil Field, Weston Co., WY; NE, Section 17, T46N, R64W (AMNH locality 3194). Specimen B: crushed body chamber from South Fork of Sage Creek, Badlands National Park, NE Section 14, T2S, R14E. Specimen C: body chamber cross section from South Fork of Sage Creek, Badlands National Park, NE Section 14, T2S, R14E.

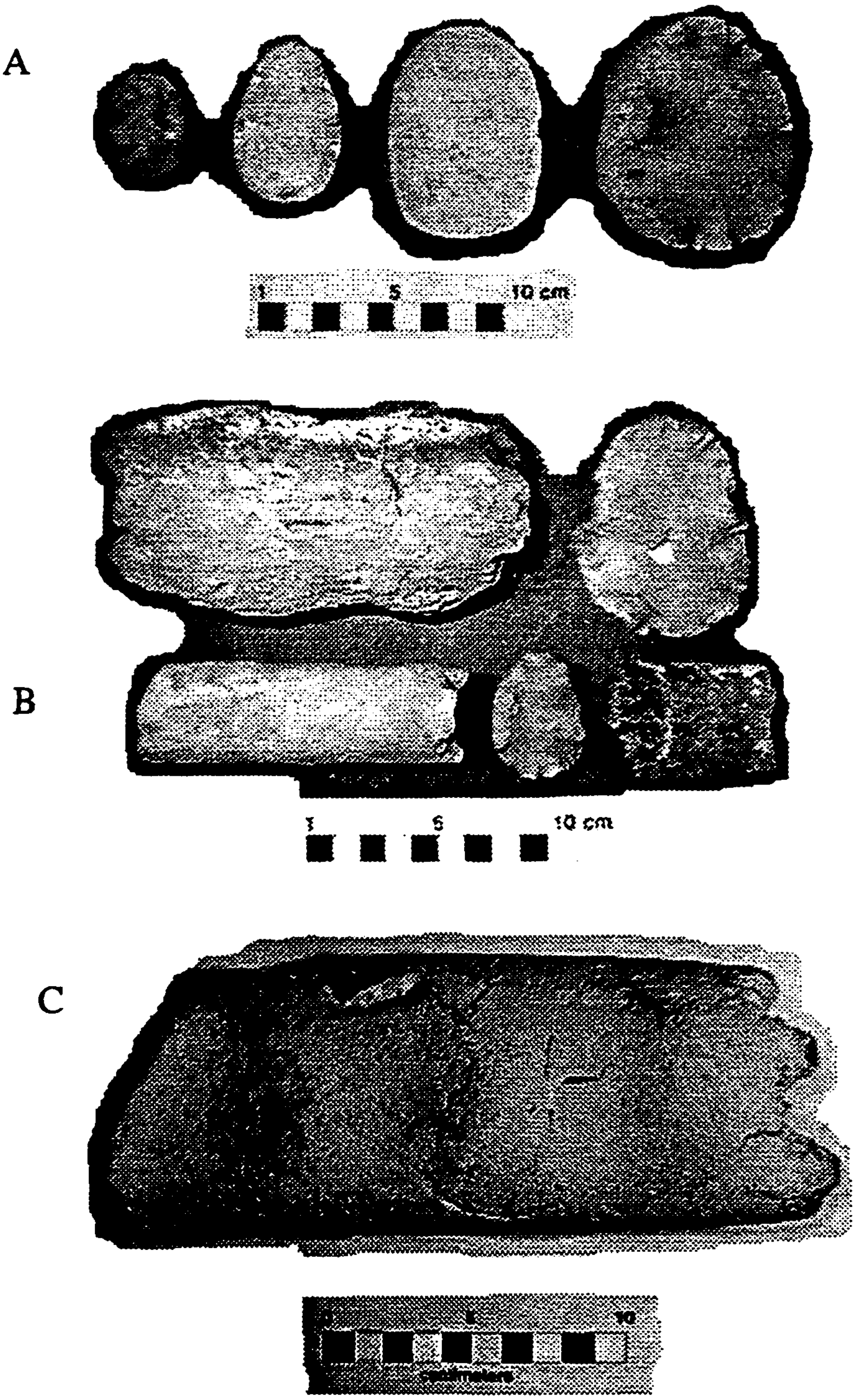


Fig. 19. *Baculites grandis* (Hall & Meek, 1854). Specimens A: cross sections show variations in profiles; from Osage Oil Field, Weston County, WY; NE, Section 17, T46N, R64W (AMNH locality 3194). Specimens B: mixed parts, (same locality as A). Specimen C: body chamber from Sage Creek float near White Butte, Badlands National Park; Section 12, T2S, R14E (AMNH locality 3219).

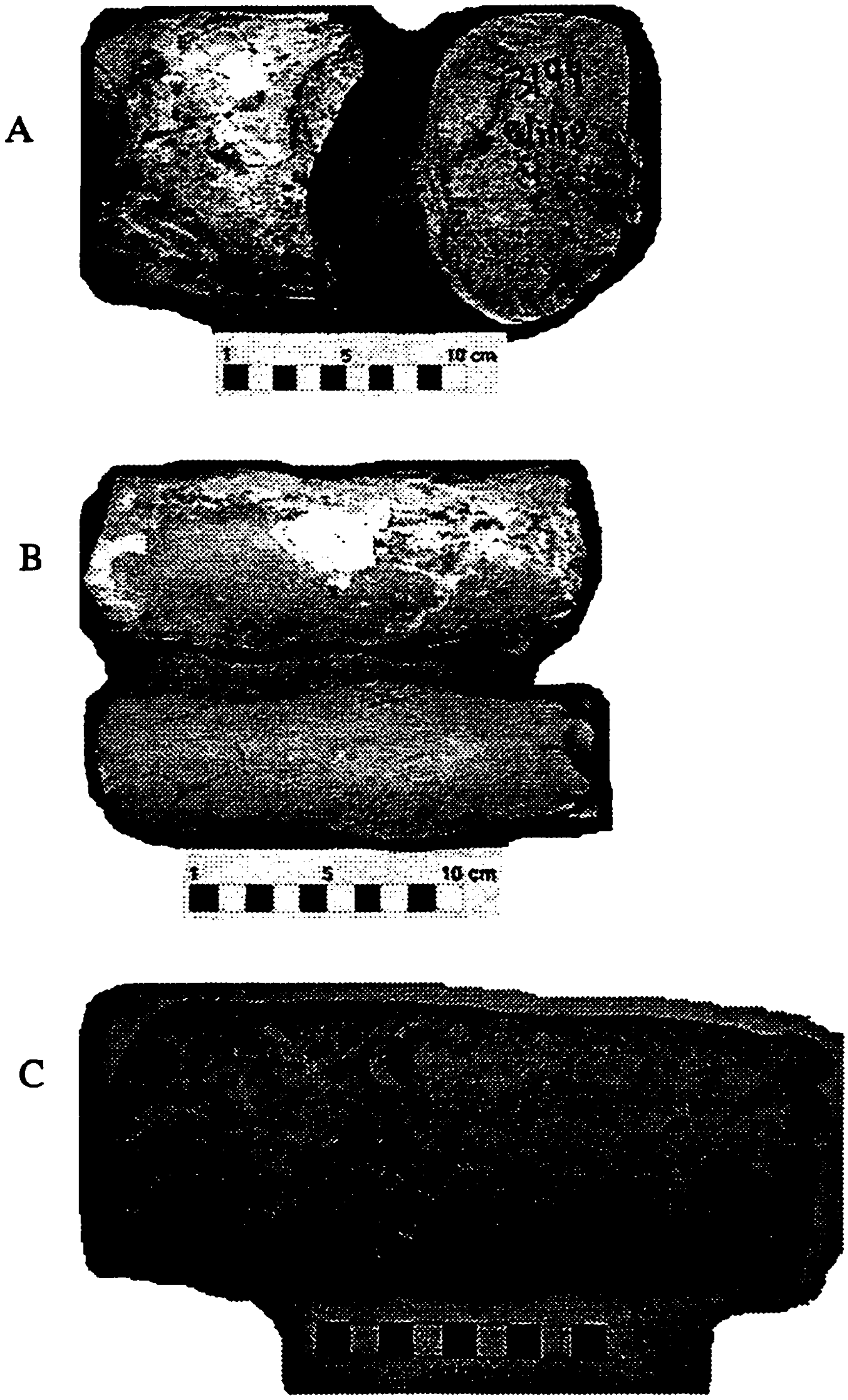


Fig. 20. ***Baculites clinolobatus*** (Elias, 1933). Specimens A: flank and cross section of body chambers from the Osage Oil Field area, Weston County, WY (NE, Sec. 17, T46N, R64W), (AMNH 3194). Specimens B: Dorsal views of body chambers (same locality). Specimen C: body chamber from Sage Creek float near White Butte, Badlands National Park; Section 12, T2S, R14E (AMNH locality 3219).

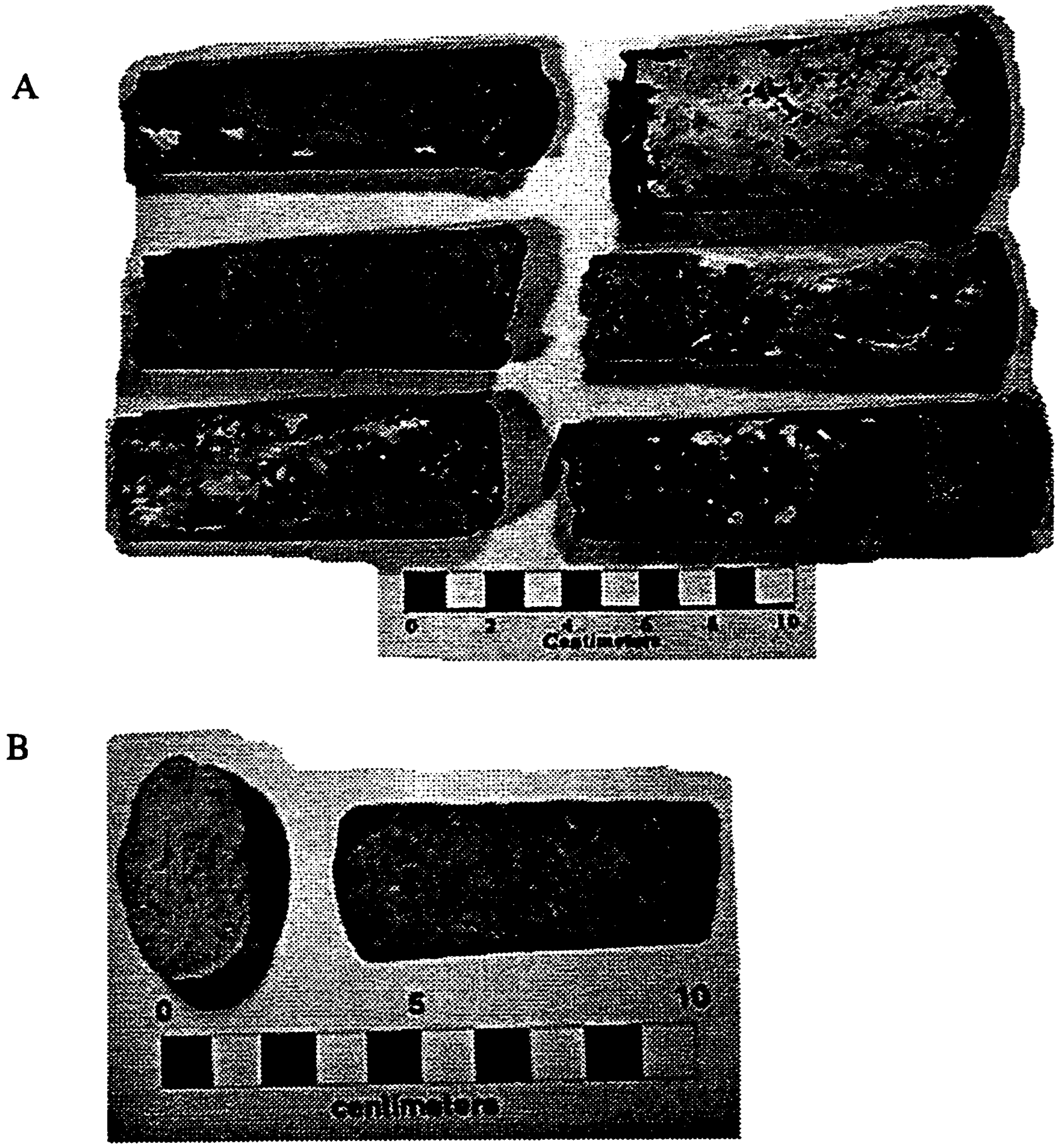


Fig. 21. *Baculites* sp. (smooth and compressed form of *Baculites clinolobatus*). Specimens A: body chambers from baculites found within and above a stratigraphic interval bearing *Baculites clinolobatus*; from Gabriel Ranch, Pedro, South Dakota NW, Section 26, T5N, R16E (AMNH locality 3184). Specimens B: body chamber cross section and flank view of same baculite species from the South Fork of Sage Creek; NE, Section 23, T2S, R14E; (AMNH Locality 3218). Body chamber is packed with glauconitic mudstone which weathers red.

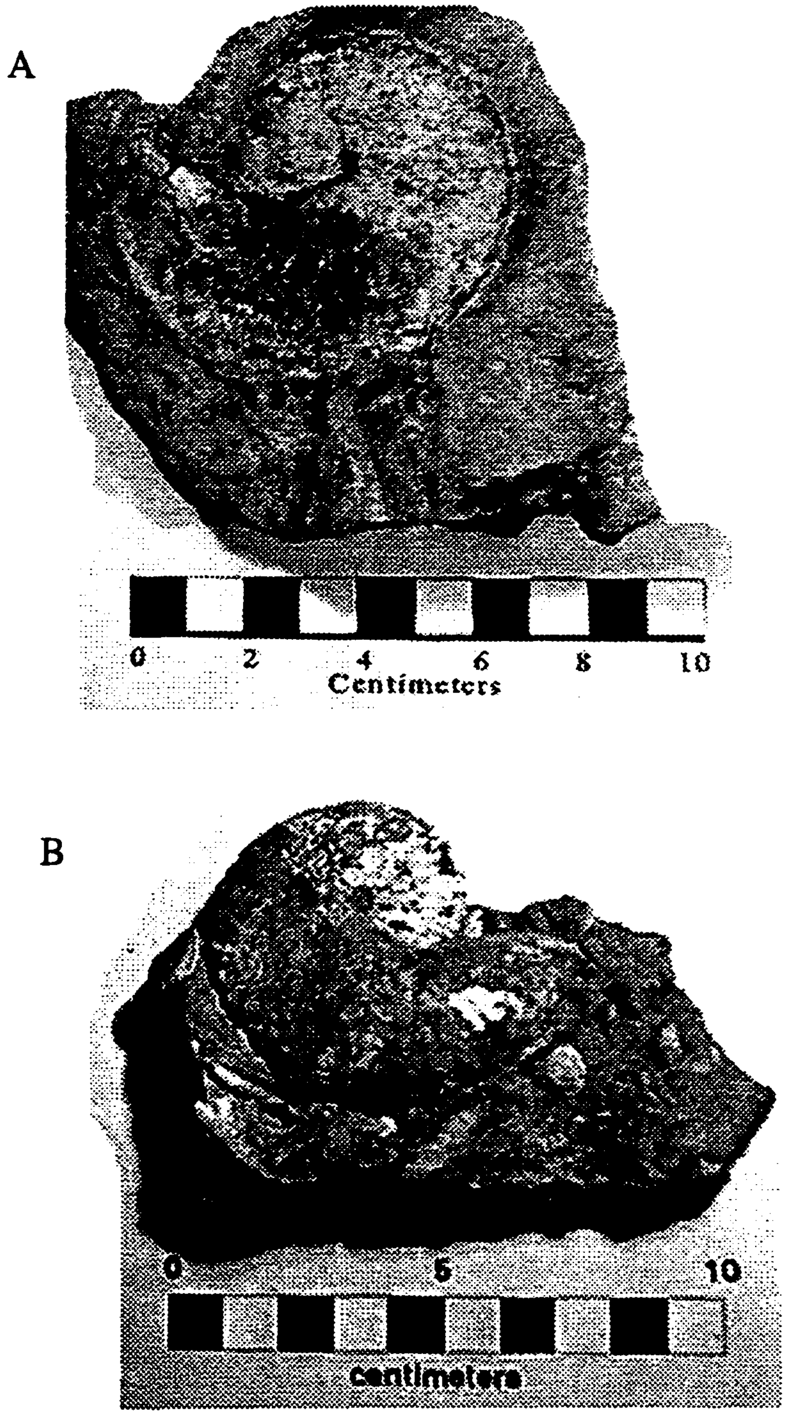


Fig. 22. Scaphites. Specimen A: *Hoploscaphites birkelundi* (Landman & Waage, 1993); collected from above the *Baculites clinolobatus* Zone on Jenson Ranch, SW, Section 25, T1N, R14E; (AMNH Locality 3208). Specimen B: *Hoploscaphites nicolletii* (Landman & Waage, 1993); collected from Trail City Member of the Fox Hills Formation on the Alan Johnson Ranch; Section 19, T20N, R27E.

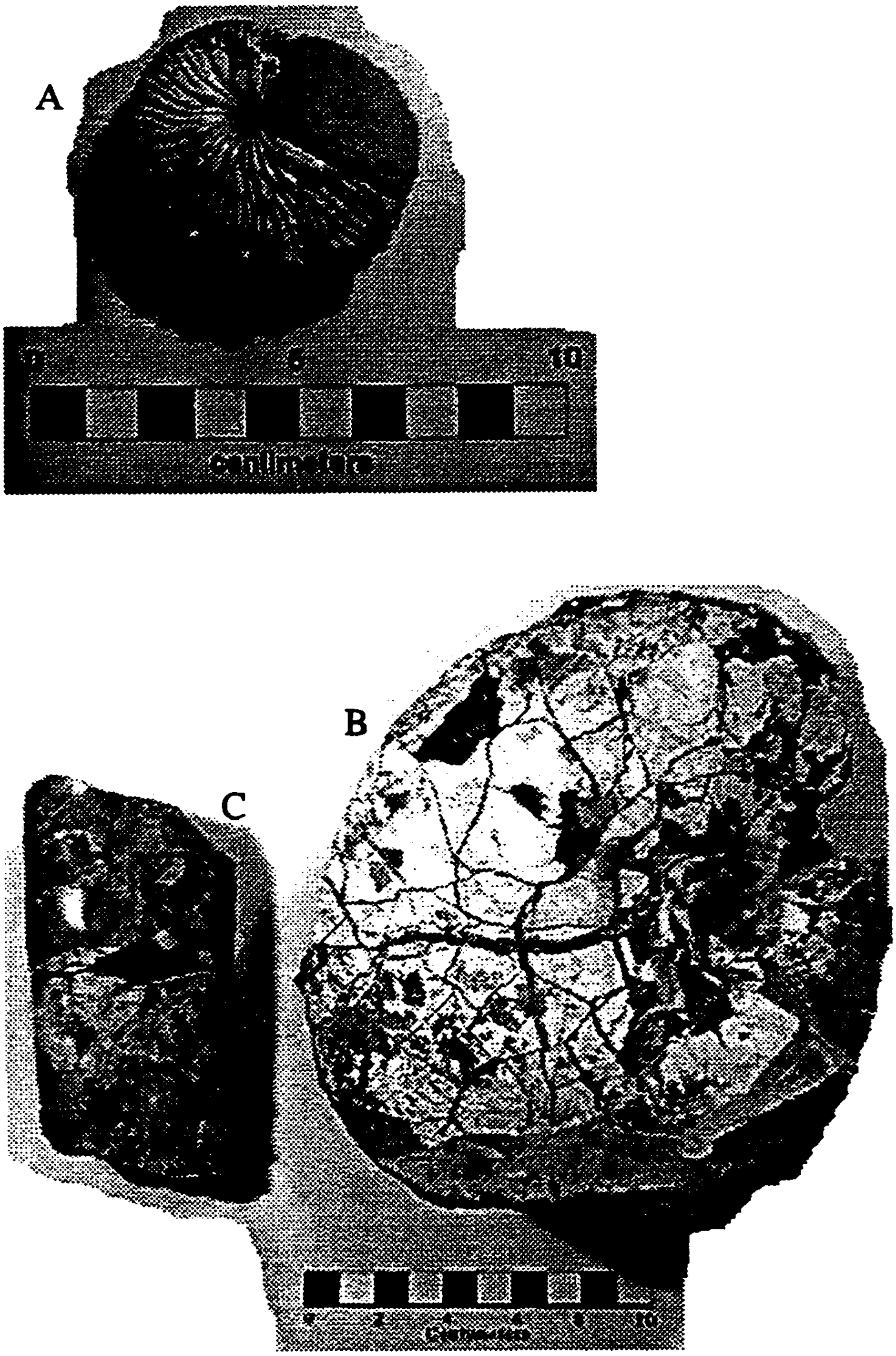


Fig. 23. Ammonites: Specimen A: *Jeletzkytes crassus* (Coryell & Salmon, 1934), from the *Baculites baculus* Zone in the Cedar Creek area (NE, Section 11, T42S, R47W; AMNH Locality 3212). Specimen B: *Placenticeras costatum* (Hyatt, 1903) that was found adjacent to a concretion bearing *Baculites baculus* (specimen C) from the Indian Creek Area, Section 22, T3S, R12E; (AMNH Locality 3225).

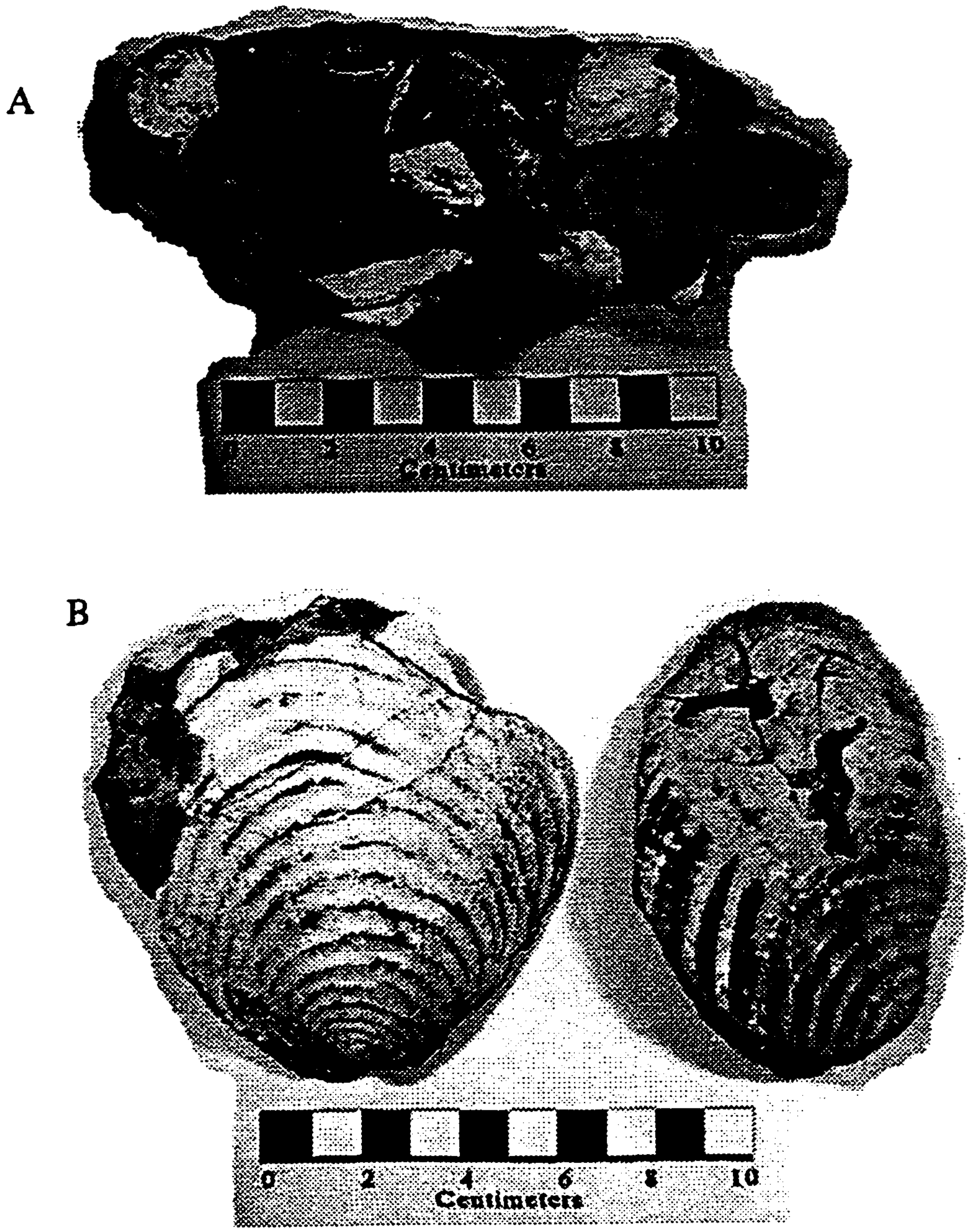


Fig. 24. Bivalves. Specimen A: Concretion bearing *Protocardium* sp. from the *Baculites reesidei* Zone from the Cedar Creek Area (NE, Section 11, T42S, R47W; AMNH Locality 3212). Specimens B: *Inoceramus sagensis* (Owen, 1852) from the *Baculites reesidei* Zone in the Cedar Creek area (same locality).

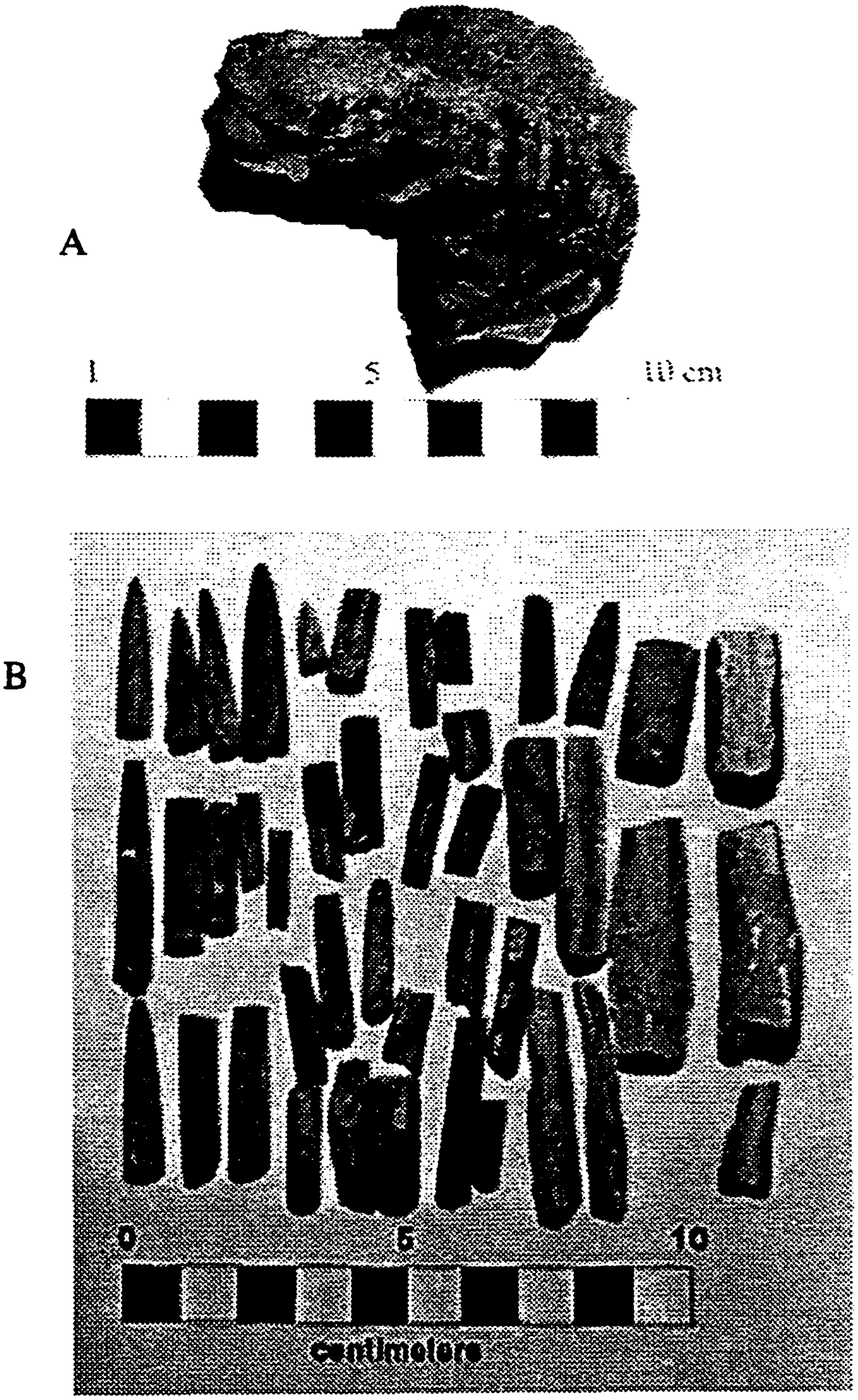


Fig. 25. Specimen A: An unidentified lobster-like crustacean from the lower *Baculites eliasi* Zone, Osage Oil Field, Weston County, Wyoming (SE, Section 17, T46N, R64W). Specimens B: Belemnites: *Belemnitella americana* (Morton) from the top of the *Baculites clinolobatus* Zone in Badlands National Park, North Unit; Section 3, T2S, R15E.

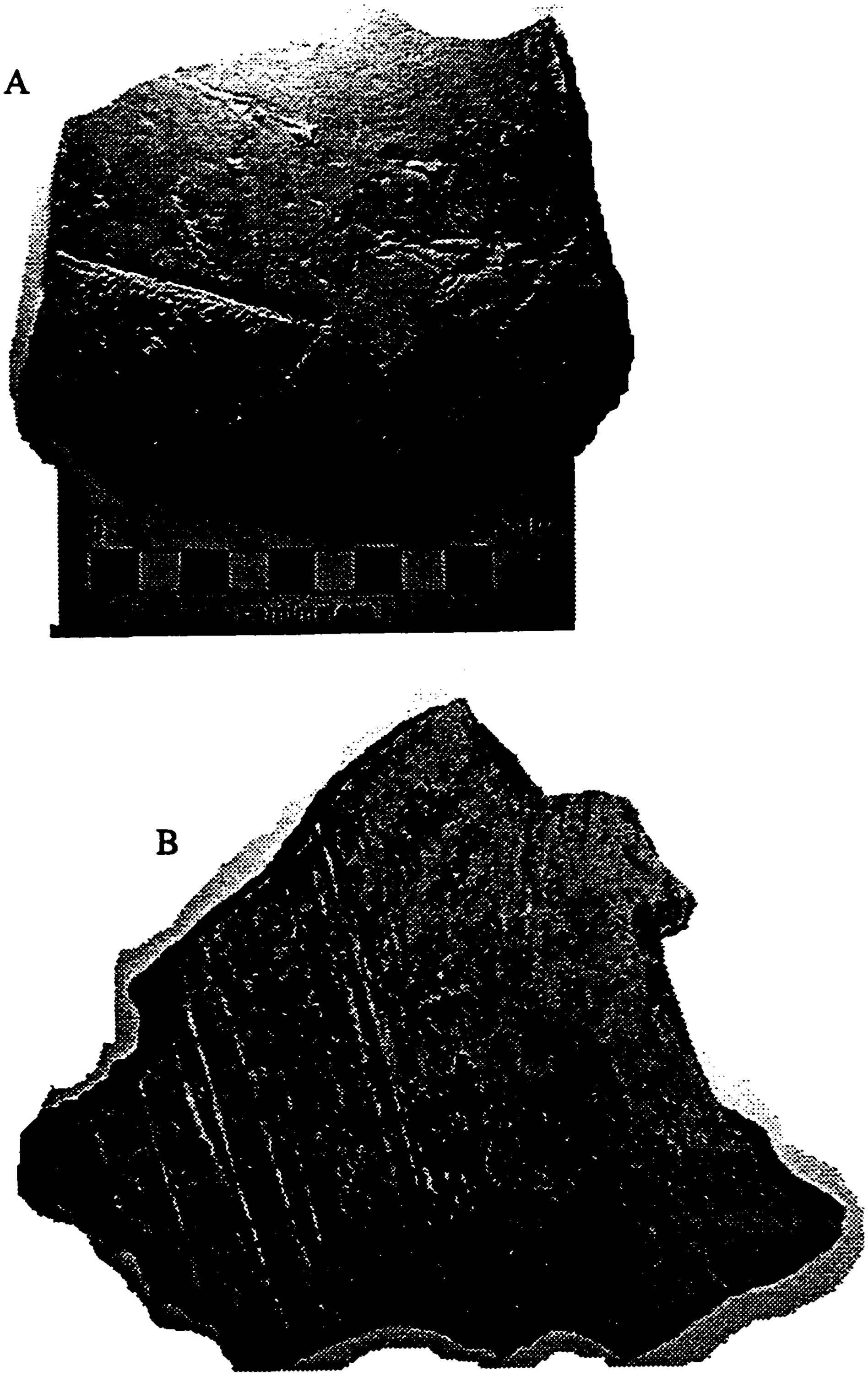


Fig. 26. Fox Hill Sandstone, Badlands National Park, North Unit. Specimen A: *Nerites* (crawling traces) and *Diplocraterion* (traces consisting of double small holes) on a slab of sandstone from Section 3, T2S, R15E. Specimen B: Drag mark casts with *Diplocraterion* traces on a sandstone slab from Section 11, T2S, R15E.

# CHAPTER 6

## FIELD LOCALITY DESCRIPTIONS

This chapter provides descriptions of selected field localities used for the evaluation of the upper Pierre Shale/lower Fox Hills interval throughout the study area. Field investigations were conducted during the summers of 1994 to 1997. Selected locality descriptions presented in this chapter are assigned AMNH identification numbers to correspond to fossil collections housed in Department of Invertebrates of the American Museum of Natural History. Field localities where measured sections were compiled and core samples were collected are shown in Fig. 27. The locations of core samples in relation to stratigraphic placement are indicated on the right side of measured sections. Analyses of the core samples are presented in Chapters 9, with complete location and analytical data presented in the appendices of this report.

Measured sections for each selected field locality describe details of lithology, including the occurrence of fossils, and other important characteristics of each locality. Defining what constitutes a "field locality" is somewhat problematic. Field localities can range in size from an exposure of a simple cutbank along a stream

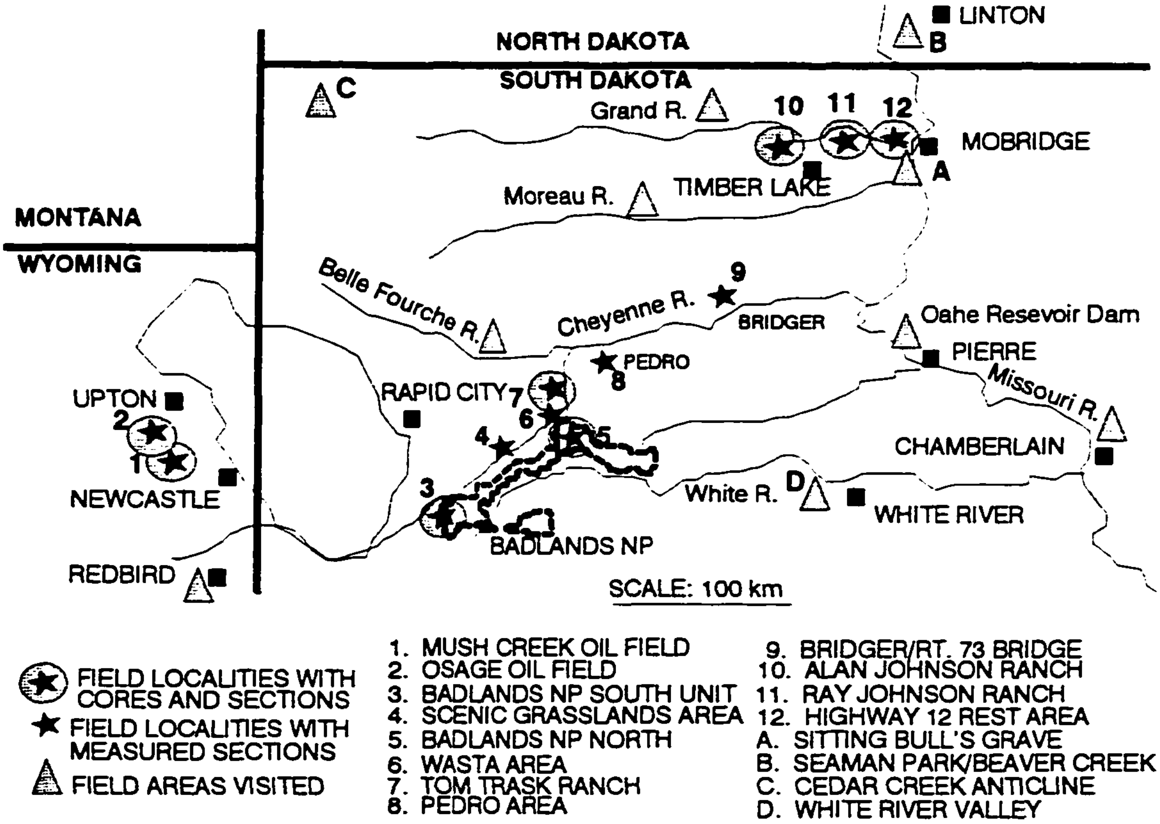


Fig. 27. Field localities within the study area. Locations were cores were collected in conjunction with measured section during the summer of 1995 are shown with gray circles. Field localities where measured sections were made are shown with stars only. Triangles indicate field localities described by previous researchers which were visited during this investigation. However, measured sections were not made in these locations because either land access or fossil collecting were not permitted, or the upper portion of the Pierre Shale and Fox Hills Formation were not well-exposed.

(measurable in meters for height and width) to an area encompassing as much as a square mile or more, with multiple exposures spread over several hillsides along a stream or river valley. In most cases fresh, unweathered exposures are limited in their extent, and required extensive hiking, climbing and sampling in order to develop a reasonable measured section description. Problems encountered in field work are numerous. The list below provides general comments regarding problems with field work in the study area.

**PROBLEMS WITH LAND ACCESS:** Natural outcrops of shale that are not deeply weathered occur only in areas of rugged terrain and usually without easy road access. In most localities on federal land (national park and national grasslands) field work involved hiking several miles through creek beds, through heavy brush, or across hilly, prairie terrain to gain access to exposures. The summer heat and humidity in South Dakota and Wyoming made fieldwork both hazardous and unbearable at times, and limited the weight of materials that could be collected and carried back to the vehicle. Where permission was gained to collect on private land these same conditions applied. The location of field localities in this report are largely a reflection of access. Many exceptional exposures or the Pierre Shale were not studied because of lack of accessibility or because land owners did not permit strangers on their land. For instance, most land north of the Cheyenne River lies within the

Cheyenne Indian Reservation where fossil collecting is not permitted. As a result the study of outcrops along the north side of the Cheyenne River and in the Moreau River Valley were excluded from this study.

**PROBLEMS INVOLVING OUTCROP EXPOUSRES:** A significant problem with field work was finding fresh exposures of outcrop that were adequate for field study and specimen collection. Even the freshest outcrops displayed some degree of surface weathering and creep of overlying materials down-slope. Other problems encountered included the occurrence of slumps and variations in the appearance of correlative units due to varying degrees of weathering and moisture content. These problems are perhaps best illustrated by the appearance of bentonite beds. Without digging trenches to reveal fresh rock, only the thickest bentonite beds can be seen in outcrop exposures. In some field localities bentonite beds were observed only when trenches or holes were dug to expose a concretion or to collect a core sample.

**PROBLEMS INVOLVING FOSSIL COLLECTION:** Perhaps the greatest problem involved in field investigation was a general lack of fossils in some horizons. Either fossils do not exist in these units, or they were overlooked or not recognized in the course of specimen collection. In addition, fossils occur out of place as "float" raising questions about their value for detailed correlation. Usually only fossils of exceptionally good condition could be used for identification on a species level. Crushed specimens and molds and casts of highly-weathered exoskeletons devoid of original calcareous shell material were often difficult or impossible to identify. This problem is particularly acute for *Baculites*, the primary genera of fossils used for correlation in this research. Immature specimens of each of the species of baculites look strikingly similar.

Field work started with the evaluation of field localities previously investigated by others in order to establish a basis for regional correlation. The first step in field investigations was an examination of exposures near the "type" reference sections on the western flank of the Black Hills in eastern Wyoming (after Gill & Cobban, 1966) and equivalent age strata in the Missouri and Grand river valleys near Mobridge, South Dakota (after Searight, 1937; Crandall, 1958). Because access was denied to the land of the original type section established by Gill & Cobban (1966) at Redbird, Wyoming a replacement section was established on public lands within the Osage and Mush Creek oil fields in Weston County, Wyoming. These new localities on Bureau of Land Management holdings are easily accessible on oil field roads, and are generally far away from private homes. Future investigation of these localities should at least not be hindered by problems involving gaining access to private land. Fortunately, government regulations during the time of this investigation did not limit the collection of invertebrate material. Collection of vertebrate material, however, was illegal on public lands in Wyoming and South Dakota. A research permit was required for fossil collection in the National Park, and all fossil material had to be donated to public repository collections.

Similarly, the original road-cuts used to establish measured sections for the study interval near Mobridge no longer exist. The original road-cuts described by Searight (1937) have vanished since the original highway was abandoned by the development and flooding caused by the Oahe Reservoir on the Missouri River. The summers of 1994 through 1997 were particularly wet; the water level in Lake Oahe Reservoir was the highest ever recorded during the summer of 1995. Land containing some of Searight's sections has been incorporated into reservation property associated with Sitting Bull's Grave. The type area near Promise, South Dakota is posted with no trespassing signs. In addition, flooding by the reservoir had made outcrop exposures along the Missouri River both inaccessible and hazardous due to instabilities associated with slumping. Replacement sections were established using public land at a rest area along SD Highway 20 supplemented with exposures along road cuts and on private ranches in the Grand River Valley area owned by Ray Johnson and Alan Johnson in localities between 10 to 20 kilometers to the west of Searight's original type sections near Sitting Bull's Grave.

Field work progressed by first conducting field reconnaissance during the summer of 1994 in cooperation with a field group collecting fossils for the American Museum of Natural History directed by Dr. Neil Landman and Dr. John A. Chamberlain, Jr. This was supplemented by three additional weeks of field study in the region. This included an aerial survey of the Cheyenne River Valley region to scout potential outcrops. This was accomplished with the enthusiastic help of a pilot, Dave Hahn (also mayor of Wall, South Dakota), who donated his time and use of his private airplane for aerial field reconnaissance in the Cheyenne River Valley region. Outcrops were examined on the Buffalo Gap National Grasslands near Scenic, South Dakota and cutbanks along Sage Creek in Badlands National Park. It was the examination of these exposures that was the motivation for this dissertation research project. Preliminary examination demonstrated that the oldest Late Cretaceous interval exposed in the park along Sage Creek displayed fauna typical of the *Baculites compressus* Zone (Neil Landman, personal communication, 1994). The top of the Cretaceous section exposed in the park are sand sheets of the Fox Hills Formation that crop out in various places below the basal Chadron Formation (Pettijohn, 1965).

Prior to the summer of 1995 permission was established to study and collect fossils in Badlands National Park with the help of Rachel Benton, park paleontologist. Field work during the summer of 1995 was focused on collecting core samples, collecting fossils, and measuring sections. The first five detailed measured sections were made of localities in Weston County, Wyoming and Mobridge, South Dakota (mentioned above); outcrops on the Tom Trask Ranch along the western flank of the Cheyenne River north of Wasta, South Dakota; and exceptional outcrop exposures in both the North and South Units of Badlands National Park.

Field work conducted during the summers of 1996 and 1997 focused on more detailed examination of outcrops within Badlands National Park and selected exposures along the Cheyenne River Valley.

Field descriptions presented below incorporate summaries from field notes. Names of fossils are included based both on field and laboratory evaluations. Measured sections are drawn with standard symbols for lithology; the unit thickness scale is common to all measured sections. The use of stratigraphic member names follow Gill & Cobban (1966) for the western flank of the Black Hills, and Searight (1937) and Crandall (1958) for the South Dakota region. Summaries of measured sections from near the two type areas in South Dakota and Wyoming are presented first because these sections serve as reference for examination and interpretation of localities in the Badlands National Park region. Discussions presented below focus on descriptions of the lithologies and highlights of field observations. It is important to note that field investigations involved many return trips to selected outcrops, and that this dissertation was written *after* field work had been completed. This section, therefore, is an attempt to present field data with minimal information about interpretations. However, some preliminary interpretations had to be included in this section to introduce concepts of stratigraphic terminology, or to provide insights into chronostratigraphic correlation. Measured sections in this chapter include only lithology and paleontology descriptions. Interpretations of the placement of member boundaries and biozonation for each section are presented in Chapter 8.

## 6.1 MOBRIDGE/GRAND RIVER AREA, CORSON COUNTY, SD

Searight (1937) mapped and described the Pierre Shale for the entire length of the Missouri River Valley from the North Dakota border southward to Nebraska. He divided the Pierre Shale into five members: Gregory Member, Sully Member, Virgin Creek Member, Mobridge Member, and Elk Butte Member, from oldest to youngest. The Fox Hills Formation overlies the Elk Butte Member. For comparison with the exposures in Badlands National Park, the interval of interest starts in the *Baculites compressus* Zone and extends upward to the transition with the Fox Hills Formation. Searight described *Baculites compressus* as an index fossil for the Sully Member. Crandall (1958) subdivided the Sully Member into two additional members: the DeGrey Member and the Verendrye Member (oldest and youngest, respectively). Crandall included the interval bearing *Baculites compressus* within the Verendrye Member.

Searight (1937) demonstrated that the thicknesses of the units varied considerably along the course of the Missouri River. He reported measured thicknesses for each of the upper three members in their type sections near Mobridge as follows: Virgin Creek Member: 188 feet (57 m), Mobridge Member: 136 feet (41 m), and the Elk Butte Member 270 feet (82 m). The Verendrye Member disappears under younger sedimentary cover near the mouth of the Grand River on the Missouri River as it existed before the flooding of Lake Oahe Reservoir.

During investigations in 1995 all the members of the Pierre Shale were examined along the Missouri Valley in South Dakota. However, in every location between the Nebraska border northward to the Mobridge area the upper members of the Pierre Shale are generally very poorly exposed on the recessed and weathered hilltops along the valley. The upper Pierre Shale is best exposed in the type area near Mobridge. The only uncovered exposure of the Verendrye Member observed during this field reconnaissance was along the hillsides below Oahe Reservoir Dam.

Below the Oahe Reservoir Dam, the calcareous marl of the Crow Creek Member forms a bed about 3 meters thick that stands out as a whitish gray strip on barren patches about halfway up the hillside below the Oahe Reservoir Dam. Above the Crow Creek Member, the gray, non-calcareous claystone and shale of the DeGrey Member contains reddish to purplish-gray, flat ironstone concretions in the range of several centimenters in thickness, and up to roughly one meter in diameter. *Chondrites* and *Planolites* type traces were the only fossils found in the concretions, and even these were scarce. Crandall (1958) described the DeGrey Member as being about 125 feet thick (38 m) in the Pierre, South Dakota area, and has a gradational contact with the overlying Verendrye Member. In the upper hillsides of the Oahe Reservoir Dam area, in a zone approximately 40 meters above the Crow Creek Member, the weathered shale become lighter in color, and becomes more supportive of plant cover (dominantly grasses). Whether this change in the surface expression reflects a change in the character of the sediment, or it merely represents a variation in the degree of surface weathering is unclear. Crandall (1958) described a similar change in the appearance of the Verendrye Member in the Pierre, South Dakota area. He stated that the claystone of the Verendrye Member weathers to a gumbo soil, and yields concretions that are weakly calcareous. Crandall observed scattered fragments of *Baculites compressus* in the member in the Pierre, South Dakota area. In the hilltop area below Oahe Reservoir Dam small dark gray-to-reddish limestone concretions were observed lying loose among the weathered shale, but no fossils were observed. Within this same interval exposed along outcrops at the edge of the Reservoir several large, gray limestone concretions were noted, however, above the dam the shoreline outcrops were too hazardous to study because of the flooding. Although both Searight (1937) and Crandall (1958) reported the occurrence of *Baculites compressus* in the Missouri River Valley, none were observed in the area below the dam. The transitional boundary between the Verendrye Member and the Virgin Creek Member is flooded by the reservoir.

Investigation of the Virgin Creek, Mobridge, and Elk Butte members in their respective type localities near Mobridge, South Dakota demonstrated that the original section exposure no longer exists. Establishing a new reference section to replace Searight (1937) was necessary to develop an understanding of the thick sequence of mudrocks of the Pierre Shale in the Mobridge/Grand River Valley area. The wet spring of 1995 also hindered sampling efforts in the original type sections. Places that were probably partially barren in previous years were covered with thick, chigger-bearing, waist-high grasses and thorns, and snakes (big snakes!). Satisfactory locations for study and sampling were found, however, with the cooperation of ranchers who took interest in this investigation.

The most significant problems with the Mobridge section are a general lack of easily recognizable stratigraphic boundaries and a general lack of macrofossils. Mello's (1969) descriptions of the upper part of the Pierre Shale in the Mobridge type area support this notion. He stated:

> "Generally speaking, the upper part of the Pierre Shale is lithologically monotonous, but it does contain many distinctive features which have been referred to by previous workers. Some of these features I have found useful in correlation. Color of the shale, steepness of outcrop slope, and size and nature of the particles produced by weathering..." (p.6)

Mello demonstrated that the physical weathering properties of shales was an inconsistent method for determining the boundaries between the Virgin Creek, Mobridge, and Elk Butte members of the Pierre Shale during the course of his investigations. He states:

> "I have found that first and last occurrences of calcareous shale vary in stratigraphic position from section to section and that no color change or other lithologically or faunally distinct horizons consistently parallel these changes. The contacts of the Mobridge Member with the Virgin Creek and Elk Butte members in north-central South Dakota are entirely gradational." (p. 5)

Searight (1937) and Crandall (1958) both describe the Mobridge Member as having a whitish appearance in relation to the darker gray shales of the Virgin Creek Member below, and the Elk Butte Member above. This criteria of color was used for the mapping of members of the Pierre Shale for a series of geologic quadrangle maps covering the length of the Missouri Valley published by the South Dakota Geological Survey in the 1950s. Mello (1969) rejected the use of specific marker horizons, such as the occurrence of concretion horizons or bentonite beds to define boundaries for the Mobridge Member. He conceded that the boundaries were gradational. He concluded that the terms "Virgin Creek," "Mobridge," and "Elk Butte" could only be used to denote the lower non-calcareous, middle calcareous, and upper non-calcareous lithologies, respectively, with no precisely defined boundaries implied.

Mello conducted a "fizz" test using a solution of 10% hydrochloric acid to detect the presence of calcareous content in the shale and reported it in qualitative terms (i.e., "very," "quite," "moderately," "slightly," "non-calcareous"). Although Mello's method was employed in the field, for this research measurements were recorded in the laboratory from fresh samples taken from cores closely inspected to reduce the possibility of calcareous content contamination by surface weathering salts (caliche). When viewed from a distance, the lighter-colored Mobridge Member stands out as a slightly steeper slope-maker than the Virgin Creek (below) or the Elk Butte Member (above). The higher calcareous content of the Mobridge Member probably provides a greater resistivity to weathering on drier, southward and westward facing slopes. Elsewhere, it is typically covered with thick prairie grasses.

Mello (1969) chose to use two prominent bentonite horizons as marker beds in the Mobridge Member. He named them the "Lower Key Bentonite" and "Upper Key Bentonite" which he described as being "widespread and generally thicker than the others." Unfortunately, numerous bentonite beds throughout the Pierre Shale section potentially fit Mello's descriptions. Many thin (~ 1 cm thick) bentonite beds and at least one a prominent bentonite bed (4-10 cm thick) occur near the top of the non-calcareous beds (Virgin Creek facies), and another two bentonite beds (4-8 cm thick) occur within the overlying, more calcareous beds (Mobridge facies). Searight (1937) stated that there were 11 thin bentonite beds in the lower Virgin Creek section near Promise, South Dakota (about 10 km south Mobridge on the west side of lake), and two in the upper Virgin Creek Member, one of which is 6-8 cm thick in the type section in the old Highway 12 road-cut (now covered below Sitting Bull's Grave). He did not record any bentonite beds in the Mobridge Member in the Mobridge area.

Mello (1969) included his "Key" bentonite beds within the upper portion of the Mobridge Member. However, his descriptions of the designation of ammonite zones in relation to these bentonite beds are inconsistent with other fauna designations for the Pierre Shale (Gill & Cobban, 1966; Gill & Cobban, 1973). Mello included the zone of *Baculites clinolobatus* within the Virgin Creek Member. Searight (1937) noted the presence of *Baculites grandis* in both the Virgin Creek Member and the Mobridge Member, and *Baculites clinolobatus* in the Mobridge Member. According to Gill & Cobban (1966), *Baculites clinolobatus* is a range fossil of the lower Mobridge Member. These inconsistencies demonstrate the need to re-establish a measured section for the Mobridge type area, linking biozonation with quantitative lithologic measures.

Mello demonstrated that foraminifera could possibly be used for both paleoenvironmental evaluation and correlation. He observed that the occurrence of the dominant types of foraminifera corresponded with the general chemical character of the shale. That is, arenaceous (siliceous) foraminifera dominated in zones where the sediment had low calcareous concentrations (such as in the Virgin Creek Member and the Elk Butte Member), whereas calcareous foraminifera dominated in sedimentary facies that were calcareous (such as the Mobridge Member). Mello also showed that macrofossils were most abundant in the zones where microfossils were also common. He observed the scarcity of macrofossils in the section where foraminifera diversity and abundance are low, particularly within the upper Mobridge Member, extending upward into the overlying Elk Butte Member. No attempt was made to resolve foraminiferal biozonation in any units during the course of this study.

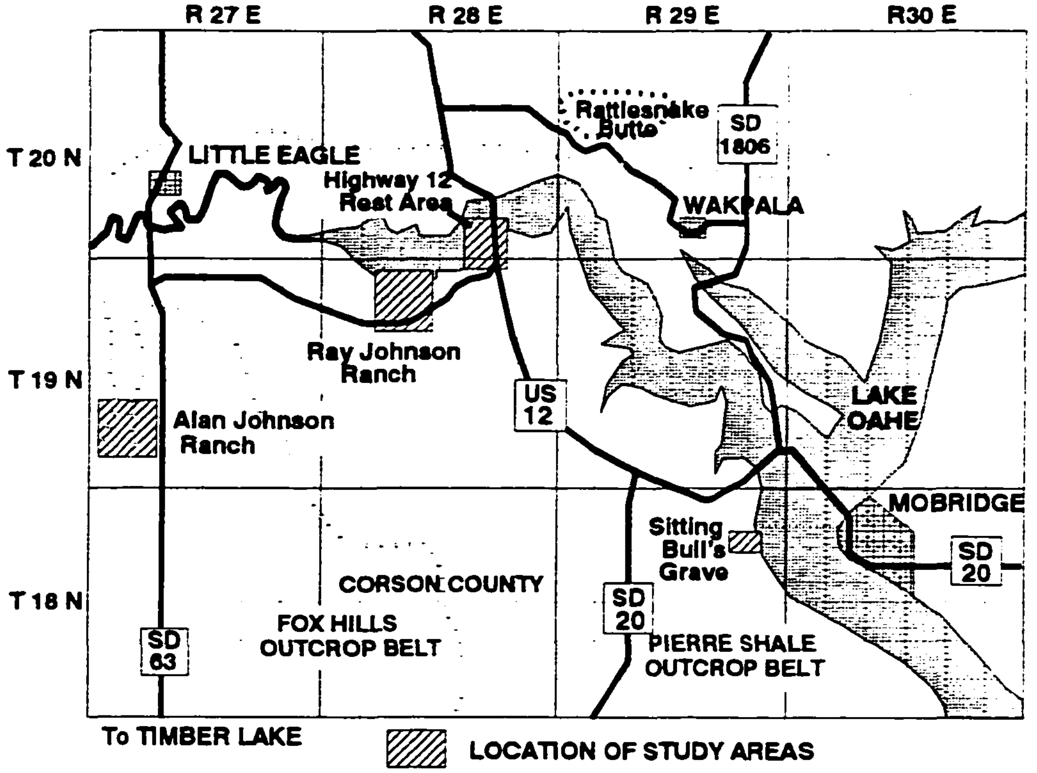
A goal of this investigation was to reconcile the differences between the section descriptions by Searight (1937) and Mello (1969) in the Grand River type area with the stratigraphic descriptions linked to ammonite biozonation presented by Gill & Cobban (1966) for the Redbird, Wyoming type area. The next step was to compare this data with the sections in the Badlands National Park area. Objectives included defining boundaries of lithologic units based on ammonite biozonation while incorporating more quantitative measures of sedimentological and geochemical data. Major questions to be addressed included the following: Was there evidence that the Kara Bentonitic Member correlated to bentonitic horizons in the Virgin Creek Member (based on the presence of *Baculites eliasi*)?; Were the calcareous facies of the Mobridge Member continuous across the study area?; How did the transition from marine mudrocks of the Pierre Shale to the base of the Fox Hills Sandstone change across the study area (related to eastward progradation of the Sheridan Delta proposed by Gill & Cobban, 1973)?; And, how did the facies relationships of the two type areas compare with the region between the two type areas, specifically in Badlands National Park?

During field reconnaissance, the combination of physical appearance and the ability of the shale to "fizz" when a drop of acid was applied was used to help determine location within the section (calcareous facies versus non-calcareous facies). Field study localities in the Grand River Valley area near Mobridge, South Dakota are shown on Fig. 28. A composite measured section for the Mobridge/Grand River Valley area (Fig. 29) combines easily accessible exposures in two roadside localities, and a third locality previously described by Landman & Waage (1993) on the land of the Alan Johnson Ranch northwest of Timber Lake, South Dakota.

### 6.1.1 US Highway 12 Rest Area

A new reference section for the Virgin Creek Member and lower Mobridge Member is located on easily accessible land which includes a combination road cut and wave-cut bluffs adjacent to a public rest area on the shore of Lake Oahe on US Highway 20 in section 35, T 20 N, R 28 E. The lower part of Fig. 29 illustrates the measured section for this locality.

On dry, barren exposures the calcareous facies of the Mobridge Member takes on a lighter gray color than the non-calcareous facies of the Virgin Creek Member (below) and the Elk Butte Member (above). On the outcrop, however, Mello's (1969) acid fizz test to determine calcareous facies versus non-calcareous facies is an easy method to define the members of the Pierre Shale. Mello (1969) stated that



LOCATION MAP OF FIELD LOCALITIES IN CORSON COUNTY, SOUTH DAKOTA

Fig. 28. Map of localities of measured sections and field investigation sites in the Mobridge/Grand River Valley area, South Dakota.

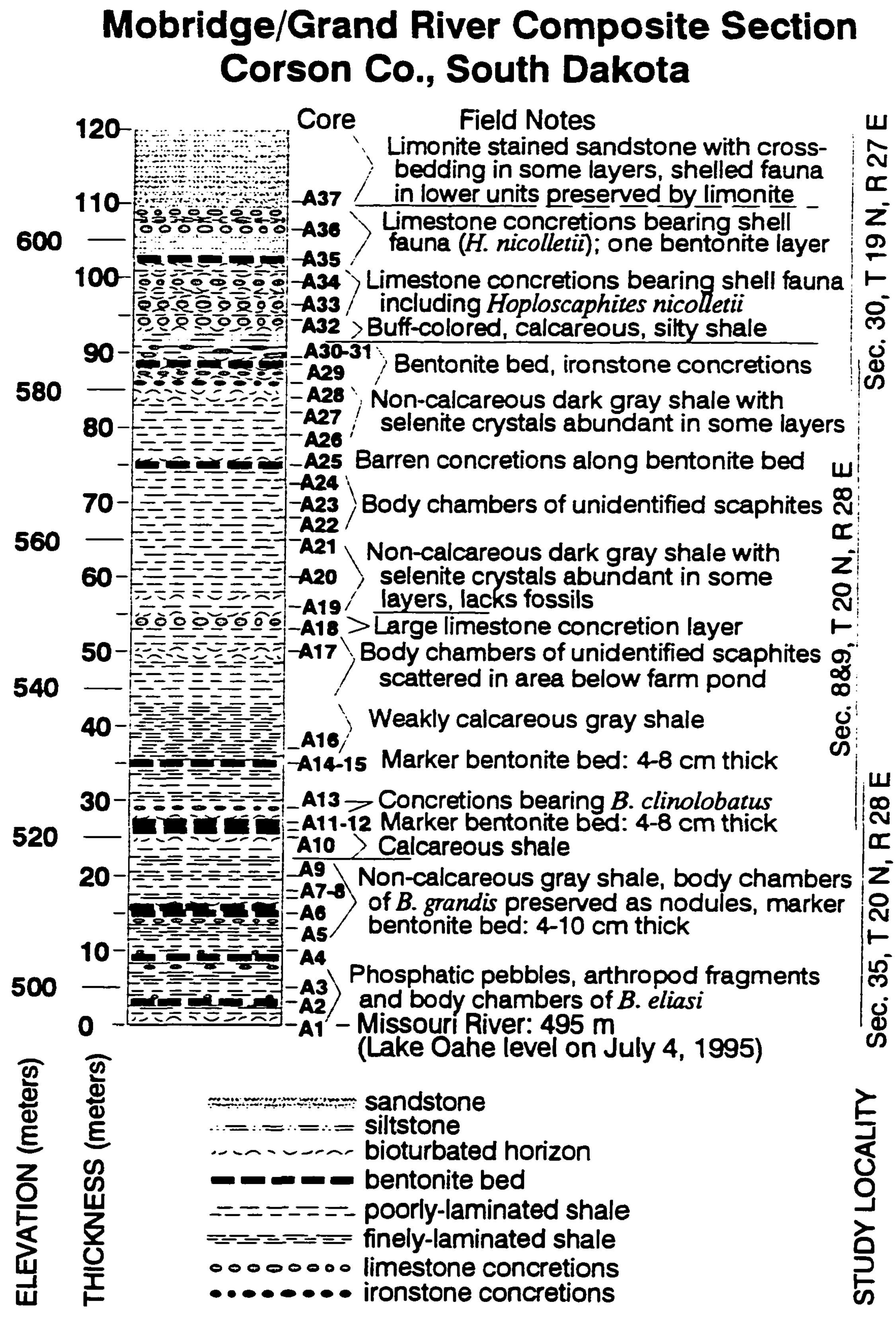


Fig. 29. Composite measured section for the Mobridge/Grand River area, SD.

defining members of the Pierre Shale in the Mobridge area is problematic using macrofossils. By comparison to other localities in this investigation, fossils in the Virgin Creek Member near Mobridge are scarce, and they are even rarer in the overlying Mobridge and Elk Butte members. However, in a road-cut adjacent to the rest area several definitive fossil specimens were found that are comparable to fossils from the Cheyenne River area and the Wyoming field area. Small, yellow-weathering concretions formed from body chambers resembling *Baculites eliasi* were observed to be common within the lower Virgin Creek Member in fresh cutbank exposures several meters above the 1995 reservoir level. These concretions occur in greatest abundance within a zone where small, yellow phosphatic nodules (some resembling coprolites) are abundant. The only other fossils observed were calcareous molds of serpulid worm tubes and fragments of crab carapaces. Many of these were found preserved within the yellow phosphatic pebbles.

Several 1-2 cm thick bentonite beds were noted within non-calcareous shale (facies of the upper Virgin Creek Member). The thinner bentonite beds appear to be discontinuous in surface exposures. Without digging a massive trench it would be practically impossible to determine the exact number of bentonite beds within this poorly exposed interval. They appear partially destroyed by bioturbation. One 4-10 cm thick bentonite near the top of the non-calcareous facies (just above core A6) preserves a smooth bottom surface whereas the upper surface appears to preserve ripple bedding with crests approximately 3 cm high and 20 cm apart (Fig. 30). These ripple marks demonstrate that sea bottom currents were episodically strong enough move sediment into ripple bedding.

Searight (1937) described the Mobridge Member as consisting of gray shale and chalk. The term "marl" is also applicable for some of the exposures of the Mobridge Member in measured section localities. Poorly preserved specimens of baculites displaying flank ribbing and smooth venter typical of *Baculites grandis* were observed just below what may be Mello's "Lower Key Bentonite" within calcareous shale (facies of the Mobridge Member indicated by core A11). A very poorly preserved body chamber cast of *Baculites clinolobatus* was observed in a concretion within two meters above this "Lower Key Bentonite." No other macrofossils were observed above the middle of the Mobridge Member. This "Lower key bentonite" crops out along the base of several slump escarpments in the lake-side bluffs south of the rest area. Gray limestone concretions were noted scattered along another thin bentonite bed approximately two meters above what might be Mello's (1969) "Lower Key Bentonite." More limestone concretions were noted in association with another prominent bentonite (4-8 cm thick), possibly Mello's "Upper Key Bentonite," approximately 8 meters above the probable "Lower Key Bentonite." This upper bentonite is approximately two meters below the highest bluff along the shore cutbank, approximately 100 meters south of the rest area parking lot.

Fig. 30. US Highway 12 Rest Area, Corson County, SD. A 4-10 cm thick bentonite bed near the top of the Virgin Creek Member displays a flat undersurface, whereas the top displays ripple bedding that has been highlighted by soft-sediment deformation and bioturbation. The bright yellow appearance of bentonites in the region is a result of mineral dissolution of the volcanic ash. This bentonite crops out along lakeside cutbanks in Sec. 35, T 20 N, R 28 E. Scale on Jacob staffs is 10 cm.

### 6.1.2 Ray Johnson Ranch

A new reference section for the upper Mobridge and Elk Butte members is located on easily accessible outcrops found along creek bed exposures and on a road-cut on an unnamed ranch access road connecting Highway 20 to a point near the rest area and the town of Little Eagle, South Dakota. This locality is on the property of Ray Johnson Ranch in sections 8 and 9, T 19 N, R 28 E. The measured section is illustrated on the middle portion of Fig. 29.

The "Lower and Upper Key Bentonite" beds within the middle of the Mobridge Member were observed along a creek bed below a farm pond about one-half kilometer north of the road in NE, Sec. 8. There is no apparent regional dip in the area, and therefore, correlation was established using an altimeter reading on the bentonite compared with the rest area locality, and a positive acid fizz test on the encasing shales around the bentonite beds. The general appearance of the strata was also recognizably similar; numerous fossil-barren gray concretions were present in float along the stream bed similar in appearance to the concretions associated with the same interval of the Key Bentonite beds in the rest area locality. Above the bentonites, the shale is relatively poorly exposed through the vicinity of a farm pond. Several poorly preserved body chambers of *Hoploscaphites* sp. were observed in the pond dam which had been excavated from this interval in the upper Mobridge Member. Upstream from the pond, closer to the road, a bed of massive limestone concretions occurs within heavily bioturbated, slightly calcareous, silty shale. Several meters above the bed of large concretions the shale becomes more fine-grained, blacker in color, non-calcareous, and finely laminated. This change in facies represents the transition from the Mobridge Member to the overlying Elk Butte Member.

The construction of the ranch access road required the removal of a large amount of sediment from the side of a small hill on the east side of the creek (~30 meters higher than the road). The material was probably used in the construction of a pond dam across the road. This road-cut provides an exceptional exposure of the upper Elk Butte Member including the Pierre Shale/Fox Hills boundary at the very top. The butte is capped with buff-colored silty shale that yielded partial body chambers of *Hoploscaphites nicolletii*, the indicator fossil of the Trail City Member of the Fox Hills Formation (Landman & Waage, 1993) (see Fig. 22B, p. 68). The upper 25 meters of the Elk Butte Member appeared to be barren of fossils. The gray to black fissile, non-calcareous shale displayed abundant selenite and barite crystals in fractures exposed while excavating to collect core samples. Small, barren limestone and ironstone concretions also occur in the upper Elk Butte Member. Four discontinuous beds of red-weathering, non-calcareous, ironstone concretions and at least one bentonite bed were observed within the top five meters of the Pierre Shale. Stringers of yellow-weathering mineral salts (jarosite) highlight of hummocky cross-stratification at the top of the formation. Although not clearly exposed, the sharp change in lithology suggests the possibility of an unconformable surface. This exposure is strikingly similar to an exposure of the Pierre Shale/Fox Hills boundary transition described by Daly (1991) for the interval exposed in Seaman Park on Beaver Creek in Linton, North Dakota (approximately 75 kilometers to the north-northeast).

The Pierre/Fox Hills contact at Seaman Park in Linton, North Dakota is well exposed at the top of a high cutbank. The gray silty shale below the contact displays stringers of yellow mineral salts (jarosite) that highlight mottled bedding textures. The contact with the tan, silty beds above is indistinct, possibly due to bioturbation. Above the formation boundary, the buff, silty-to-sandy mudstone of the Fox Hills Formation displays thin- to thick-bedded pods of current sorted sediment mottled by bioturbation. Unlike the Trail City Member in Corson County, South Dakota, however, there are no fossiliferous concretions.

### 6.1.3 Alan Johnson Ranch

The uppermost Pierre Shale and the Trail City and Timber Lake members of the Fox Hills Formation crop out along the valley of Oak Creek on the west side of SD Highway 63 on the Alan Johnson Ranch. A section was measured, and core samples for sedimentological and geochemical analyses were collected from fairly well exposed outcrops in SW, Sec. 30, T 19 N, R 27 E (top portion of Fig. 29). In this locality the Pierre Shale is poorly exposed along the creek and lowest portions of the hillsides. The transition to the silty gray shale of the Trail City is poorly exposed. However, a change in the steepness of the slope along the lowest hillsides probably represent the transition from the Pierre Shale to the siltier Trail City Member. Three prominent beds of concretions exposed on the lower hillsides yielded *Hoploscaphites nicolletii*. Two additional concretions beds within the transition to the rust colored, sandier Timber Lake Member yielded additional specimens of *Hoploscaphites nicolletii*. Landman & Waage (1993) describe four different faunal zones for this 10 meter thick interval, each with a different characteristic molluscan fauna: 1) a lower *Hoploscaphites nicolletii* Assemblage Zone, 2) *Limopsis - Gervillia* Assemblage Zone, 3) an upper *Hoploscaphites nicolletii* Assemblage Zone, and 4) *Protocardia-Oxytoma* Assemblage Zone (Landman & Waage, 1993). Representative specimens of each of these concretion zones were observed in float on the hillsides of Alan Johnson Ranch.

The buff-colored, silty shale around the concretions in the Trail City Member lacked distinct bedding structures, possibly due to heavy bioturbation. Ammonites preserved as casts or as original shell material are fairly common as float. The sandstone of the overlying Timber Lake Member displays lamination and flaggy cross bedding in its lower exposures; higher up, it displays massive cross bedding more typical of sandstones formed in near-shore and littoral depositional environments. The transition from the Trail City Member to the Timber Lake Member is also marked by a change in slope. The Timber Lake Member forms steep bluffs throughout the hilltops along the Grand River Valley. This break in slope is also apparent along the hillsides of the Moreau River Valley south of Timber Lake, South Dakota, and is probably responsible for similar breaks in slope along the hilltops of the Cheyenne, Bad, and White rivers in the central and south-central portions of South Dakota.

The communities of Mobridge and Timber Lake have small museums that display local fossils. The museum in Timber Lake has a particularly important collection of fossils from the Grand River Valley region, and is an excellent starting place to begin research in the vicinity.

## 6.2 WESTERN FLANK OF THE BLACK HILLS, WESTON CO., WYOMING

In the type area on the Old Woman Anticline near Redbird, Wyoming, Gill & Cobban (1966) divided the Pierre Shale into three members: the Lower Unnamed Shale Member, the Kara Bentonitic Member, and the Upper Unnamed Shale Member. The Fox Hills Formation (undivided) overlies the Upper Unnamed Shale Member. For comparison with the section in Badlands National Park, according to Gill & Cobban, the interval containing the range zones of *Didymoceras cheyennense*, *Baculites compressus*, and *Baculites cuneatus* occur in the upper portion of the Lower Unnamed Shale Member, and is either missing or covered in the type area. According to Gill & Cobban's section measurements at Redbird, the interval encompassing the *Baculites compressus* Zone upward to the base of the Fox Hills Formation is in the order of 1061 feet (323 m), encompassing 345 feet (105 m) of the upper portion of the Lower Unnamed Shale Member, 36 feet (11 m) of the Kara Bentonitic Member, and 680 feet (207 m) of the Upper Unnamed Shale Member.

Unfortunately, access to the private lands in the Redbird, Wyoming type area was not permitted during this investigation. Therefore, investigations of the upper Pierre Shale/Fox Hills along the western flank of the Black Hills focused on accessible outcrops in Weston County, Wyoming (Fig. 31). Field evaluation of outcrops began with examination of roadside outcrops along US Highway 16 between Moorcroft and Upton,. Wyoming, and along Wyoming routes 116, 450, and 451 in Weston County. Whereas the small roadside cuts yielded fossils, they proved generally unusable for the establishment of correlative sections. However, a measurable section encompassing the upper Pierre Shale/Fox Hills interval was found on public land accessible via oil field roads in the Osage Oil Field in sections 16, 17, and 22, T46N, R64W. Additional field reconnaissance secured a second location in the Mush Creek Oil Field in section 10, T44N, R63W.

A composite measured section for the study interval in Weston County,

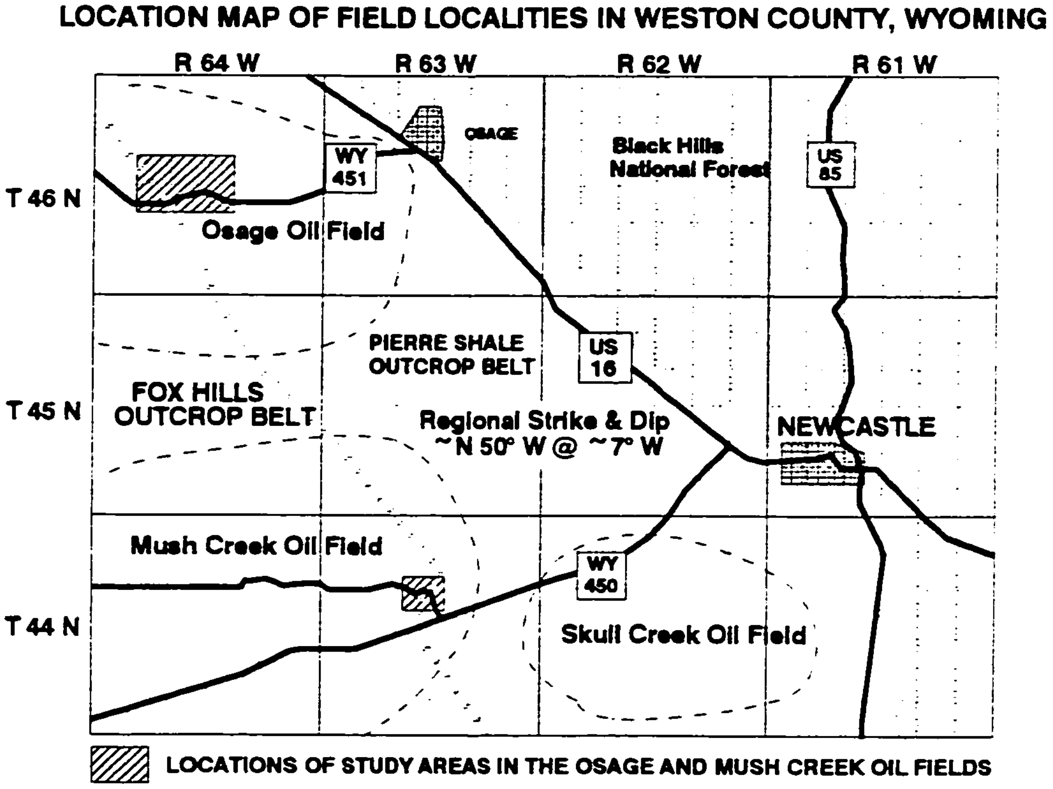


Fig. 31. Map of a portion of Weston County, Wyoming showing study localities.

Wyoming, including stratigraphic locations of core samples, is presented in Fig. 32. This composite measured section includes intervals from three study localities. The lowest interval (encompassing cores E1-E3) in the upper portion of the Lower Unnamed Shale Member in the Osage Oil Field. The middle interval encompasses the Kara Bentonitic Member and the Upper Unnamed Shale Member (in a continuous measured section from core E4 to core E25). Core E25 was collected from a prominent limestone concretion marker horizon at the top of the Pierre Shale near the top of the *Baculites clinolobatus* Zone). The upper portion of this composite measured section represents a locality in the Mush Creek Oil Field. It starts at the top of the same concretion marker horizon at the top of the *Baculites clinolobatus* Zone and continues upward into the Fox Hills Formation. Two cores, E26 and E27, were collected from this upper interval. Details about each of the intervals are presented below.

### 6.2.1 Osage Oil Field (AMNH Locality 3194)

The upper Pierre Shale/Fox Hills interval is partially exposed on the southern side of the broad valley of Sheep Canyon Creek. The strata of the Pierre Shale is dipping gently to the southwest at between 5° (measured on a bedding surface near the top of the *Baculites clinolobatus* Zone) and 7°(measured on a bedding surface within the Kara Bentonitic Member). Because the beds are dipping at slightly

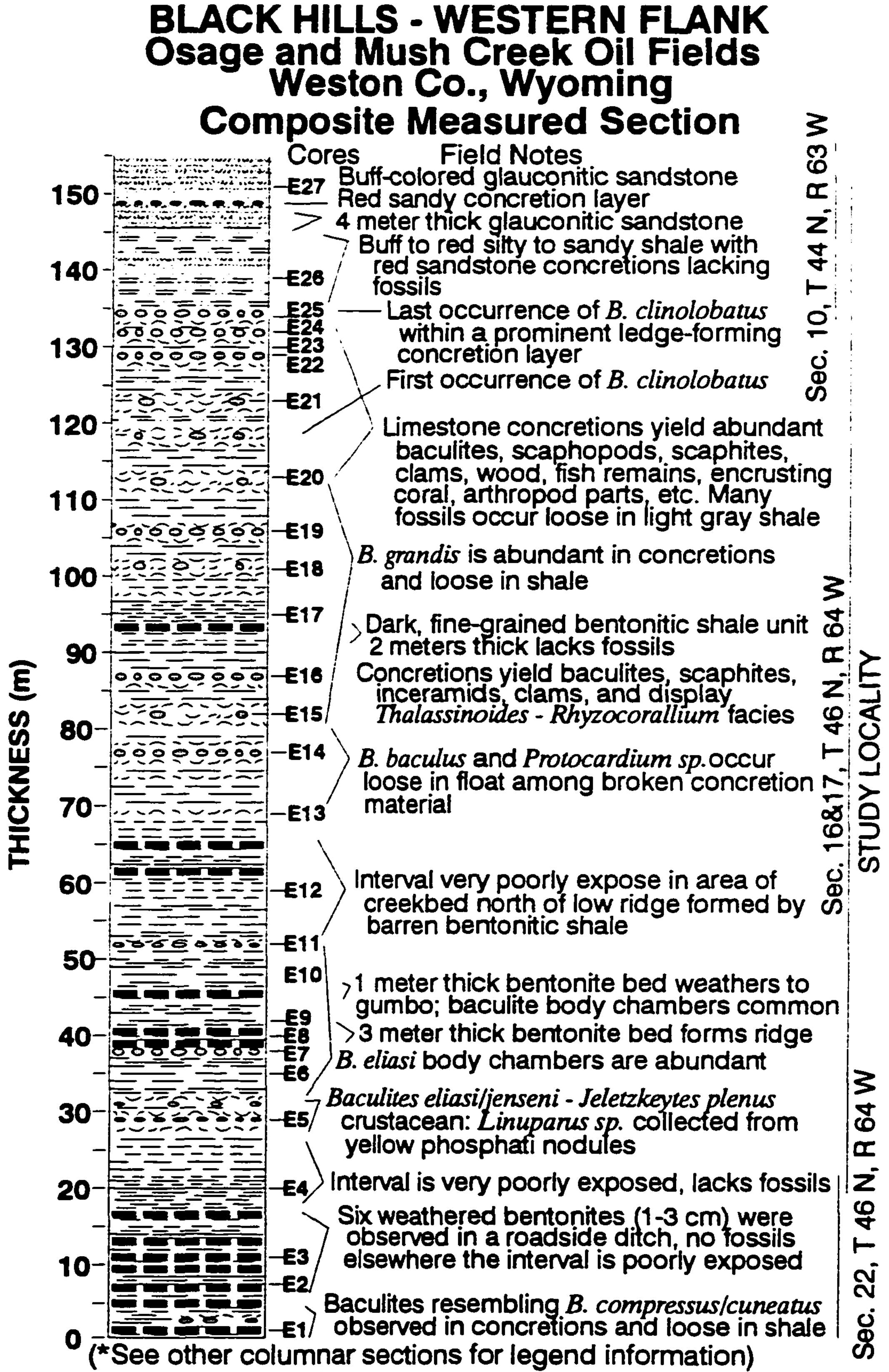


Fig. 32. Composite measured section of the upper Pierre Shale and lower the Fox Hills Formation in the Osage and Mush Creek Oil Fields in Weston County, Wyoming.

different angles, the measured total thickness of the study interval may be slightly greater than the thickness presented in the measured section. For example, the thickness of the study interval measured by Gill & Cobban (1966) on the Old Woman Anticline is nearly double the measured thickness presented in this report for the Osage Oil Field. A thickness of 150 meters was measured from the base of the *Baculites compressus* Zone to the base of the first massive sandstone of the Fox Hills Formation based on a triangulation projection of surface distances with a dip angle of 5°. An estimate based on a dip of 7° would change the measured thickness of 150 meters to approximately 200 meters. For comparison, Gill & Cobban's measured thickness of the same stratigraphic interval at Redbird is 323 meters.

In general, the study interval in the Osage Oil Field is very poorly exposed. The most obvious stratigraphic feature in the Osage Oil Field study area is a resistant bentonitic shale unit. Due to the gentle regional dip to the west, this unit forms a low ridge that rises above the surrounding grasslands. This ridge strikes approximately N 35°W across NW section 16, T 46 N, R 64 W, and the beds dip approximately 7°W into the Powder River Basin. Examination of the ridge showed that the more resistant bed consists of a massive bentonite approximately 3 meters thick (cores E8 and E9). Stratigraphically above the massive bentonite were additional thin bentonite beds and another 1 meter thick bentonite bed, about 9 meters above the base of the lower bentonite. An abundance of nodular casts and concretions encasing the body chambers of *Baculites eliasi* helped to establish that this prominent ridge-forming marker horizon is the Kara Bentonitic Member, marking the boundary between the Lower and Upper Unnamed Shale members. At Osage, the Kara Bentonitic Member consists of silty montmorillonite-rich swelling clays that weather to a barren sticky gumbo when wet. Upon drying, the bentonite displays a thick popcorn-like texture. The bentonite layers are generally devoid of vegetation. Between 5 and 10 meters below the most prominent ridge-forming bed is a zone of fossiliferous phosphatic concretions bearing specimens of lobster-like crustaceans in light yellow-gray weathering concretions (core E5) (see Fig. 25, p. 71). The ammonite *Jeletzkytes plenus* was observed within this horizon. Specimens of *Baculites eliasi* also first appear in this horizon and occur in abundance through the Kara Bentonitic Member. A 20 to 30 meter thick interval above the Kara Bentonitic Member containing fossils of *Baculites eliasi* is very poorly exposed in the vicinity of an intermittent creek bed on the west side of the ridge.

Another well exposed stratigraphic interval approximately 20 meters thick contains the upper portion of the Lower Unnamed Shale Member in the center of section 22, T 46 N, R 64 W (cores E1-E3). This exposure is along a small hill where the main oil field access road (WY Route 451) cuts into a low, gentle ridge about 16 meters high. Running water in ditches along the road have exposed gray silty shale with numerous thin, rusty-colored bentonite beds spaced between 0.3 to 2 meters apart. Fossils found as float in concretions along the hillside resemble *Baculites compressus* at the base and *Baculites reesidei* near the top. The Kara Bentonitic Member is not exposed along this section of road, however, based on the trend of the ridge of Kara Bentonitic Member to the north and west of the road (mentioned above). This interval is interpolated as occurring between 20 to 30 meters stratigraphically below the base of the Kara Bentonitic Member. The occurrence of *Baculites compressus* through *Baculites reesidei* is significant because Gill & Cobban (1966) observed that the interval was "covered, thin, or missing" in the Redbird section.

The creek on the west side of the ridge formed by the Kara Bentonite Member flows into a small pond in NE, Sec. 17, T 46 N, R 64 W. West of the creek the land rises gradually to a low escarpment about 700 meters to the west. On this slope beds of fossiliferous concretions occur in increasing abundance up-section. Specimens of *Baculites baculus* occur in abundance as float on the lowest slope west of the creek. Along with the baculites are abundant specimens of the bivalve *Protocardium* sp. The ammonite *Rhaeboceras* sp. is not uncommon. The weathered host rock of these concretions and fossils is a silty, bioturbated marl. Westward and up-slope the fragments of fossils and concretions litter the surface. Up-section, baculites changes from resembling *Baculites baculus* to resembling *Baculites grandis*.

The upper *Baculites grandis* through *Baculites clinolobatus* zones in the Upper

Unnamed Shale Member of the Pierre Shale are generally poorly exposed in section 17. However, large fossiliferous concretions are abundant in both zones and appear to occur in laterally continuous beds. A small, intermittent stream channel through the southeast corner of section 17 and the southwest corner of section 16 provides access to relatively fresh exposures of the shale in this interval. Approximately 25 meters below the first occurrence of *Baculites clinolobatus* is a prominent bentonite bed about one meter thick (below core E17). This bed represents a division between the lower and upper *Baculites grandis* Zone. Above this bentonite bed the formation is increasingly calcareous as suggested by the abundance of calcareous concretion material. Concretions in the upper *Baculites grandis* Zone display a diverse fauna as compared with localities in South Dakota. Osage concretions contain baculites, *Hoploscaphites* sp., inoceramid fragments, scaphopods, gastropods, bivalves (*Protocardium* sp.), encrusting corals, bryozoans, arthropod fragments, wood fragments, fish bone and scales. The concretions preserve detail of bioturbation networks in these shell hash beds including *Thalassinoides, Planolites, Rhyzocorallium*, and *Teichichnus*. Many baculite shells appear to have been packed with fecal pellets, probably by small crustaceans.

A very prominent bed of concretions bearing *Baculites clinolobatus* forms a well-developed escarpment that trends northwestward diagonally across section 17, T 46 N, R 64 W (core E25). This concretion bed marks the top of the most fossiliferous zones in the Pierre Shale. Above the *Baculites clinolobatus* Zone fossils are absent except for massive bioturbation networks exposed by weathering on the bottom and sides of massive limestone concretions (Fig. 33). Above this ledge-forming concretion zone the sediment becomes increasingly sandy and stained with limonite for approximately 15 meters up-section until the first massive sandstones of the lower Fox Hills Formation occurs. In the Osage Oil Field these beds above the *Baculites clinolobatus*-bearing concretions are very poorly exposed and deeply weathered. A few sandstone ledges and rust-colored concretions crop out amongst the alluvial cover. A much better exposure of the upper Pierre Shale transition with the overlying Fox Hills Formation is exposed in the Mush Creek Oil Field.

### 6.2.2 Mush Creek Oil Field

An exceptional exposure of the upper Pierre Shale/Fox Hills transition interval was created by an excavation for an oil well platform in the side of a bluff in SE, Sec. 10, T 44 N, R 63 W. This locality already had fairly steep hillsides beneath a ledge-forming escarpment of Fox Hills Sandstone, so the excavation exposed fresh, unweathered bedrock. The bluff is on the northeast side of Mush Creek at a bend in Fairview Road just under one mile north of the intersection with Highway 450 (see Fig 31).

On the south side of the road where it bends near the abandoned oil platform

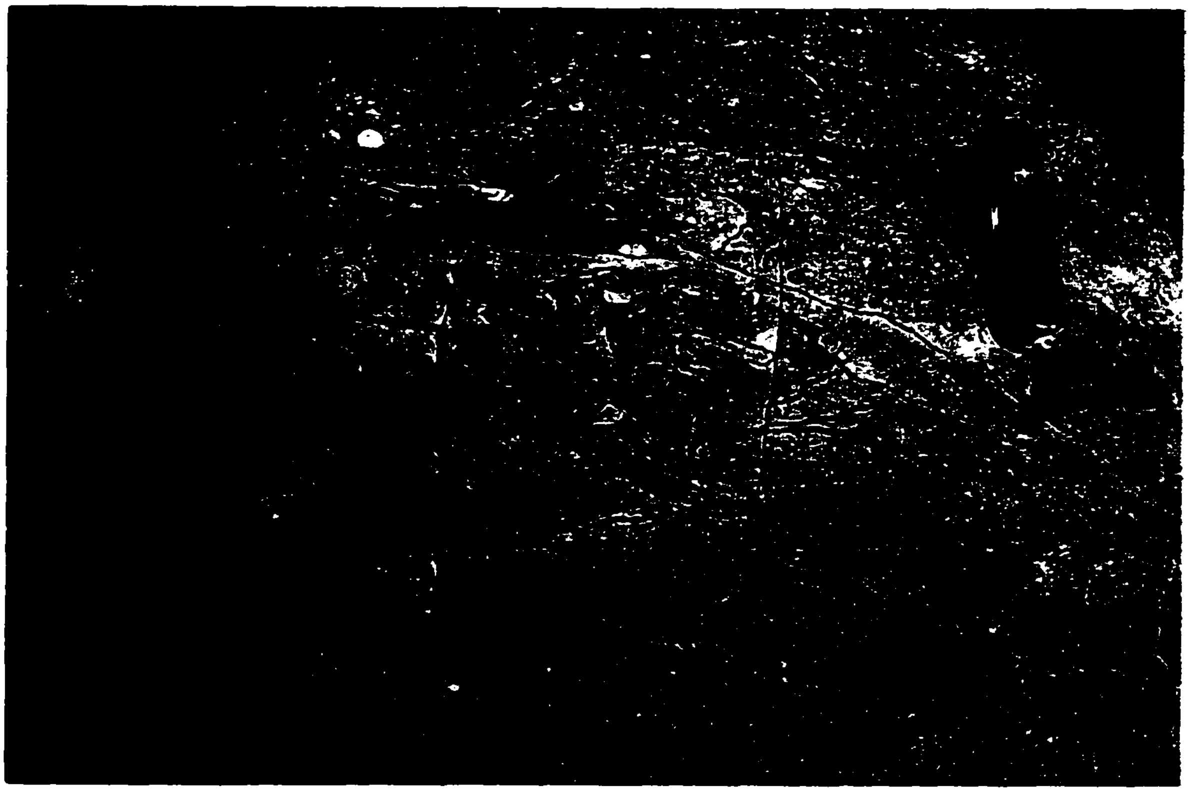


Fig. 33. Osage Oil Field, Weston County, Wyoming. Surface weathering showing a complex bioturbation network preserved on the side of a large limestone concretion from above the *Baculites clinolobatus* Zone in Sec. 17, T64N, R64W. Large burrows represent *Thalassinoides*. Smaller burrows are *Chondrites* and *Planolites*. Length of knife is 9 cm. Burrow borders were highlighted with a marker pen.

excavation, large concretions bearing *Baculites clinolobatus* occur in a poorly exposed, but traceable horizon, along ravines carved into the upper Pierre Shale. On the north side of the hill the land rises to bluffs of massive Fox Hills Sandstone. In the interval between *Baculites clinolobatus* and the massive sandstone bluff, several buff to red iron-stained silty sandstone concretion horizons crop out among beds of red-weathering siltstone and fine-grained sandstone. The oil well platform excavation is in the top of this interval and has exposed massive glauconitic marly sandstone layers (several meters thick) at the base of a massive sandstone that forms the Fox Hills Sandstone escarpment (core E27). The glauconitic sandstone displays thorough bioturbation which destroyed original bedding structures. This glauconite gives the sandstone a drab-green appearance in fresh exposures, but weathers to a rusty limonite along fractures and exposed surfaces. Based on this observation, it is probably the leaching of glauconite that is the source of much of the limonite staining in the uppermost Pierre Shale in all locations where such staining is observed. A ledge-forming bench beneath the massive upper sandstone units possibly represents an unconformity between the upper Pierre Shale and the base of the Fox Hills Sandstone (just above core E26). The outcrop appearance suggests that the boundary represents a major change from shallow muddy marine facies below to higher energy near-shore or littoral facies above. Unfortunately, no fossils were observed anywhere above the *Baculites clinolobatus* Zone.

In the Redbird area, Gill & Cobban (1966) described the contact with the overlying Fox Hills as gradational, with the boundary being placed arbitrarily at the base of a 1.2 foot (36 cm) thick bentonite (above the *Baculites clinolobatus* Zone) overlain by a 13 foot (4 m) thick, medium greenish-gray, glauconitic sandstone. Weathering of the sandstone produces orange-brown limonitic masses at the base of the Fox Hills. In the Mush Creek locality the contact between the Pierre and the Fox Hills appears somewhat gradational. No prominent bentonite was observed. In the Mush Creek locality the base of the Fox Hills is best represented by the base of the massive glauconitic sandstone unit exposed in the excavation for the oil well platform.

## 6.3 BADLANDS NATIONAL PARK AREA

Non-marine strata of the Tertiary White River Group cover much of the region south and east of the Black Hills in South Dakota and Nebraska. In the Badlands National Park region the upper Pierre Shale crops out beneath the White River Group along stream banks of tributaries of the Cheyenne and White rivers. Outcrops throughout the Badlands National Park area reveal an upper Pierre Shale section in every location studied. Concretions and fossils typical of the *Baculites clinolobatus* Zone were observed in every locality described below. The location of measured sections in the Badlands National Park area is presented in Fig. 34. Localities were established in both the North and South (Stronghold) units of Badlands National Park

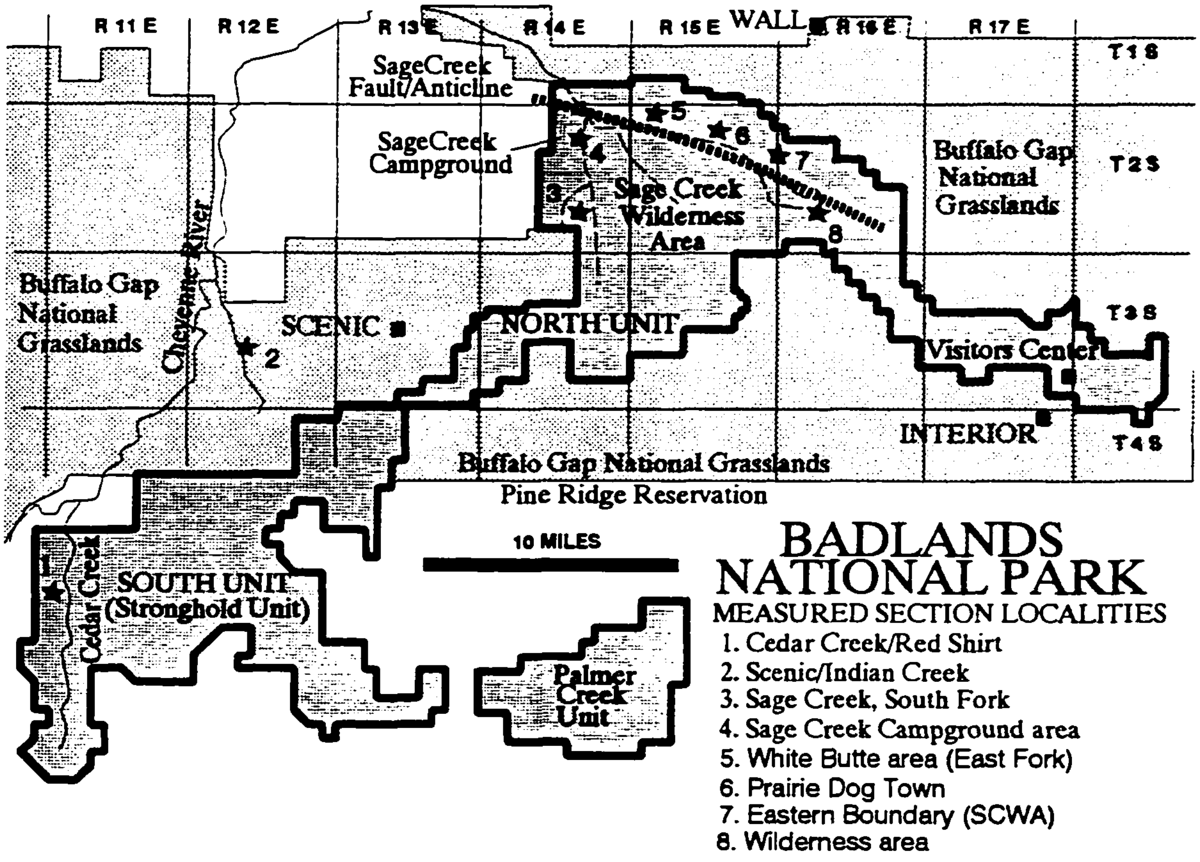


Fig. 34. Location of measured sections in the Badlands National Park area, South Dakota.

with the permission of the National Park Service. Cores for sedimentological and geochemical analyses were collected from the Cedar Creek cutbank near Redshirt Episcopal Church on the western side of the South Unit of Badlands National Park, and from the Sage Creek Campground area in the North Unit of Badlands National Park. A locality beyond the park boundary but between the North and South units was established in the Buffalo Gap National Grasslands west of Scenic, South Dakota. Supplemental localities in the Cheyenne River Valley are discussed in the following section of this chapter.

Badlands National Park was first proclaimed a national monument on January 25, 1939, and raised to national park status by Congress on November 10, 1978. The park was originally established to protect the unique fossil resources of the area, particularly the mammalian faunas the White River beds. The earliest mention of Cretaceous age rocks in the Sage Creek area was an examination of fossils from the creek banks by Evans & Shumard (1854) when the park area was still part of the Nebraska Territory. Throughout the history of exploration and study there was never any attempt to differentiate the Pierre Shale into smaller stratigraphic intervals, with the exception of the uppermost interval between the gray shale typical of the Pierre Shale and below the massive sandy beds of the Fox Hills Formation exposed throughout the region. During early paleontological investigations of the area this interval was referred to as the "Rusty Beds" or "Rusty Member of the Pierre Shale

(Cook, 1922). Toepelman (1922) described this upper interval as a "sandy phase of Pierre." The earliest description of the Badlands stratigraphy by Ward (1922) referred to the upper Pierre Shale as "yellow-brown, variegated with browner and purpler colors in upper portions, forming the top 35 feet" of the Pierre Shale, and called it the "Interior phase of the Pierre." Wanless (1923) described the interval as a "sandy phase of Pierre" but observed that it rested on the Pierre shale with a very irregular surface. He assigned the interval the name "Interior Formation." Ward (1926) vacillated on whether the interval was Pierre Shale or Fox Hills. He also referred to the interval as the "Interior Formation," but concluded that it was equivalent to the basal Fox Hills. Dunham (1961) then added insight by stating that the interval represented a weathering profile associated with leaching of the upper Pierre Shale during Eocene time. He referred to the interval as a "weathered zone" in the Interior Formation. This same conclusion was supported somewhat by Pettijohn (1965). Pettijohn, however, recognized that an outcrop in Section 3, T 2 S, R 15 E (near the Roberts Prairie Dog Town area in the North Unit of Badlands National Park) belonged to the Fox Hills Formation. Pettijohn (1966) named this ancient weathered interval the Yellow Mounds Weathering Profile. He went on to describe the regional extent of the Yellow Mounds Weathering Profile throughout the Western Interior Region. He observed that the weathering profile affected surface exposures associated with a regional Late Eocene peneplain. Sedimentary formations ranging from as old as the Niobrara Formation to as young as the Eocene Slim Buttes Formation were affected by a period of meteoric weathering (which formed an "Eocene paleosol"), and were, according to Pettijohn, in place prior to the deposition of sediments of the overlying Chadron Formation.

Raymond & King (1976) mapped the region encompassing the North Unit of Badlands National Park, but did not attempt to differentiate the Pierre Shale into separate members, nor did they recognize the Fox Hills Formation described by Pettijohn. The upper part of the formation was simply included in a mapped interval called the "Interior zone of local usage." During the course of this investigation, national park personnel preferred the name Yellow Mounds Weathering Profile which was the name applied to the interval at the top of Pierre Shale after published papers by Pettijohn (1965), Retallack (1983) and Retallack (1985). Retallack also interpreted the highly colored interval to represent a deep surface weathering imprint affecting the upper portion of both the Pierre Shale and Fox Hills formations, and that these formations had experienced erosion prior to deposition of Eocene Chadron sediments. Although Retallack recognized both the Pierre Shale and Fox Hills as lithologic units within the park, he made no attempt to differentiate or to identify characteristics of the sediments below what he interpreted as the Cretaceous/Tertiary boundary. As a result, the relationship between Pettijohn's and Retallack's "Yellow Mounds Weathering Profile" and the age and nature of the sediments on which it is imprinted in the national park area remained unclear.

Our discovery of specimens of *Baculites clinolobatus* and other marine species, and the occurrence and significance of glauconitic sand in the uppermost Pierre Shale and Fox Hills formation within the interval affected by Retallack's "Yellow Mounds Weathering Profile" are discussed below. A definition of stratigraphic nomenclature is needed to differentiate the "Yellow Mounds Weathering Profile" from the sedimentary formations that were affected by this late period of weathering. Therefore, the interval of sediments above the *Baculites clinolobatus* Zone and **below** the Fox Hills Formation in the Badlands National Park area is assigned the name **Interior Zone** (after Raymond & King, 1976). The term "Interior Zone" for such beds will be used for the remainder of the discussion in this report. For the sake of clarification, the Interior Zone and overlying remnants of the Fox Hills Formation (made up of sediments of Early Maastrichtian age) in the Badlands National Park area were heavily affected by post depositional, meteoric dissolution processes which occurred during periods of exposure beginning as early as latest Cretaceous time, but continuing into Late Eocene time. The altered weathering imprint on the Cretaceous sediments is called "Yellow Mounds Weathering Profile" (Pettijohn, 1965; Retallack, 1985). Unfortunately, the confusion caused by this "diagenetic relationship" has led to a somewhat chronic nomenclature problem. This is perhaps best illustrated by a common conversation among interested scientists who have grown accustomed to describing the occurrence of fossils in the "Yellow Mounds:" According to Pettijohn's (1966) discussion, this would mean sediments ranging from Early Campanian (Niobrara Formation) to Late Eocene (Golden Valley Formation), depending on the location where the Yellow Mounds is observed. The processes of meteoric weathering are still occurring today, and it is perhaps impossible to differentiate between weathering that occurred in the Early Tertiary from periods of meteoric weathering that may have followed. For the sake of locality discussions below, the term "Yellow Mounds-style weathering" is used in this dissertation without making any assertions as to when the meteoric weathering actually occurred, and is applied to beds in both the upper Pierre Shale and Fox Hills Formation wherever these sediments appear to be altered by ancient or recent weathering processes.

### 6.3.1 Cedar Creek, South Unit Badlands National Park, (AMNH Locality 3212)

The upper Pierre Shale is well exposed in a slumping cutbank along Cedar Creek in the South Unit of Badlands National Park approximately one-half kilometer east of the Redshirt Episcopal Church in SW, SE, Sec. 11, T 42 N, R 47 W (Fig. 35). A measured section for the locality, showing stratigraphic positions for collected core samples, is presented in Fig. 36.

Concretions in the creek bed at the base of the cutbank yield fossils resembling *Baculites compressus*. Because Crandall (1958) observed that this species is an index

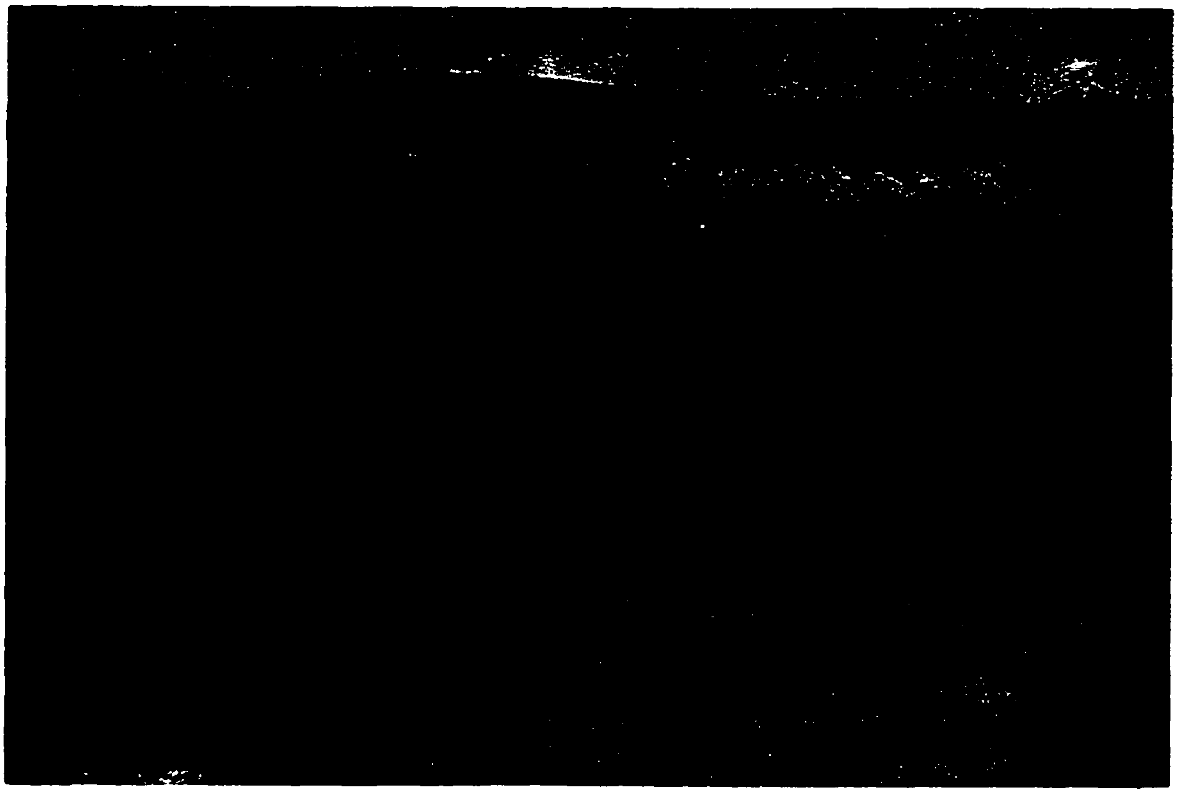


Fig. 35. Cedar Creek cutbank locality, Badlands National Park, South Unit. This photograph is a view of the large cutbank along Cedar Creek below Redshirt Epsicopal Church. Preliminary interpretations are as follows. The darker gray shale of the Verendrye Member (*Baculites compressus* to *Baculites reesidei*) make up the lower third of the hillside. An unconformity separates the underlying Verendrye Member form the overlying Virgin Creek Member. The lighter gray-colored shale on the middle of the slope represent the Virgin Creek Member (*Baculites baculus/grandis* Zones). A 4-10 cm thick bentonite forms a white streak just below the yellow mounds and possible represents a bentonite layer in the *Baculites clinolobatus* Zone. The upper third of the slope represent the "Yellow Mounds" weathering profile imprinted on strata equivalent to the Mobridge and Elk Butte Members. Sandstone typical of Fox Hills lithology is not present beneath the cap of Chadron Formation represented by the grass covered hilltop. Total thickness of the Cretaceous interval is about 48 meters.

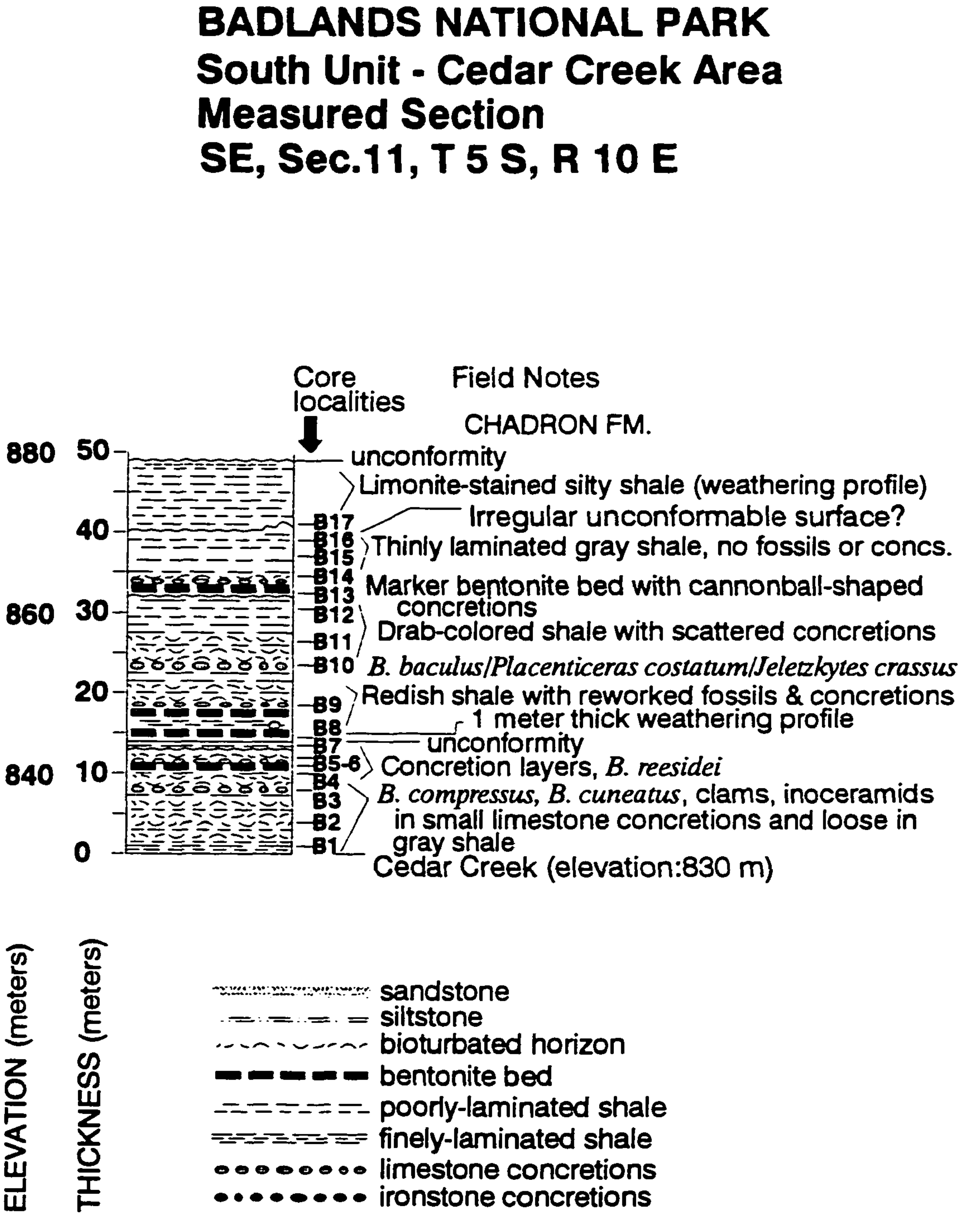


Fig. 36. Measured section for the cutbank and hillside below Redshirt Church, Cedar Creek, South Unit, Badlands National Park.

fossil for the Verendrye Member, the occurrence of this ammonite species means that the member name can be applied to the stratigraphic interval along the creek. The overlying zones of *Baculites cuneatus* and *Baculites reesidei* are well exposed in the lower portion of the hillsides with exceptional specimens found both in situ and as float. Fossils are very abundant and well preserved in both the shale and in concretions that resemble complex bioturbation networks (*Thalassinoides*) preserved in the shale (Fig. 37). Fossils that occur in abundance include the clams *Inoceramus sagensis* and *Protocardia texana*; the ammonite *Jeletzkytes nodosus* is not uncommon, occurring both in concretions and loose in the shale. Most shells appear to be broken by bioturbation or transport. However, many clam specimens and larger baculite fragments are in nearly perfect condition, maintaining their original pearly, iridescent shell luster.

The strata bearing these fossiliferous beds are dipping gently northeast at about 5-10° as depicted by several laterally continuous concretion-bearing beds which crop out along the lower north end of this massive cutbank outcrop exposure. These concretions appear to be associated with thin, discontinuous sand sheets or bentonite beds which are highlighted by yellow-weathering mineral salts (jarosite). These dipping beds appear to be truncated along an unconformity approximately 14 meters above creek level (at core C7 on the measured section). This unconformity is most obvious when observed from a distance of about 100 meters away from the outcrop

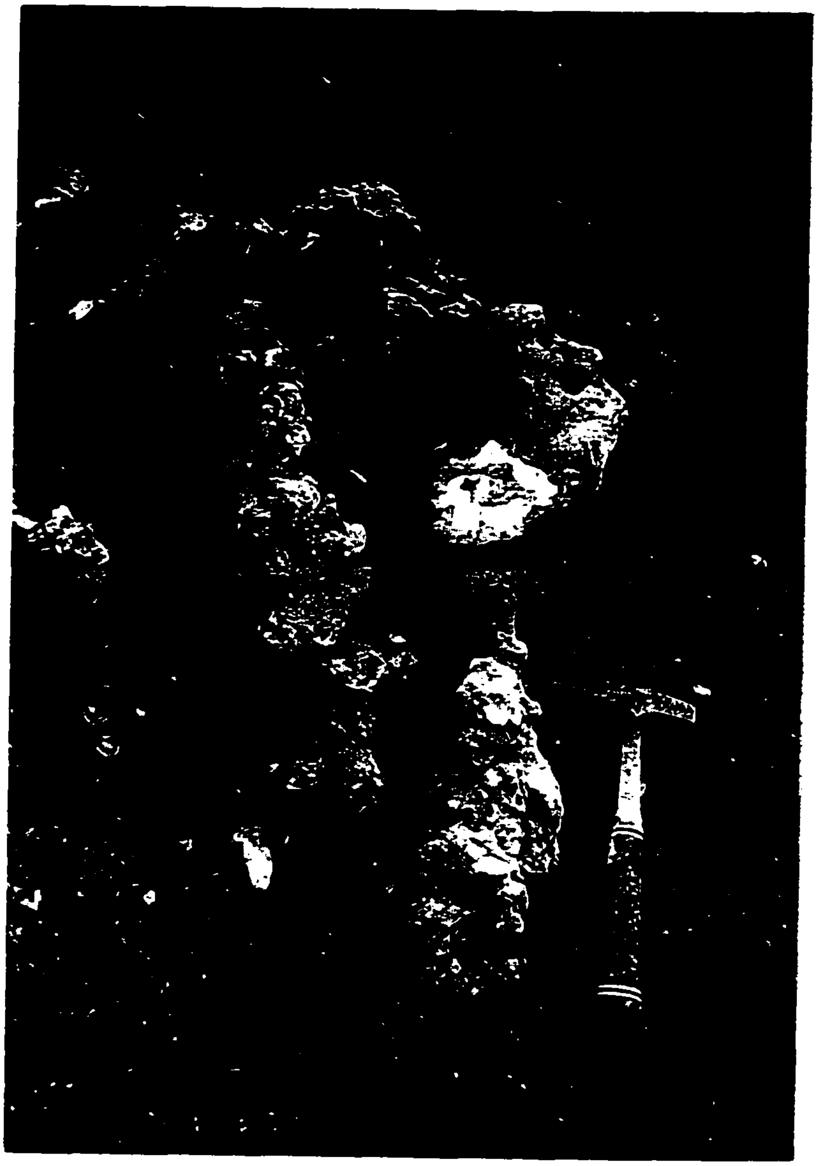


Fig. 37. Cedar Creek cutbank locality, South Unit, Badlands National Park. A large limestone concretion preserves a complex network of burrows (*Thalassinoides*) packed with shell material, mostly clams and ammonite fragments. Numerous similar concretions in this layer represent a concretion bed near the top of the *Baculites reesidei* Zone. The abundance of clams suggest the water depths were shallow. The concretion is about one meter top to bottom.

(Fig. 38). It appears as a recognizable change in lithology with dark gray shale below, and more variable, lighter, rusty-colored shale above. From creek level (where *Baculites compressus* occurs) upward to the unconformity, the shale is generally homogeneous in appearance. Using Crandall's (1958) definition, the name "Verendrye Member" might best apply for the whole interval below the unconformity.

A rust-colored bed approximately 2 meters thick lies on top of the unconformity and highlights the boundary. The abundance of limonite stain in this bed overlying the unconformity suggests that the interval may have experienced subaerial weathering prior to the resumptions of marine sedimentation (based on the occurrence of marine fossils higher in the section). Immediately above the unconformable surface and the 2 meter thick limonite-stained bed, the shale becomes darker, but retains a reddish-brown-gray color upward to the top of fresh exposures on the cutbank. This interval presented perhaps the greatest challenge to the investigation of the Pierre Shale anywhere in the study area. A concretion bearing a body chamber most clearly resembling *Didymoceras cheyennense* was found in a concretion near the top of the cutbank (at core C9). This specimen is illustrated in Fig 13, p. 59.

Samples of shell material of the *Didymoceras*, along with other baculite shell material were analyzed for strontium isotopic contents for geochronology information

Fig. 38. Cedar Creek cutbank locality, South Unit, Badlands National Park. Truncation of gently-dipping clinoform beds by submarine erosion give the appearance of an angular unconformity. The overlying, lighter-colored units contain intraclasts and reworked Campanian fossils (including *Didymoceras cheyenennse*). Phil is collecting a core sample at the unconformable boundary between the Verendrye Member (below) and the Virgin Creek Member (above). Specimens collected below the boundary include *Baculites reesidei*. Above the boundary the reddish color of the sediment suggests that the sediment may have been partially oxidized by subaerial exposure prior to being reworked and redeposited.

(discussed in Chapter 9). The discovery of this fossil created great anxiety about our interpretations because it was found out of place in relation to Cobban's chronology of ammonite biozonation form the Western Interior. However, in retrospect, the discovery forced the close examination of field work, and ultimately served as a very critical piece of evidence for our concluding interpretations.

The zone where the *Didymoceras* was found also yielded abundant red-weathering ironstone concretions and gray limestone concretions, both bearing *Inoceramus sagensis* and crushed, small, poorly-preserved baculites that could not be identified as a particular species. One large pedestal-like concretion yielded a specimen of *Placenticeras costatum* (Fig. 39). These concretions display fairly irregular orientations, some with their longest axis in a vertical direction. They also do not appear to occur in laterally continuous beds like concretions observed elsewhere. The lack of regular bedding and the concretions' unusual orientations suggested that they may have been reworked from older sediments.

Despite the weathered surface cover in the interval immediately above the cutbank it is possible to discern at least one laterally continuous bed of large limestone concretions bearing crushed body chambers resembling *Baculites baculus* or possibly *Baculites grandis*. This concretion horizon is 9 meters above the unconformity (23 m above the creek). The shale around the limestone concretions has an drab or olive gray color and is slightly calcareous. This color consistency

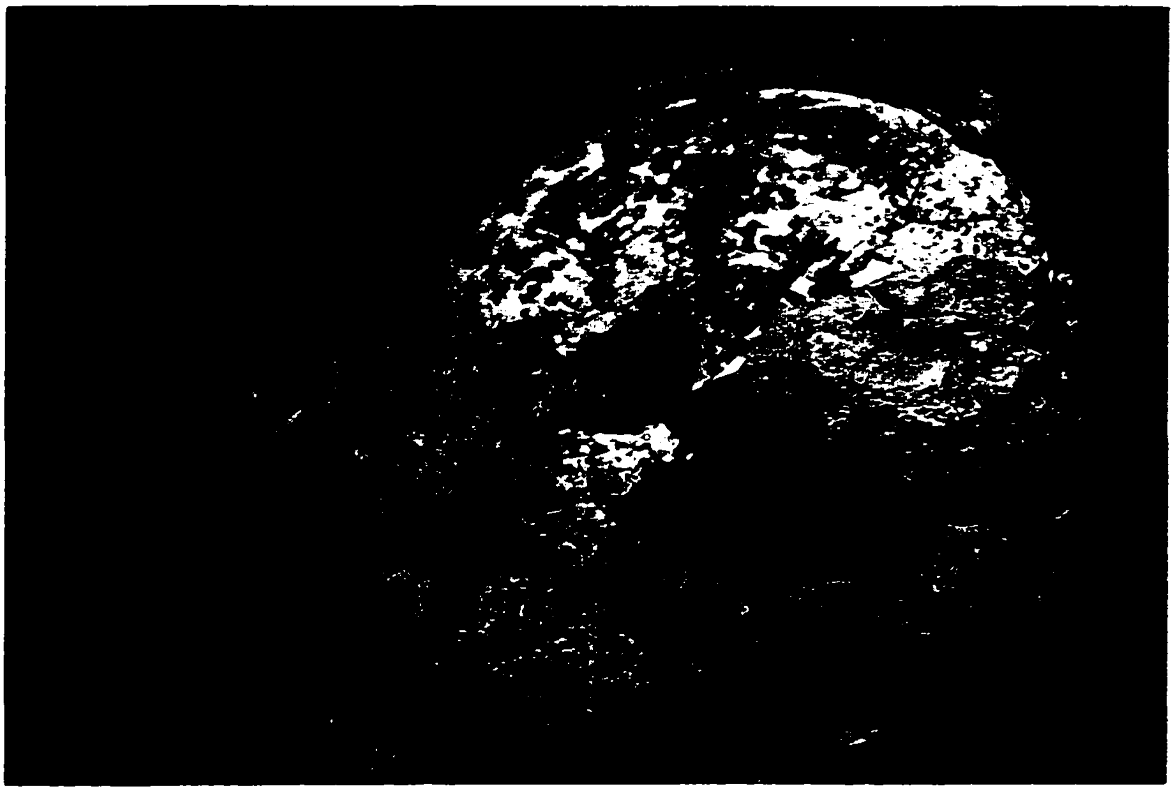


Fig. 39. Cedar Creek cutbank locality, South Unit, Badlands National Park. A *Placenticeras costatum* caps an unusual limestone concretion exposed by erosion of the poorly consolidated shale at the top of the cutbank. The ammonite was found just below a bed of massive concretions bearing baculites specimens must resembling *Baculites baculus* (SE, Sec. 11, T 42 N, R 47 W). The ammonite is approximately 35 cm in diameter.

continues up-section to a distinct bentonite bed (approximately 32 meters above the creek). The bentonite is 8-10 cm thick and yields abundant cannonball shaped concretions (~ 15 cm diameter) with thin selenite-bearing crusts. Above the bentonite the shale turns darker gray, non-calcareous, and becomes thinly laminated with small selenite flakes. This dark interval is only a few meters thick, and quickly changes up-section to the deep reddish orange and yellowish colors typical of the "Yellow Mounds Weathering Profile" (beneath the overlying basal Chadron Formation) of Retallak (1983). Evidence that this weathering phenomenon is pre-Eocene is seen in the occurrence of fractures colored with limonite stain that penetrate in places deep into the underlying gray shale. From a distance, the color is observed to change along an irregular surface within or near the base of the weathering profile. This color change surface displays the classic appearance of an unconformity (below core B17).

Above the interval bearing the *Didymoceras* specimen the shale grades from non-calcareous to slightly calcareous (near the large concretion layer), back to non-calcareous shale below the Yellow Mounds Weathering Profile. Based on this criterion and using Mello's (1969) definitions, the member names "Virgin Creek," "Mobridge," and "Elk Butte" might be applied to this interval, however, without observed diagnostic fossils this interpretation is provisional. The lack of sandstone beds and Fox Hills fauna beneath the Chadron Formation suggests that the Fox Hills

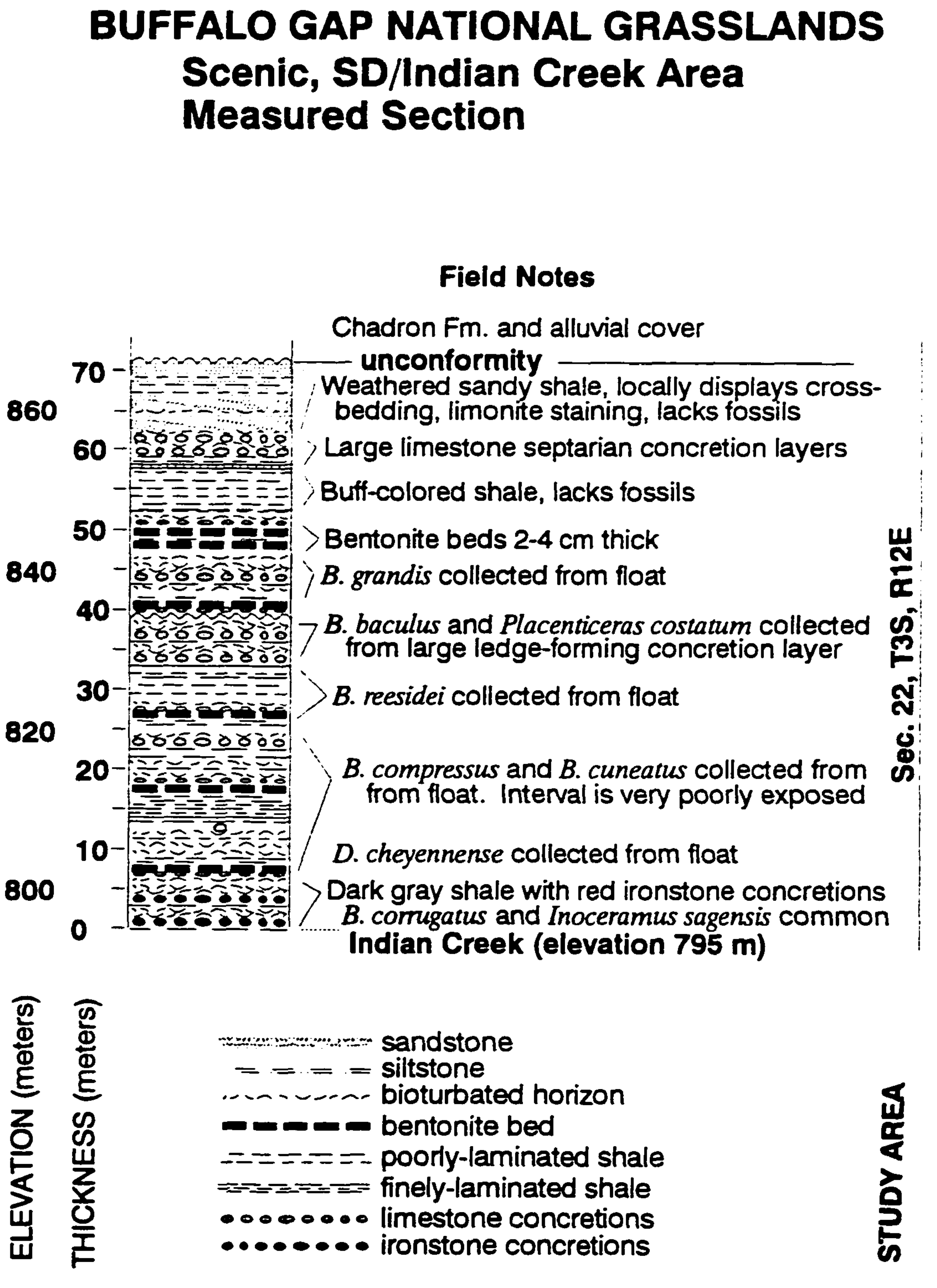
Formation was either never deposited or was stripped away by erosion.

### 6.3.2 Indian Creek Area west of Scenic, SD (AMNH Locality 3225)

A 10 kilometer gravel road that extends directly west from the town of Scenic, South Dakota leads to the valley of Indian Creek, a tributary of the Cheyenne River. The creek meanders along a narrow flood plain in a valley carved into the upper Pierre Shale. Much of the Indian Creek valley is part of the Buffalo Gap National Grasslands. Outcrops of weathered shale bearing fossiliferous concretions are widely dispersed throughout this large roadless area. Access is limited to walking through thick grassy slopes and by driving a two-track jeep trail that is not passable when wet.

Fig. 40 represents a measured section for the hillsides on the eastern side of Indian Creek throughout section 22, T3S, R12E. Thickness of units were measured using specific elevations from recognizable locations on a topographic map of the area in conjunction with a hand operated altimeter and a Global Positioning System receiver. Most of the valley is covered in thick grass, with deeply weathered exposures of the shale limited to small intermittent drainages scattered on the hillsides, and slumped cutbanks along Cedar Creek.

A cutbank along Indian Creek in NW, Sec. 27, T 3 S, R 12 E revealed a red-weathering concretion-bearing zone of large inoceramids, probably *Inoceramus sagensis*. Nearly complete, but very fragile, specimens resembling *Baculites*



**BUFFALO GAP NATIONAL GRASSLANDS**
**Scenic, SD/Indian Creek Area**
**Measured Section**

Fig. 40. Measured section for the Buffalo Gap National Grasslands area west of Scenic, South Dakota.

*corrugatus* were found weathering directly from the fresh shale exposed by the stream (see Fig. 14A, p. 60). Shells lie preferentially with their long axes in a north to northeast direction. The strata in the cutbank also displays a slight dip in a northeast direction. Two body chamber fragments resembling *Didymoceras cheyennense* were also collected from the upper stream cutbank.

On the lower hillsides along Indian Creek the Pierre Shale is very poorly exposed. Fossil fragments among pieces of broken concretions occur as float on patches of weathered shale in the deep prairie grass. Fragments of fossils resembling *Baculites compressus* were observed as float.

A general change in the appearance of the weathered shale occurs approximately 30 meters above creek level. Abundant large limestone concretions bearing inoceramids, the ammonite *Placenticeras costatum*, and baculites most resembling *Baculites baculus* were observed within an interval between 35 to 40 meters above stream level. The concretions appear to occur along laterally continuous beds. The abundance of concretions in this interval, along with a higher calcareous content of the shale, is probably responsible for the more resistant weathering character of this interval. It forms the cap-rock for a grassy north-to-south-trending ridge through the middle of section 22, T3S, R12E. This ridge is approximately 30 to 35 meters below the basal Chadron Formation. Specimens of body chambers resembling *Baculites grandis* are fairly common in the light gray shales on the hillsides above the ridge-forming unit. Specimens were collected from concretions above a prominent bentonitic horizon approximately 48 meters above creek level. No specimens resembling *Baculites clinolobatus* were collected in the Indian Creek area; large limestone septarian concretions, however, are abundant along the upper hillsides. These nodules resemble similar deeply-weathered concretions in the upper *Baculites clinolobatus* Zone in the North Unit of Badlands National Park (discussed below).

Above this weathered concretion-bearing interval, the shale grades upward into buff and red colored mudrocks typical of the interval referred to as the Yellow Mounds Weathering Profile in the park. At Indian Creek, the uppermost portion of this interval is quite variable in appearance and composition. It is found in outcrops along eastern Indian Creek Valley hilltops. Limonite has accumulated in more porous, sandy layers which occur as small scattered pods through the shale near the top of the Cretaceous section. In places, these iron stains appear to enhance cross bedding structures. However, no massive sand beds typical of Fox Hills-type lithology were observed in the Indian Creek area. The overlying Chadron Formation sandstone and mudrock is very white in contrast to the yellow and red coloration of the Interior Zone. Gravel conglomerate of Pleistocene terraces form a resistant cap-rock along the ridge along the eastern side of the valley. Gravel from these terrace deposits cover much of the uppermost slopes of the hillsides.

The total thickness of the exposed Pierre Shale section is slightly more than 70 meters, with less than 60 meters for the interval including the *Baculites compressus* Zone to the base of the Chadron Formation.

### 6.3.3 Sage Creek Wilderness Area, North Unit, Badlands National Park

The upper Pierre Shale/Fox Hills interval is exposed along the tributaries of Sage Creek throughout much of the Sage Creek Wilderness area. Several AMNH fossil collecting localities have been designated throughout wilderness area in the North Unit of Badlands National Park. During the summer of 1995 a composite reference section was compiled; core samples for sedimentological and geochemical analyses were collected from three locations around the Sage Creek Campground and from an exposure of the Fox Hills Formation along the Sage Rim Road east of the campground. This composite measured section is illustrated in Fig. 41. The collection of core samples is discussed below.

Fossils from of the *Baculites compressus* and *Baculites cuneatus* zones were collected from the creek bed and cutbank on the east side of Sage Creek just a short distance north of the Sage Rim Road bridge in SE, Sec. 34, T 1 S, R 14 E (AMNH Locality 3207) (Fig. 42). Core samples C1 through C6 were collected from this cutbank. Fossils collected from concretions along the creek include the nautiloid *Eutrephoceras dekayi*, the ammonites *Placenticeras meeki* and *Jeletzkeytes nodosus*,

**BADLANDS NATIONAL PARK**
**Sage Creek Campground Area**
**Measured Section**

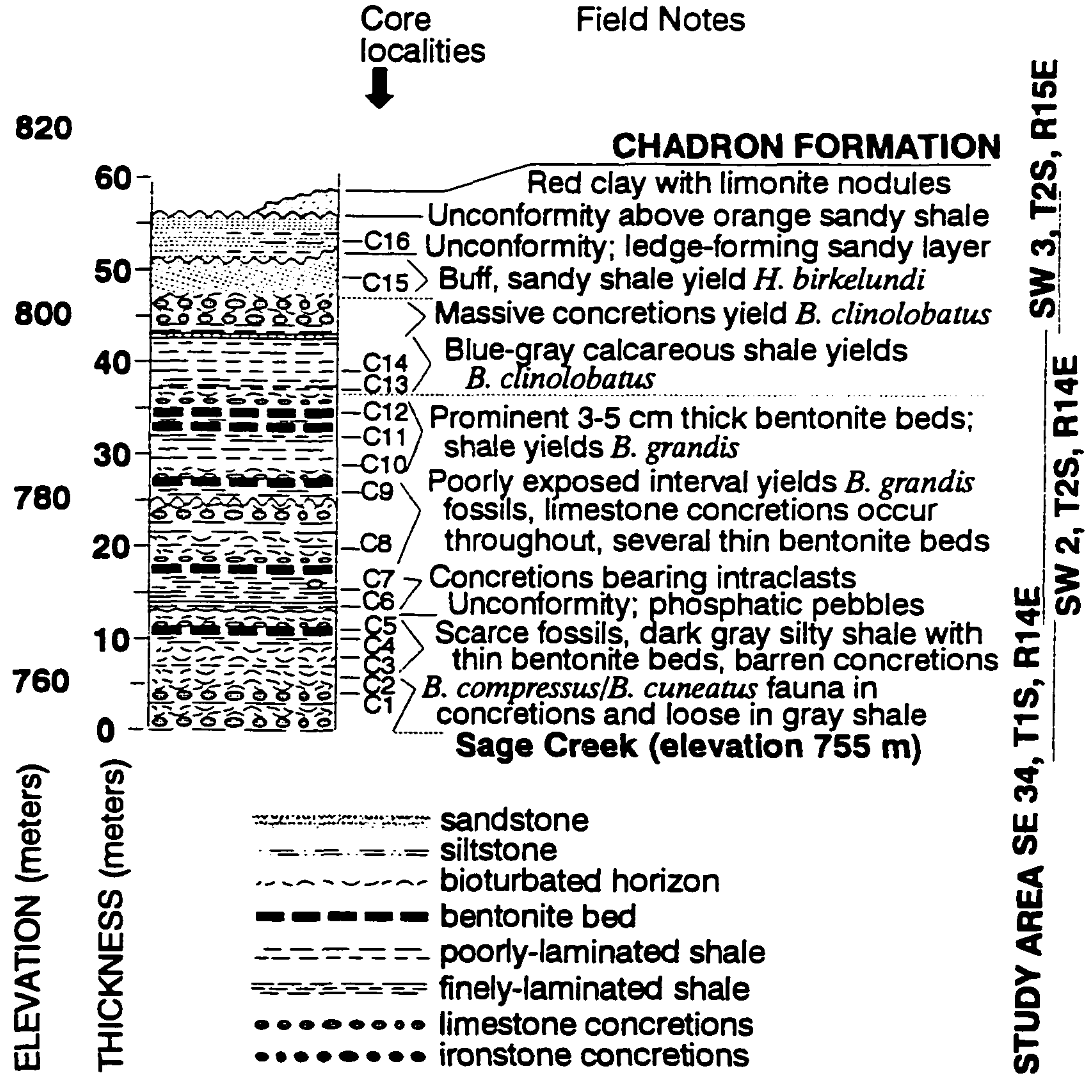


Fig. 41. Composite measured section from localities in the vicinity of the Sage Creek Campground in the North Unit, Badlands National Park.

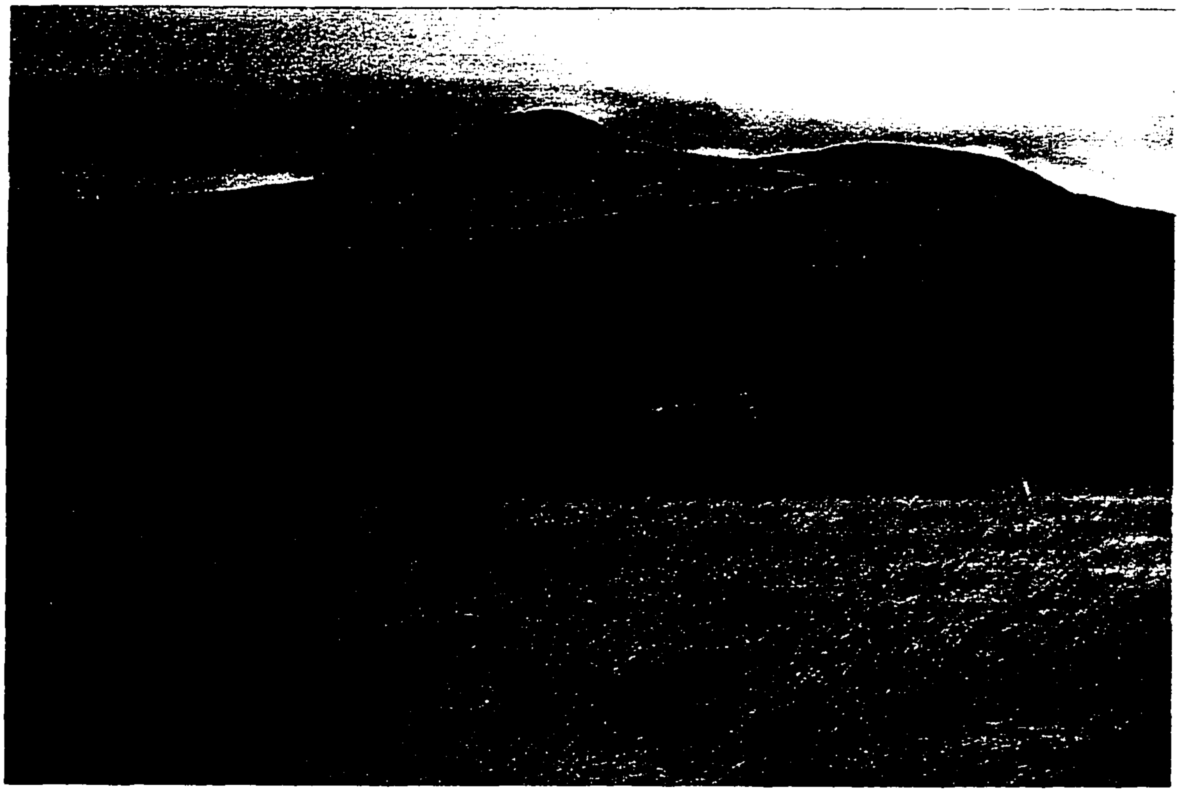


Fig. 42. Cutbank along Sage Creek on the north side of the Sage Rim Road bridge (SW, Sec. 35, T1S, R14E), Badlands National Park, North Unit. Concretions bearing *Baculites compressus* Zone fauna are abundant along creek level. A large slump is supplying the stream with a fresh supply of fossils. The change in color on the high wall of the cutbank is a fault that juxtaposes light-colored bentonitic shale of the *Baculites grandis* Zone next to the darker, silty, fossil-poor mudrocks of the *Baculites reesidei* Zone. The cutbank is approximately 25 meters high.

and the large clam *Inoceramus sagensis*. Above the creek level, fossils are less abundant with the exception of numerous crab carapaces in small yellow phosphatic nodules. These occur in a horizon near the top of the north side of the slumped cutbank. Thin bentonite beds near the top of the cutbank reveal a gentle southward dip of about 15°. This cutbank is bisected by an east-to-west-trending normal fault with the hanging wall down-thrown on the south side of the fault. Along the fault, shale bearing *Baculites grandis* is juxtaposed with silty shale, bearing large septarian limestone concretions typical of the *Baculites reesidei* Zone throughout the Sage Creek drainage area.

Cores C7 through C14 were collected for the upper portion of the Pierre Shale from well exposed outcrops of the *Baculites grandis* and *Baculites clinolobatus* zones. These zones occur in a hillside exposure several hundred yard northwest along a steep trail leading away from the Sage Creek Campground to a sandstone-capped ridge on a low hill in SW, Sec. 2, T 2 S, R 14 E. Cores C15 and C16 were collected from a exposure of Fox Hills Sandstone in SW, Sec. 3, T 2 S, R 15 E near the Roberts Prairie Dog Town locality (discussed below).

Additional field observations conducted during the summers of 1996 and 1997 throughout the Sage Creek Wilderness Area revealed that the upper Pierre Shale was highly variable throughout its lateral extent of outcrop exposures along the various tributaries of Sage Creek. Supplemental measured sections and fossil collections are presented below to refine details of the lithology of the upper Pierre Shale/Fox Hills transition in the park.

### 6.3.4 South Fork of Sage Creek, North Unit, Badlands National Park

Perhaps the best exposures of the Pierre Shale in the park are along the South Fork of Sage Creek. The strata along the South Fork of Sage Creek are nearly flat lying to very-gently-dipping towards the south. South of the Sage Creek Campground the *Baculites compressus/cuneatus* interval disappears into the subsurface. A measured section was compiled from a massive cutbank in NE, Sec. 24, T 2 S, R 14 E (Fig. 43). The cutbank is near the junction to two unnamed tributaries of the headwaters of the South Fork of Sage Creek. The cutbank is illustrated in Fig. 44. At creek level nearly complete specimens of *Baculites reesidei* were observed weathering from the shale in the cutbank. The silty shale encasing the fossils is cross-bedded, and suggests a north-to-northeast current orientation.

A well-defined unconformable surface within the Pierre Shale is exposed along the South Fork of Sage Creek (Fig. 45). Beneath the unconformity the dark gray shale bears fossils of *Baculites reesidei*. Above the hiatus is light gray shale displaying weathered bentonite layers and fossils of *Baculites grandis*. The unconformable boundary preserves an abundance of limonite stain on the lower surface, penetrating downward approximately one meter into the underlying darker

# BADLANDS NATIONAL PARK
# Sage Creek Wilderness Area
# South Fork of Sage Creek
# Measure Section

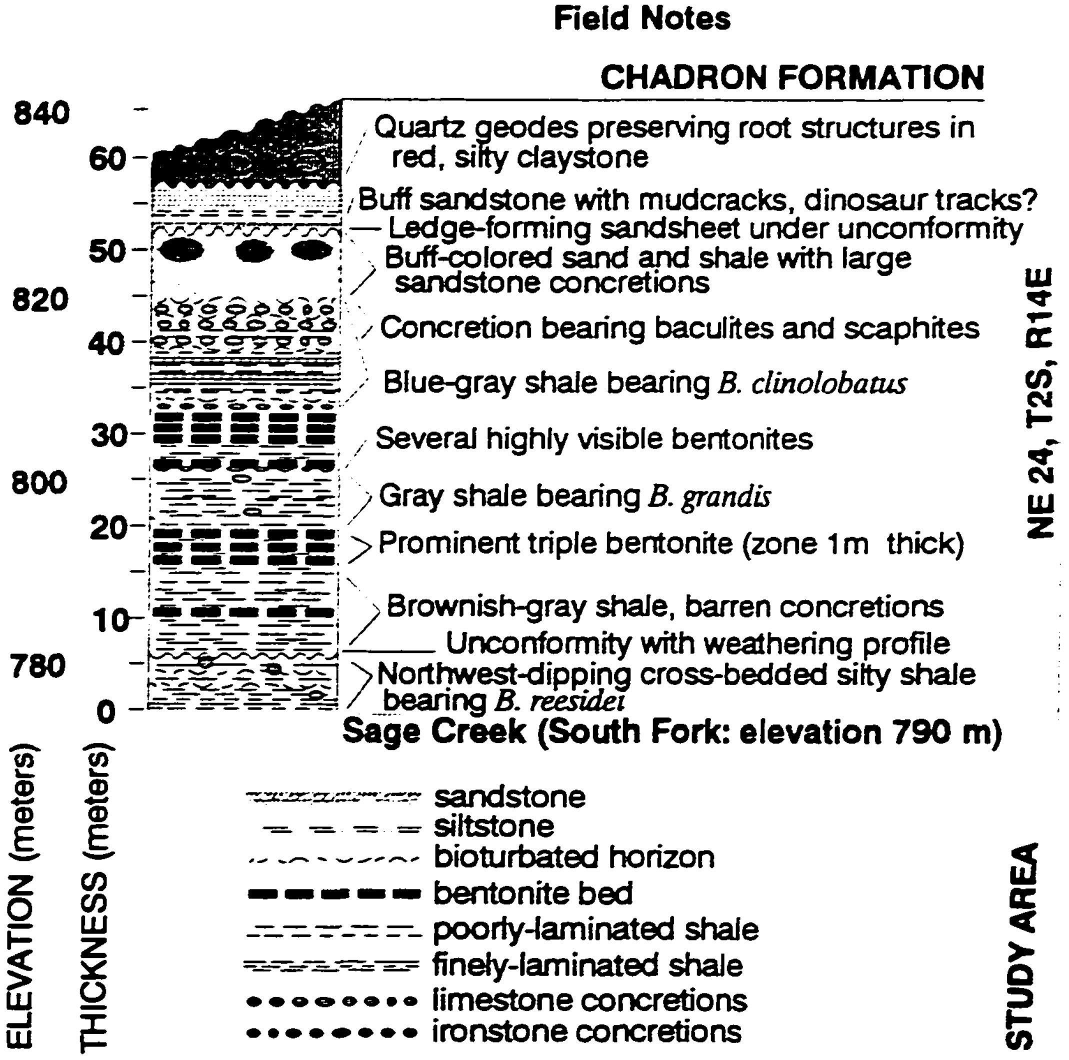


Fig. 43. Measured section for the South Fork of Sage Creek area, Sage Creek Wilderness Area, North Unit, Badlands National Park.

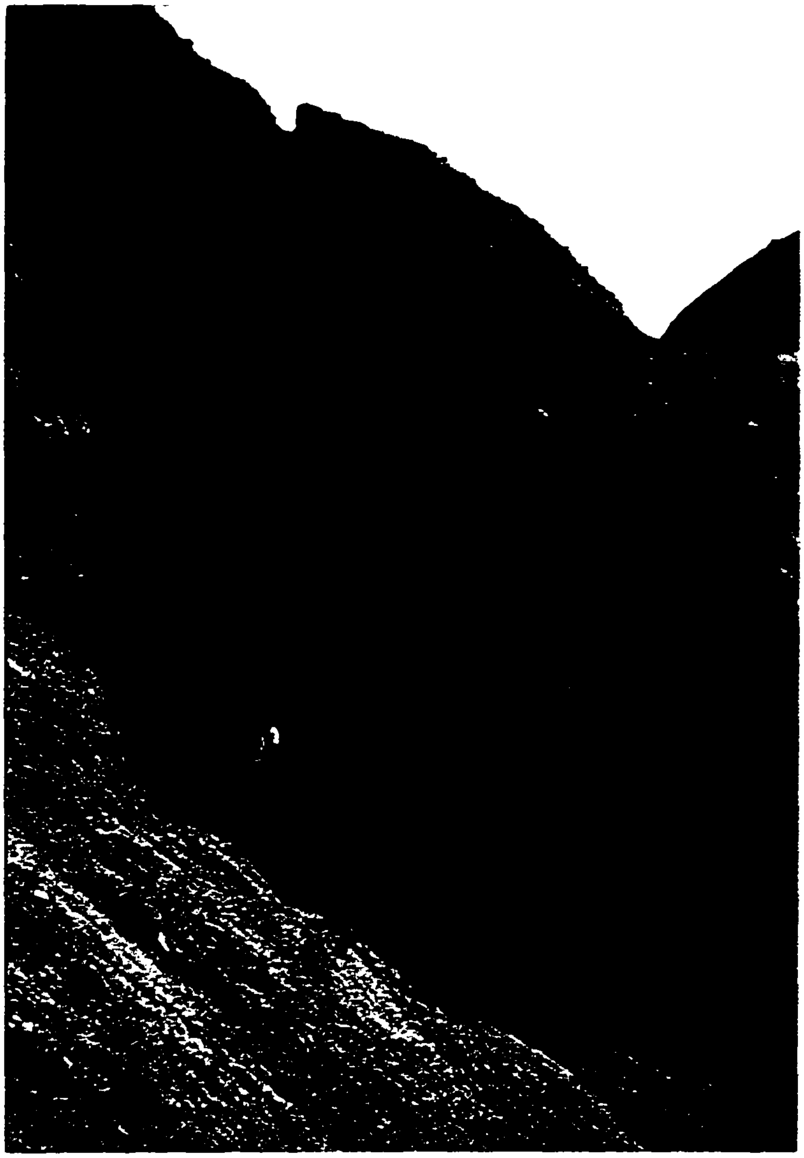


Fig. 44. South Fork of Sage Creek, Sage Creek Wilderness Area, Badlands National Park, North Unit (NE, NW, Sec. 14, T 2 S, R 14 E). Phil is standing on a concretion at the top of the *Baculites reesidei* Zone marking the Campanian/Maastrichtian boundary unconformity. Several bentonite beds crop out approximately a meter above his head within the lower *Baculites grandis* Zone. Three additional bentonite beds crop out near the top of the cutbank. The *Baculites clinolobatus* Zone caps the cutbank exposure.

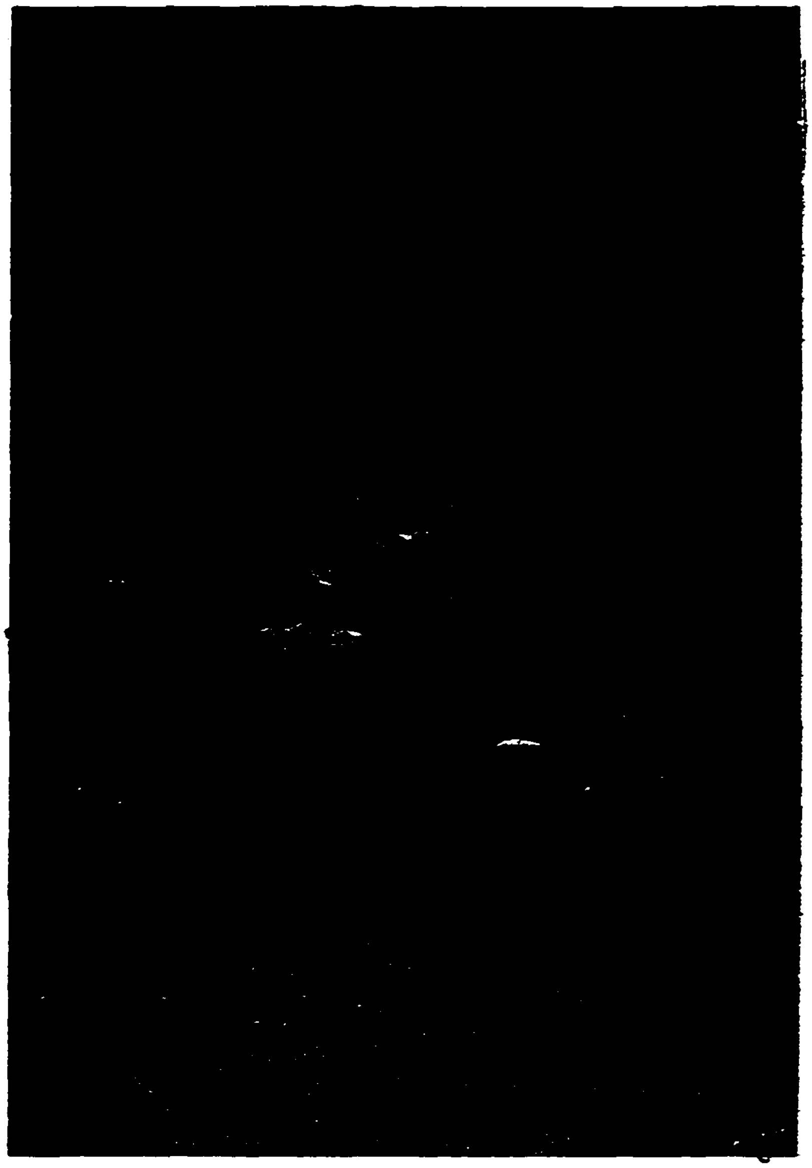


Fig. 45. An unconformable boundary on the top of the Verendrye Member displays an iron-rich weathering profile, possible evidence of subaerial exposure. The overlying Virgin Creek Member does not display a weathered appearance. The weathering profile suggests that seas may have withdrawn from the Badlands National Park region for a period representing the Campanian to Maastrichtian transition.

gray shale. To contrast, the shale immediately above the unconformity displays no limonite stain. The presence of the limonite-stained interval suggests that the unconformable surface may have been exposed to subaerial weathering prior to deposition of the sediments of the *Baculites grandis* Zone. Based on comparison with the lithologies and fossils in the Missouri Valley region, the interval below the unconformity could be assigned to the Verendrye Member, and the bentonitic interval bearing *Baculites grandis* above the unconformity could be assigned to the Virgin Creek Member.

Three very closely spaced bentonite beds occur near the base of the Virgin Creek Member (3 cm, 2 cm, and 5 cm from bottom to top; see Fig. 44). A specimen best resembling *Baculites grandis* was collected from just below the thickest upper bentonite in this lower bentonite zone. An undetermined number of thin stringers of very thin yellow-weathering bentonite layers occur intermittently above this lower bentonite zone. Five meters above this horizon three more very prominent bentonite beds occur (2 cm, 3 cm, and 2 cm, bottom to top, respectively). Only the more massive lower and upper bentonite beds appear conspicuously traceable from one outcrop to the next along South Fork of Sage Creek.

The *Baculites clinolobatus* Zone is very fossiliferous and easily defined along the hillsides of the South Fork of Sage Creek. On the freshest outcrops in NE, Sec. 24, T 2 S, R 14 E, the shale is calcareous, and displays a bright bluish gray appearance. Ledges of calcareous concretionary limestone crop out intermittently in fresh exposures. The top of the bluish-gray shale is capped by a limestone concretion bed, above which the sediment turns buff to brown due to limonite staining associated with Yellow Mounds-style weathering.

Specimens of baculites, as well as other marine fossils, litter the surface of a small hill in great abundance. This locality is in NW, SW, Sec. 14, T 2 S, R 14 E, (named "Baculite Butte" by this survey - AMNH Locality 3218.) The baculites occur in the transition interval between the bluish-gray, calcareous shales containing large limestone concretion (including large specimens of *Baculites clinolobatus*) and the overlying weathered sandy shale affected by Yellow Mounds-style weathering. The baculites in this upper sandy shale interval are preserved as casts in glauconitic marly sand (see Fig. 21B, p. 67). These baculites are generally much smaller that *Baculites clinolobatus* specimens observed elsewhere, and possibly represent a different species. They have a smooth ventral surface, lack flank ribbing, and have a more compressed cross-section profile. Additional fossils collected in this baculite-rich interval include unidentified arthropod fragments, a tooth of the Maastrichtian shark *Scapanorhynchus texanus*, and a species of ammonite resembling *Hoploscaphites birkelundi* (see Fig. 22A, p. 68).

Along the South Fork of Sage Creek near "Baculite Butte" the transition from the upper *Baculites clinolobatus* Zone to the overlying, heavily weathered sandy shale is gradational, yet the boundary marks a significant change in the style of sedimentation of the Pierre Shale. This is the interval referred to as "the Interior Zone of local usage" by Raymond & King (1976). The lower portion of this interval contains the compressed variant form of *Baculites clinolobatus* preserved with calcareous glauconitic sand encasing body chambers and portions of phragmocones. This interval becomes increasingly sandy up-section, and highly variable in its lateral character, ranging from shaley to sandy in the distance of several meters, and displays large scale cross-stratification in some intervals (highlighted by limonite stain). Where cross-stratification is visible, the beds dip southward, indicating that current direction was from the north.

A concretionary sand bed (0.2 to 0.5 meters thick) forms a prominent ledge along the top of many hillside exposures along the South Fork of Sage Creek (Fig. 46). This ledge, which typically forms a cap-rock on low hills, probably represents an unconformable surface throughout the Sage Creek Wilderness Area. Where exposed beneath the higher buttes in the wilderness area, it crops out several meters below the base of the Chadron Formation. The origin of this ledge forming horizon is not evident from exposures in the South Fork area. It has a heavily altered appearance due to the diagenetic effects attributed to Yellow Mounds-style weathering. However, elsewhere in the park there is clear evidence of unconformable relations between the strata below and above this ledge-forming concretionary layer

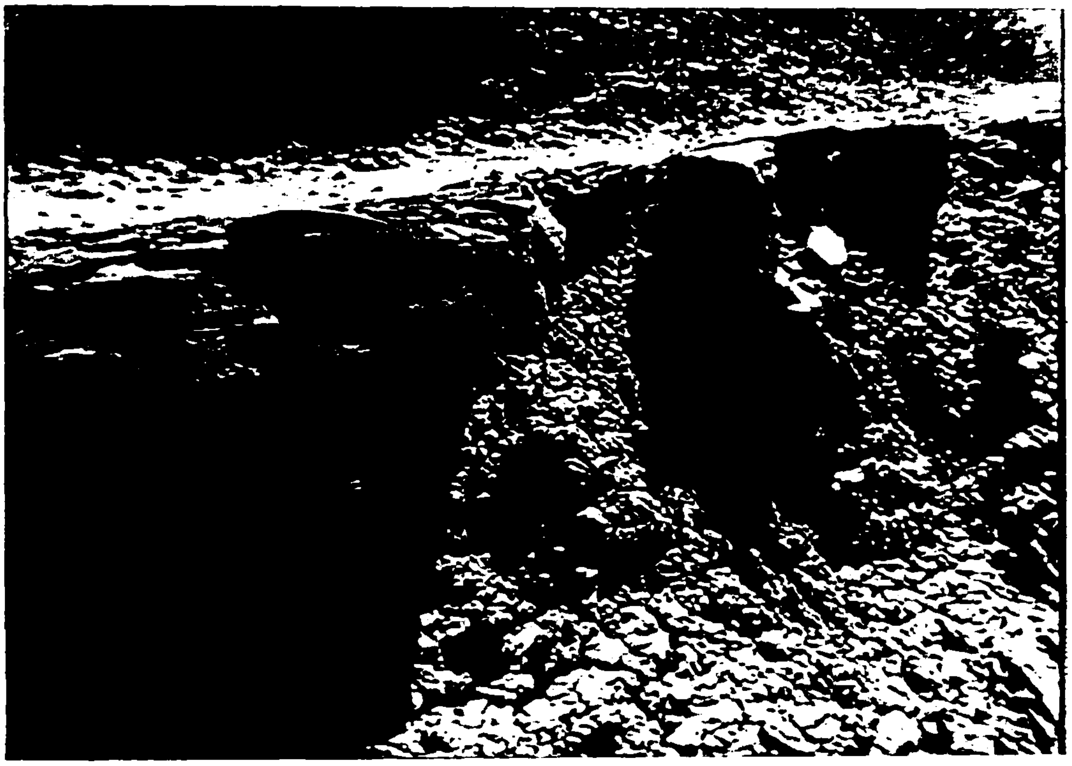


Fig. 46. South Fork of Sage Creek, Sage Creek Wilderness Area, Badlands National Park, North Unit. A prominent ledge forming sandy unit forms the cap of Pierre Shale. This .3m to .5m thick ledge is a widely-distributed sand layer that has been heavily cemented by limonite and calcite (caliche). Above this bed the poorly-consolidated, deeply-weathered sands and mudrocks of the Fox Hills Formation are commonly barren of vegetation throughout the Sage Creek Wilderness area. South of the Sage Creek fault zone the Fox Hills lithology is less sandy, which suggests that deeper water conditions prevailed. The hammer is approximately 1 foot for scale.

(particularly in the Roberts Prairie Dog Town area, discussed below). The hiatus is marked by the occurrence of large, brown, limonite-cemented sandstone concretions, which in some places merge together to form a continuous sheet. Processes associated with eluviation and accumulation in soil profile development (Yellow Mounds Weathering Profile [Pettijohn, 1965; Rettalack, 1985]) are probably responsible for the formation of these concretions (discussed in Chapter 8). However, the change in lithology associated with the unconformable boundary surface seems to have served as the germination layer where many of these concretions developed. The ironstone concretions occur throughout the Yellow Mounds weathering profile, but are particularly large and well developed in the lower portion of the weathering profile; they are not limited to the unconformable boundary layer.

Above this ledge-forming unit (representing an unconformable surface) the lithology takes on a different character from the sediments below. Sandy and silty mudrock ranging in thickness between 2 and 5 meters below the base of the Chadron Formation occur on hilltops throughout the South Fork of Sage Creek and beyond. It has a heavily weathered appearance typical of sediments affected by Yellow Mounds-style weathering. This unit is generally less consolidated than the underlying Pierre Shale, and appears buff to orange-red in color due to a high limonite content. Throughout exposures in the southern end of the South Fork drainage basin the interval is not as sandy as equivalent strata found along the northern boundary of the wilderness area (discussed in sections below). Based on its sandy content and its stratigraphic position, this unit is assigned to the Fox Hills Formation.

The top of this buff-to-orange-red unit is overlain by a bright red sandy mudrock that contains abundant evidence of a terrestrial soil profile development, including root trace structure, desiccation cracks, and pods of caliche. This unit is assigned to the Chamberlain Pass Formation after Evans & Terry (1993), Terry & Evans (1994), and Dennis Terry (personal communication, 1997); these researchers have collected Eocene bone material and termite mounds from this unit. The assignment of Eocene age to this unit seems appropriate because it probably represents a surface lag deposit spanning as much as 20 million years from middle Maastrichtian time to late Eocene time when the sediments of the Chadron Formation began to accumulate. The unit ranges in thickness between 0 and 10 meters, with its thickest exposure observed at the southern end of the South Fork drainage area in NE, Sec. 24, T 2 S, R 14 E. In this area the Chamberlain Pass unit is barren of fossils with the exception of root- and bioturbation-traces in mud bearing desiccation cracks. As an intriguing note, however, tridactyl markings resembling theropod tracks were observed on a slab of mudrock bearing desiccation cracks from the base of this unit, suggesting that this unit is indeed Cretaceous in age in its lower extent. Unfortunately, the size of the slab in this remote section of the wilderness area made it impossible to collect, and photographs of the structures proved inconclusive. This area should be a target of further research!

A small east-to-west-trending normal fault possibly exits in NW, Sec. 23, T 2 S, R 14 E. The fault is not very apparent on the ground; it was discovered by ground reconnaissance to determine the nature of an east-to-west-trending lineament on an aerial photograph. The only direct evidence of the fault observed in the field was the offset of a ledge-forming freshwater limestone in the middle of the Chadron Formation. The limestone bed displays as much as 5 meters of offset on the north side of a low butte in SE, NW, Sec. 24, T 2 S, R 14 E. Unlike the Sage Creek Fault System, the hanging wall is on the south side of this normal fault. The structure adds some complexity to the facies of the Pierre Shale along the South Fork of Sage Creek. Strata on the north side of the fault have dropped between five and ten meters relative to the north side. South of the fault, beds containing fossils of *Baculites reesidei* dip steeply northward (about 15°) and appear to be truncated along the unconformable boundary beneath light bluish-gray strata bearing *Baculites clinolobatus*. The interval of the *Baculites grandis* Zone bentonite beds were either not recognized or are missing. Also, there is no weathering profile preserved on top of the beds below the unconformity. This exposure probably demonstrates that tectonic movement had occurred after deposition of the Campanian age sediments and prior to deposition of the Early Maastrichtian age sediments. Unfortunately, the top of this exposure is truncated by Quaternary alluvium, so there are no sediments of the

Interior Zone preserved in the immediate area of this structure. Several hundred meters south of this structure the strata appear to be dipping very gently to the south. Only the upper portion of the sediments affected by the Yellow Mounds weathering profile are exposed along creek level, and these eventually vanish beneath younger sedimentary cover farther south.

### 6.3.5 White Butte (AMNH Locality 3219), North Unit, Badlands National Park

White Butte is a prominent landmark in the Sage Creek Wilderness Area along the East Fork of Sage Creek. A measured section for White Butte is presented in Fig. 47. The hill is capped with a resistant freshwater limestone layer in the middle Chadron Formation along the boundary between SE, Sec. 1 and NE, Sec. 12, T 2 S, R 14 E. On the southern side of the butte the East Fork of Sage Creek has carved a large cutbank, exposing the upper Pierre Shale starting with the top of the *Baculites compressus* Zone at creek level (representing the Verendrye Member of the Pierre Shale). Along Sage Creek below White Butte the *Baculites cuneatus* Zone is covered by talus and slumped debris from the slopes above. However, *Baculites cuneatus* were observed and collected from large, gray concretions found in the creek bed several hundred meters downstream from the White Butte exposures. Bowling ball- to beach ball-sized limestone concretions found in the gravel bars along Sage Creek immediately below White Butte yielded nearly complete specimens of *Baculites*

# BADLANDS NATIONAL PARK
# Sage Creek Wilderness Area
# White Butte
# Measured Section

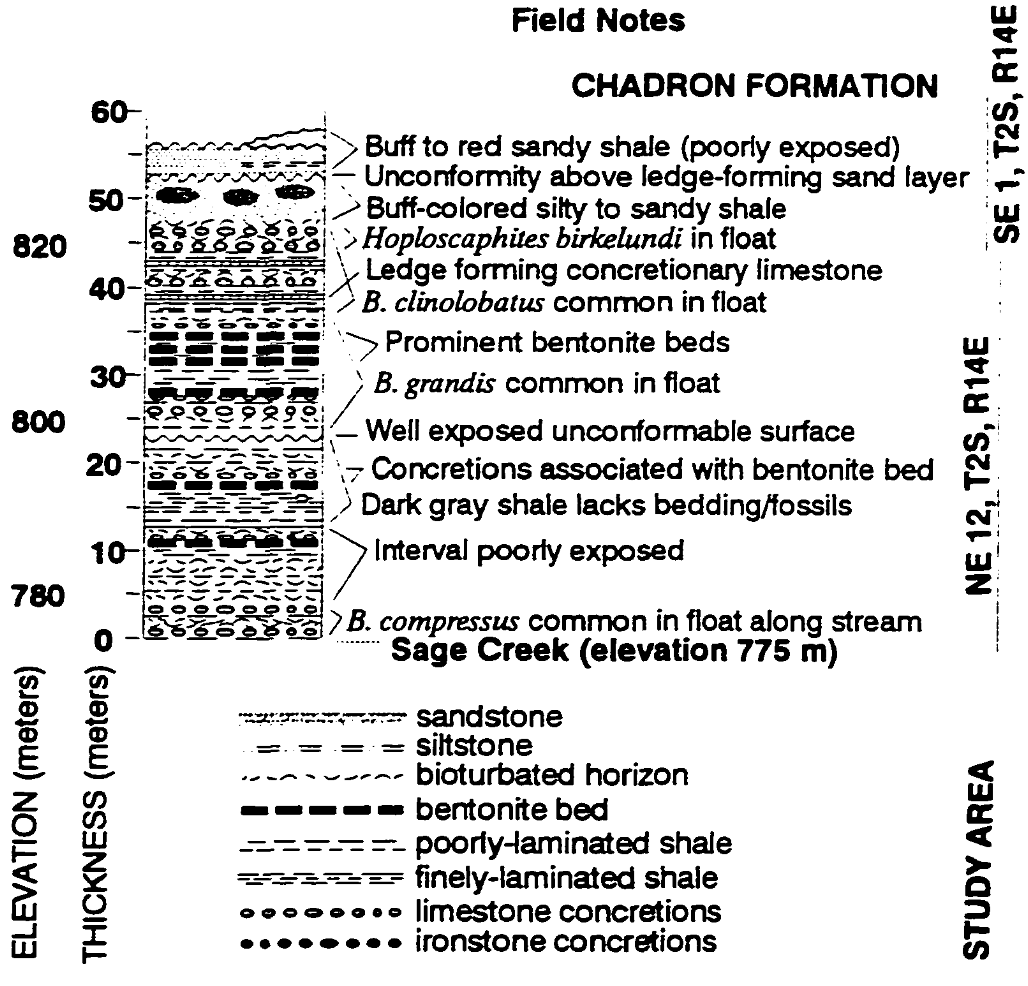


Fig. 47. Measured section for White Butte along the East Fork of Sage Creek, Sage Creek Wilderness Area, Badlands National Park, North Unit.

*compressus* and inoceramids. The weathered surfaces of the concretions are covered with *Thalassinoides* and *Planolites* bioturbation structures. The *Baculites reesidei* Zone is generally barren of fossils; only a few crushed and poorly preserved body chambers of baculites and inoceramid fragments were observed loose in the shale. Large limestone concretions in this interval display large septarian veins filled with yellow calcite. A thin bentonite layer with small limestone concretions was observed 12 meters above the creek bed. A second bentonite layer crops out near the top of this barren interval (approximately 18 meters above creek level) and contains numerous fist- to head-sized limestone concretions (lacking fossils). The shale of the *Baculites reesidei* Zone on the butte is generally very homogeneous in composition. Its lack of apparent bedding structures suggests two possibilities: Bioturbation may have thoroughly mixed the sediment. Alternatively, diagenetic processes related to meteoric weathering and the leaching of calcareous shell material may have completely eliminated bedding structures prior to deposition of the overlying sediments.

A very distinct unconformity is apparent approximately 22 meters above creek level. This boundary is particularly apparent when observed from a short distance away (from the opposite side of the creek). Beneath the unconformity the dark gray shale lacks distinct bedding structures. Above the unconformity thinly laminated bedding structure is more defined, and the shale has a brownish-olive gray color.

Many small, yellow phosphatic nodules were observed as float along and below this unconformable surface. Fossils of *Baculites grandis,* the diagnostic species of the Virgin Creek Member, are abundant in float on the sides of White Butte, and weathering from above the unconformity. Most fossils are small casts of body chambers and phragmocones, lacking original shell material. Similar to exposures along the South Fork of Sage Creek, the Virgin Creek Member on White Butte displays many thin bentonite beds that appear as yellow streaks on fresher exposures. Small limestone concretions are common within, or slightly above and below the bentonite beds. One prominent bentonite about 3 cm thick occurs 28 meters above creek level. Several more occur between 31 and 35 meters above creek level. The appearance of bedding and undisturbed bentonite beds suggests that water conditions were deep enough and current conditions were slow enough to prevent the reworking of the sediments. The occurrence of well-defined bedding raise the possibility that bioturbation was hindered, perhaps by anoxia caused by stagnation of deeper water in the seaway.

The shale changes in character again approximately 37 meters above creek level. Ledge-forming lenses of micritic limestone, including fossils of *Baculites clinolobatus* crop out discontinuously through a 10 meter thick section. In addition, large limestone concretions are abundant. Crushed fragments of baculite shells in hash layers were observed, and possibly represent storm-related rapid-kill events.

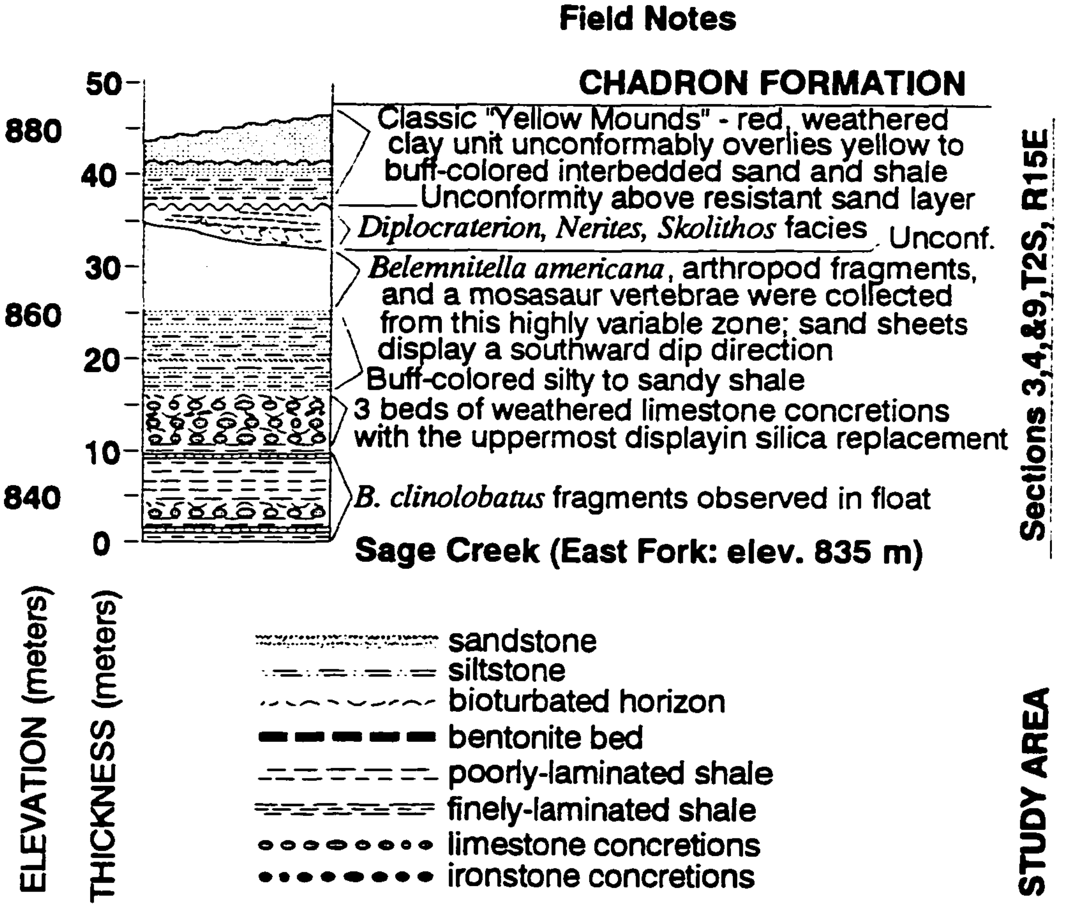
The limestone, concretions, and marly shale displays a light gray color, typical of the Mobridge Member in the Missouri Valley section. Unfortunately, this zone is very poorly exposed along the upper hillsides of White Butte. Two scaphite specimens resembling *Hoploscaphites birkelundi* were collected from approximately 45 meters above creek level at the transition to the overlying tan and buff-colored beds of the lower Interior Zone (this interval is very poorly exposed). The Interior Zone is approximately 5 meters thick on White Butte. The same ledge-forming, concretionary sand layer observed along the South Fork of Sage Creek is well exposed along a drainage on the northwest side of White Butte in SE, Sec. 1, T 2 S, R 14 E. This bed represents an unconformable boundary between the upper Pierre Shale (Interior Zone) and the Fox Hills Formation. By following the creek bed northward from White Butte this boundary is more evident in exposures closer to the top of the ridge below the south side of Sage Rim Road. An undulating surface between beds exposed along the ravines clearly demonstrates that this ledge-forming layer is an unconformity. The sediment above this layer in the White Butte area is a silty and sandy mudrock that is highly variable in composition. Based on its composition and stratigraphic location it represents the lower Fox Hills Formation. It is heavily stained by limonite, and is generally very poorly exposed. Only a thin trace of red "Chamberlain Pass" lithology weathers to a rust colored mud beneath exposures of the basal white sandy beds of Chadron Formation. The 1 meter thick freshwater limestone cap-rock in the Chadron Formation that tops the butte yields plant remains.

### 6.3.6 Roberts Prairie Dog Town Area, North Unit, Badlands National Park

In the Roberts Prairie Dog Town area Cretaceous and Tertiary strata plunge southeastward off the crest of the Sage Creek Anticline. A measured section for the locality is shown in Fig. 48. One of the best exposures of Fox Hills Sandstone in the park crops out in NW section 3, T 2 S, R 15 E along ravines on either side of the wilderness access trail-head parking area (on the south side of Sage Rim Road, just west of the prairie dog town interpretive display). A resistant sandstone layer as much as 0.3 meter thick crops out along several small ravines. Additional thin to thick-bedded sandstone strata occur above this basal layer with shaley mudstone between the sand sheets. This local unit was first recognized as Fox Hill Sandstone by Pettijohn (1965). The ledge represents a truncation surface on the top of southward-dipping clinoform beds at the top of the Interior Zone (Figs. 49 and 50). This concretionary sand ledge is the same stratigraphic horizon that defines the base of the Fox Hills Formation along the South Fork of Sage Creek and on White Butte.

In the Roberts Prairie Dog Town area the occurrence of a thick bed of thinly laminated, medium-grained sandstone displaying local cross-bedding clearly defines the basal unit of the Fox Hills Formation. The sandstone contains *Diplocraterion, Skolithos, Nerites*, and other traces consistent with a shallow marine mudbank

# BADLANDS NATIONAL PARK
## Sage Creek Wilderness Area
## Roberts Prairie Dog Town Area
## Measured Section



Field Notes

CHADRON FORMATION

Classic "Yellow Mounds" - red, weathered clay unit unconformably overlies yellow to buff-colored interbedded sand and shale

Unconformity above resistant sand layer

*Diplocraterion, Nerites, Skolithos* facies. Unconf.

*Belemnitella americana*, arthropod fragments, and a mosasaur vertebrae were collected from this highly variable zone; sand sheets display a southward dip direction

Buff-colored silty to sandy shale

3 beds of weathered limestone concretions with the uppermost displayin silica replacement

*B. clinolobatus* fragments observed in float

Sage Creek (East Fork: elev. 835 m)

Fig. 48. Measured section for the area south of the Sage Rim Road near the Roberts Prairie Dog Town, Sage Creek Wilderness Area, Badlands National Park, North Unit.

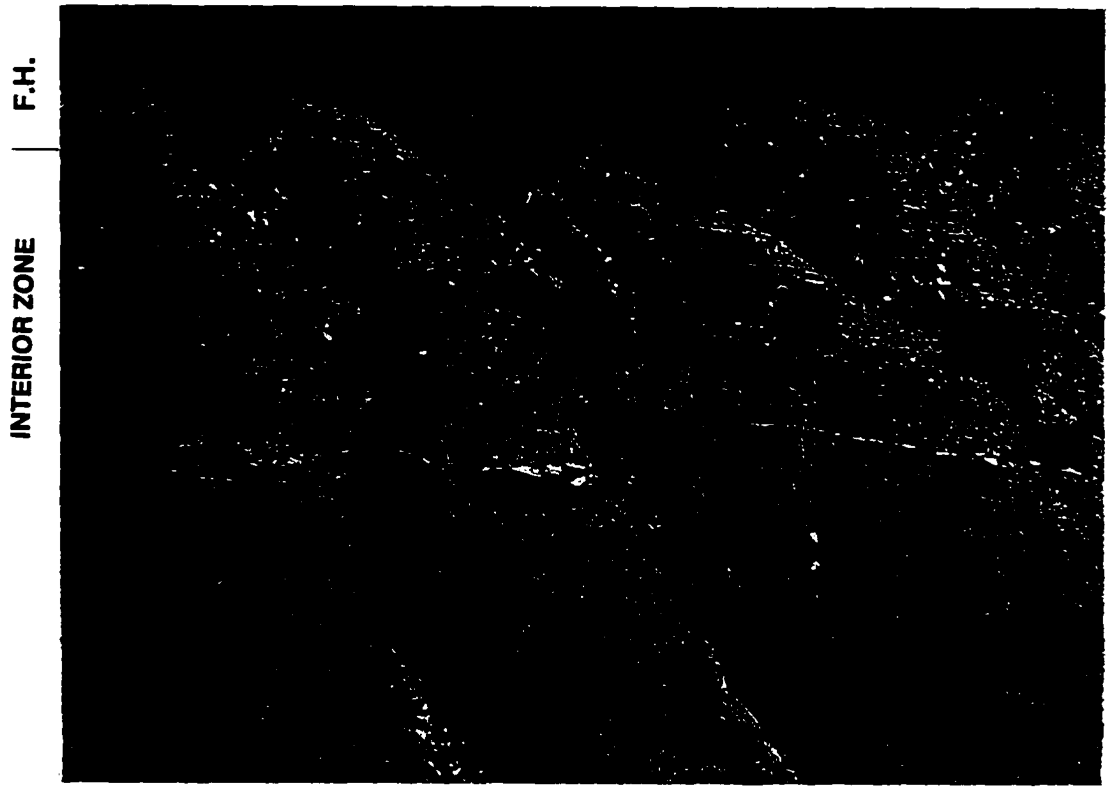


Fig. 49. Roberts Prairie Dog Town area, Sage Creek Wilderness Area, Badlands National Park, North Unit. Southward-dipping clinoform beds of the upper Interior Zone at the top of the Pierre Shale are overlain by flat-lying sandy and silty beds of the Lower Unit of the Fox Hills Formation in NE, Sec. 3, T2S, R15E. Thin sand beds highlight the clinoform beds. This unit indicates that a mudbank prograded southward across the Badlands National Park region after *Baculites clinolobatus* time. This exposure is approximately 8 meters thick.

Fig. 50. Roberts Prairie Dog Town area, Sage Creek Wilderness Area, Badlands National Park, North Unit. A ledge-forming sandstone of the base of the Fox Hills caps the gently-dipping clinoform beds of the Interior Zone at the top of the Pierre Shale. This sandstone bed gives the appearance of an unconformity at the base of the Fox Hills. Sand and shale above this layer possibly represent a tidal flat or a flood plain deposit. This ledge-forming sandstone crops out only in a small area in NE, Sec. 3, T2S, R15E. In other parts of the park, this sand bed is missing and the boundary has a hard caliche crust. Both indicate that sea level was falling at the end of Pierre Shale deposition. The hammer is about one foot long.

environment (see Fig. 26, p. 72). Unfortunately, no shelled fossils were preserved. Below the basal Fox Hills sandstone the uppermost beds of the Interior Zone yielded specimens of belemnites (*Belemnitella americana*, see Fig. 25B, p. 71) and a mosasaur tailbone vertebra (collected by Rachel Benton for the National Park Service, and later identified by Gorden L. Bell, Jr. (personal communication, 1997) as either "*Mosasaurus*" or "*Prognatodon.*" It has been added to the Badlands National Park collection at the South Dakota School of Mines and Technology's Geology Museum. This was only the second mosasaur fossil ever reported in the park; the first one was found in a concretion in the South Fork of Sage Creek near the campground by a ranger in 1996.

Two buffalo trails lead southward from the wilderness access parking area into the valley of the East Fork of Sage Creek. The western trail leads to an outcrop area consisting of a striking series of small "yellow mounds" (Fig. 51). These mounds sit on top of a resistant concretionary sand layer defining the boundary between lower and upper units within the Fox Hills Formation. The significance of this lithology change is unclear. The mounds are about 5 meters high. The lower three meters consist of even-bedded sand and shale couplets bearing poorly preserved *skolithos*-like burrows. *Skolithos*-like burrows in the even-bedded sandstone layers suggest a tidal flat depositional environment. The upper 2 meters of each mound consist of a red-weathering soil profile (also barren of fossils). This interval probably represents the

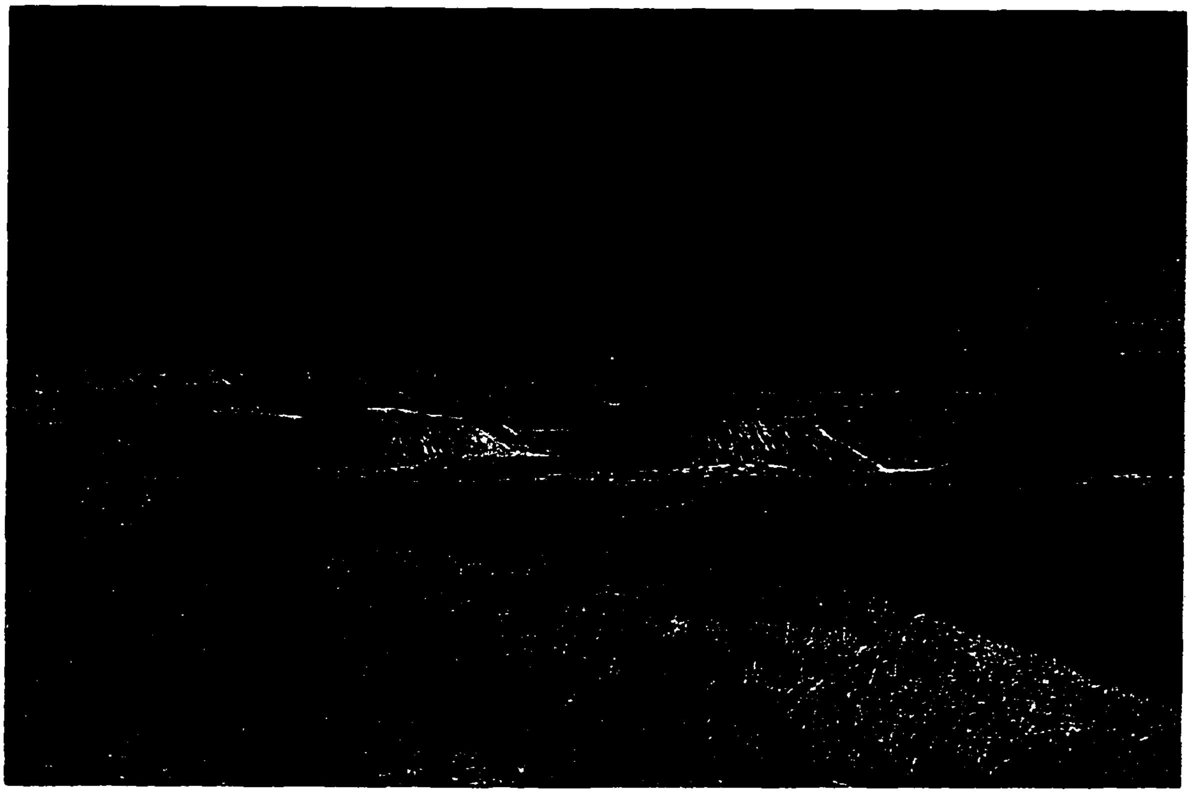


Fig. 51. Roberts Prairie Dog Town area, Sage Creek Wilderness Area, Badlands National Park, North Unit. Classic "Yellow Mounds" in SW, Sec. 3, T2S, R15E, are located along the right path from the Sage Creek Wilderness Area access parking area 200 meters west of the Robert Prairie Dog Town parking area. Each mound is approximately 5 meters high. The surface at the base of the mounds is a hard unconformable surface that truncates clinoform sand sheets in the underlying Lower Unit of the Fox Hills Formation. These mounds actually consist of three units (above the bench-forming unconformity). 1) A lower yellow unit consisting of alternating sand and shale couplets that are generally weathered yellow in color and display evidence of shallow marine bioturbation. 2) A one meter thick red unit of deeply weathered mudrock overlying the Mounds Member represents the Chamberlain Pass Formation (or the "Interior Red Clay" after Retallack, 1985). 3) White conglomerate of the Chadron Formation caps each mound.

red clay of the Chamberlain Pass Formation. The top of each mound is capped by a thin, white blotch of Chadron Formation.

Along the trail to the "yellow mounds" the path crosses a fault that trends in a NW-SE direction parallel to the hillside escarpment. Chadron Formation on the hanging wall on the south side of the fault is adjacent to sediments of the Interior Zone on the north side of the fault (an offset of as much as 30 meters). Below the fault a zone of very chaotic terrain is preserved in the transition interval above the bluish-gray shale of the *Baculites clinolobatus* Zone. Within and down-slope of the fault zone (south) limonite-cemented sandstone concretions preserve massive soft-sediment deformation structures perhaps typical of a slump. In addition, on the south side of the fault the beds several meters below the Pierre/Fox Hills unconformity display a classic Bouma sequence, including a basal sand sheet overlain by a heavily contorted mudstone bed, resting under a thin fine clay interval at the top (Fig. 52). Glide planes and folds in the contorted beds suggest that the sediments had flowed in a southward direction, consistent with the general dip of the beds on the south side of the Sage Creek Anticline/Fault System.

The Interior Zone, including the buried slump, is approximately 25 meters thick in the Roberts Prairie Dog Town area (nearly twice as thick as in the South Fork of Sage Creek or the Sage Creek Campground area). The Fox Hills Formation is approximately three meters thick beneath the red clay of the Chamberlain Pass

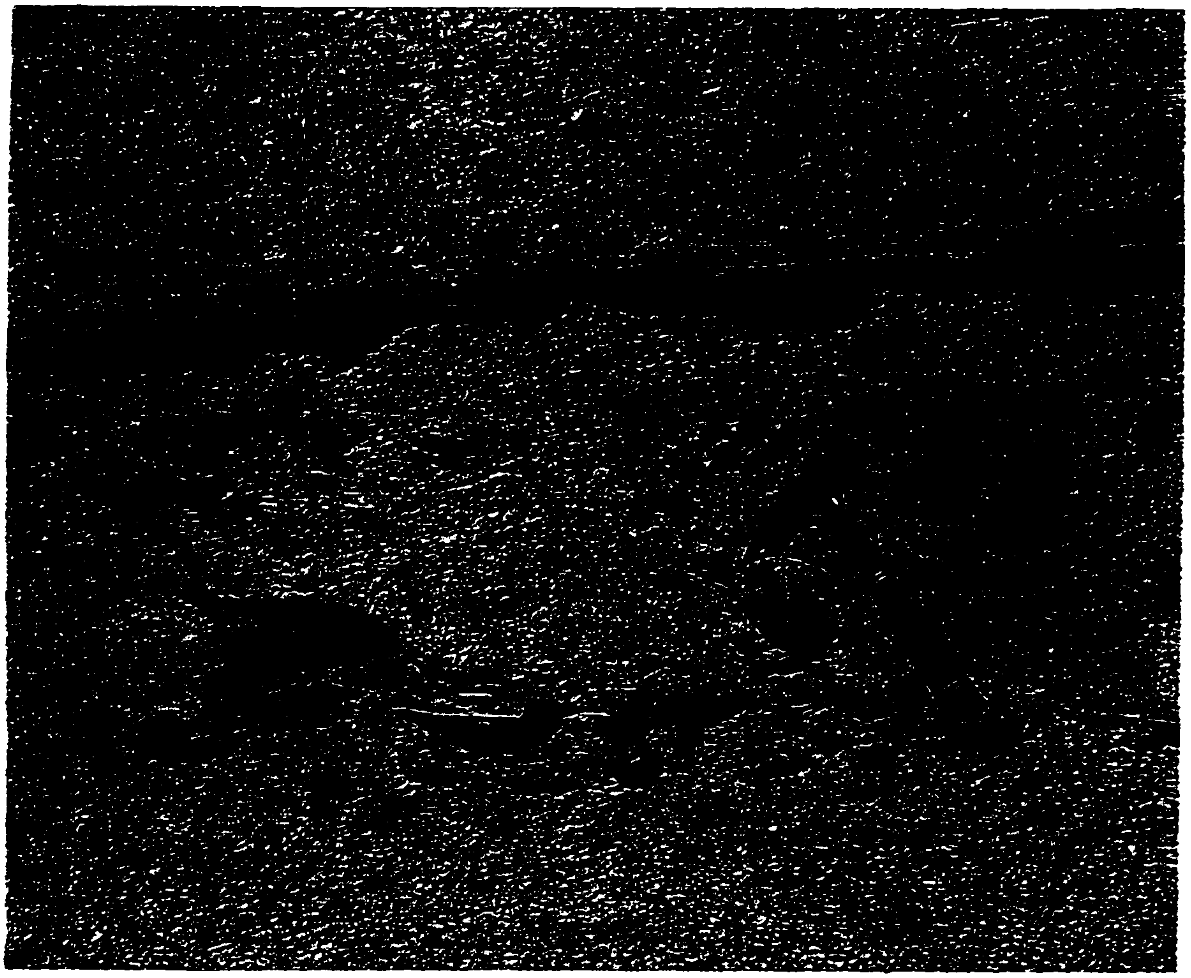


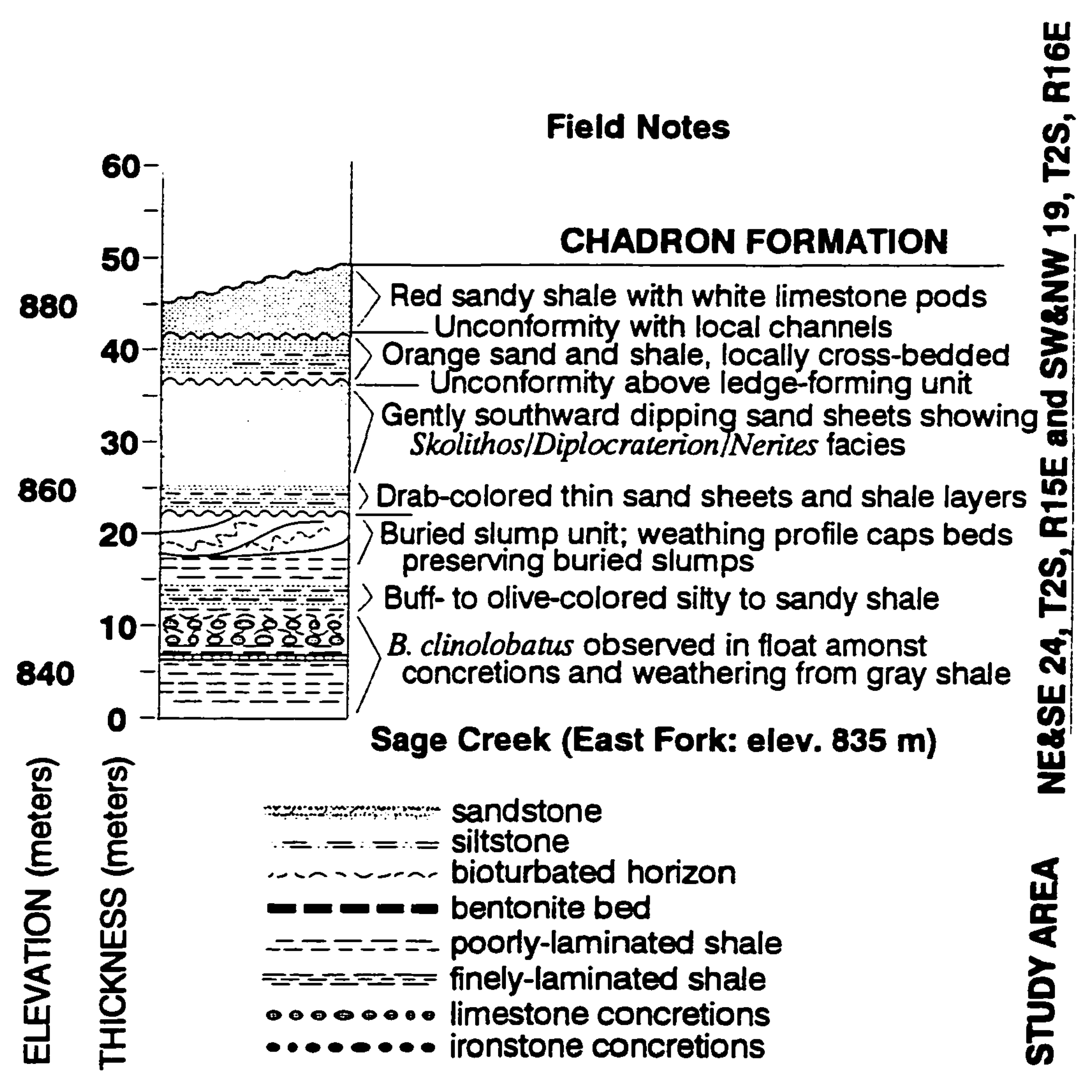
Fig. 52. Ledge forming sand-sheets bound a layer of contorted bed so muddy siltstone and sand cemented by limonite. The beds represent a possible "Bouma sequence" having a basal sand sheet, contorted beds, and an upper clay layer below the next overlying sand sheet. The ledge-forming sand sheets are about 60 cm apart. The beds occur in the Lower Unit of the Fox Hills Formation.

Formation. The Interior Zone grows progressively thicker eastward to its thickest extent in the Grassy Tables Overlook area.

### 6.3.7 Grassy Tables Overlook Area, North Unit, Badlands National Park

North of the Grassy Tables Overlook along the Sage Rim Road, strata of Cretaceous and Tertiary age are flat-lying to very gently-dipping to the northwest. The overlook is situated on top of the south-facing Badlands Escarpment. Cretaceous rocks crop out along the base of the escarpment along ravines that drain into the East Fork of Sage Creek. South of the escarpment a series of NW-SE-trending faults are exposed. These faults break the crest of the Sage Creek Anticline. South of Sage Creek the Cretaceous strata dip 10-20° to the southwest and vanish under younger sedimentary cover (see Fig. 110, p. 375).

The section in the Grassy Tables Overlook area provides perhaps the best exposures of the Interior Zone and the thickest Fox Hills exposure in the park. A measured section for the area is presented in Fig. 53. Along the crest of the anticline the East Fork of Sage Creek has carved downward into the gray shale bearing large limestone concretions typical of the *Baculites clinolobatus* Zone. A short distance above the limestone concretions, the shale grades into brown limonitic sandy mudrock and shale. Buried slumps occur in the Interior Zone throughout an area of several hundred hectares extending throughout SW, Sec. 12, T 2 S, R 15 E and NW, Sec.



BADLANDS NATIONAL PARK
Sage Creek Wilderness Area
Grassy Tables Overlook Area
Measured Section

Fig. 53. Measured section for the area south of the Sage Rim Road near the Grassy Tables Overlook, Sage Creek Wilderness Area, Badlands National Park, North Unit.

13, T 2 S, R 15 E in the area south of the Grassy Tables Overlook on the Sage Rim Road (Stoffer, Messina, & Chamberlain, 1997). The buried slumps are most evident in fresh creek bed exposures in SE, SW, Sec. 12, T 2 S, R 15 E. The extent of the slumped area is perhaps best revealed by the occurrence of large limonite-cemented concretions preserving soft sediment deformation features, the most important being large roll-type structures that preserve tight folds in the buried slumps (Fig. 54). The long axis of the roll-type concretions is in a NW-SE direction, parallel to the general trend of the Sage Creek Anticline/Fault system.

Fresh exposures in creek bed cutbanks in NE, NW, sec. 13, T2S, R15E display a 4- to 5-meter-thick horizon of highly chaotic bedding with glide plane surfaces and tight folds typical of the toe of a massive slump. This horizon lies on top of flat-lying sandy shale. Offset along the glide planes indicate that slump movement was in a southwest direction. The upper surface of the slump zone has been beveled by erosion with horizontal even-bedded sediments deposited on top (Fig. 55), suggesting a possible location for the Pierre/Fox Hills boundary.

Numerous small normal faults were observed along the base of the Chadron Formation throughout the Grassy Tables study area (Sections 12 and 13, T 2 S, R 15 E). The hanging wall is down-thrown on the south side of each fault, and the general strike direction of all faults observed is in a NW-SE direction. One small normal fault cuts across several small drainages in a west-northwest direction in SW, SW,

Fig. 54. Grassy Tables Overlook area, Sage Creek Wilderness Area, Badlands National Park, North Unit. A large concretion preserves rollover-type soft sediment deformation associated with submarine slumping (NW, Sec. 19, T2S, R16E). East-to-west orientation of "roll-type" concretions in the area are consistent with the model for slumping on a southward prograding mudbank during deposition of sediments representing the Interior Zone. The Jacobs staff is 1.5 meters long.

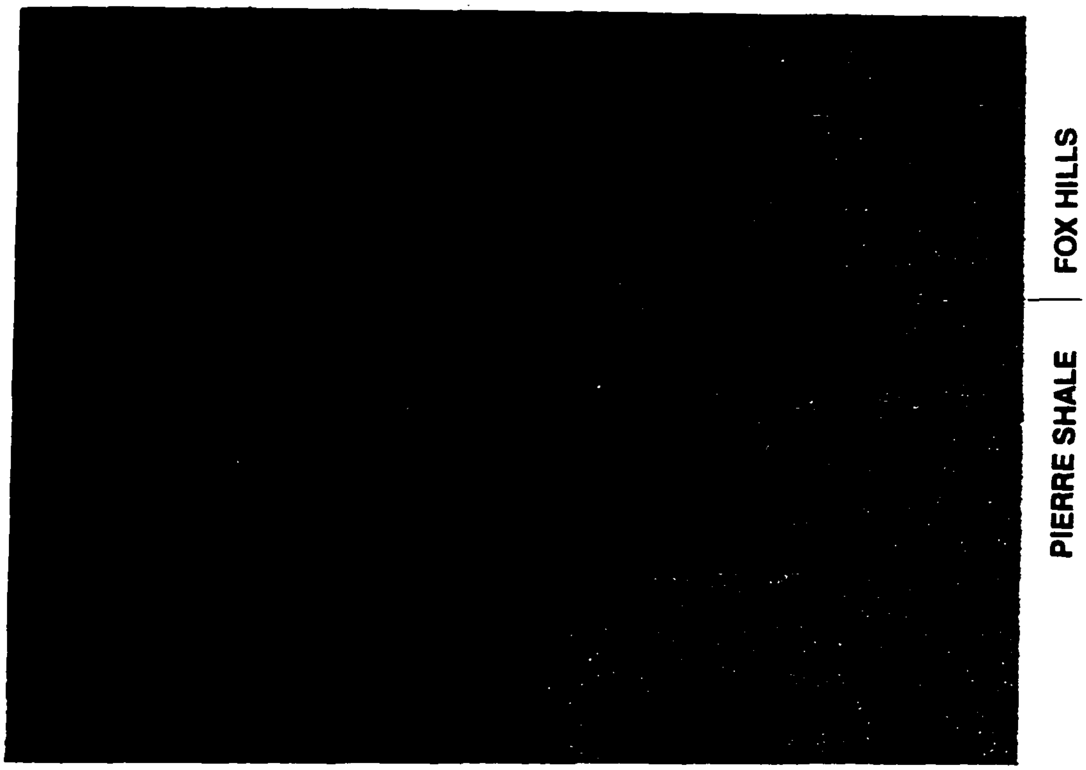


Fig. 55. Grassy Tables Overlook area, Sage Creek Wilderness Area, Badlands National Park, North Unit. Buried slumped beds crop out along the creek bed in SW, NE, Sec. 24, T2S, R15E. The upper surface of red- and white-colored slump beds are truncated and overlain by undisturbed drab-colored sand and shale beds (just above walking stick used for scale). Beds of the slump were possibly exposed to subaerial pedogenic alteration before marine sedimentation continued. Fluctuating sea level and shifting depositional lobes probably account for local unconformable surfaces. This truncation surface represents the unconformable boundary between the Interior Zone of the Pierre Shale and the Lower Unit of the Fox Hills Formation. The Jacobs staff is 1.5 meters long.

Sec. 12, T2S, R15E. This fault displays offset extending upward from the slumped horizon through the upper Interior Zone into Fox Hills Formation, the Chamberlain Pass Formation, and into the Chadron Formation. The down-thrown block on the south side of the fault displays an offset of approximately 20 meters. Whether the fault extends beneath the buried slump is unknown.

Another NW-SE striking normal fault is exposed along the south side of a low ridge capped by Chadron Formation that runs diagonally across the northern portion of Section 13. On the south side of the fault (on the down-thrown hanging wall) multiple layers of buried slump deposits reach a thickness of approximately 20 meters.

The slumps occur within the upper Interior Zone. The upper surface of the slump deposits appears to have been beveled by erosion. The top of the slump beds displays a rusty-pink weathered character which suggests that they were exposed to meteoric weathering. The overlying, flat-lying sandy shale beds on top of the slump have a gray and olive-drab color more typical of unweathered marine mudrock. If the top of the slump beds were subaerially exposed, it would suggest that sea level had dropped near the end of *Baculites clinolobatus* time, and subaerial exposure occurred prior to deposition of additional marine facies of the Fox Hills Formation.

A lower unit of the Fox Hills Formation in the Grassy Tables Overlook area consists of a 15 meter thick interval exposed between the top of the slump zone several meters above the creek bed, and below a bench-forming unconformity (Fig. 56). This unit consists of thin, buff-colored sandstone beds with intervening buff-to-light gray-colored shale layers. Within the upper 10 meters of this interval 24 thin sand sheets were counted ranging from 2 to 20 centimeters in thickness. All of the beds dip southward at an angle of approximately 10° and grow generally thinner- and finer-grained in the southward direction. Slabs of sandstone from this interval reveal drag marks and flute and sole markings on their bottom sides typical of storm-generated, turbidity current-deposited sand sheets (see Fig. 26B, p. 72). Trace fossils of *Diplocraterion*, *Skolithos*, and *Thalassinoides* were observed in the sand sheets. Considering both the slump interval below, and the stacked succession of sand and shale sand sheets above, the interval probably represents facies of a clinoform-style mudbank or series of mudbanks which prograded southward from a sediment source area to the north. The relationship of the slump interval to pre-existing basement structures is unclear. It is evident, however, that deeper water conditions existed on the south side of the general trend of the Sage Creek Anticline/Fault System, and that this greater depth to the south initiated the movement of slump material in a southward direction. The proximity of the thick interval of stacked slumps and clinoform beds on the south side of the fault is significant because it suggests that movement along the fault zone occurred during sedimentation.

A highly visible change in lithology occurs above the lower sandy interval

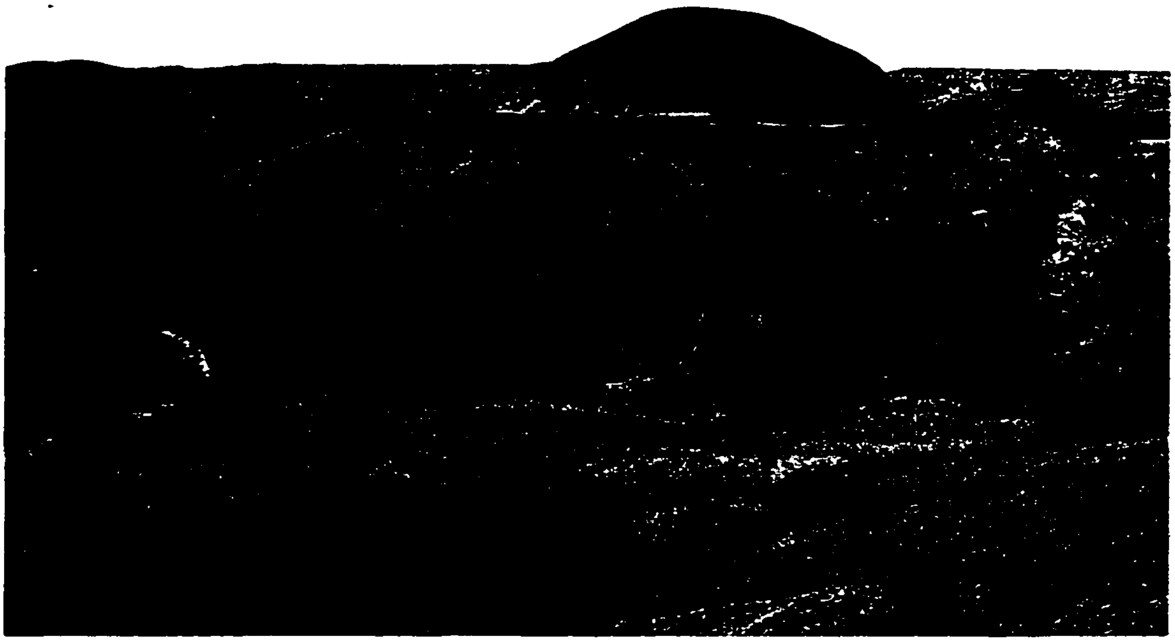


Fig. 56. Grassy Tables Overlook area, Sage Creek Wilderness Area, Badlands National Park, North Unit. A small hill approximately 25 meters high from the creek to the top of the hill displays the Interior Zone and the thickest section of Fox Hills Formation in the park. The exposure of the Interior Zone (upper Pierre Shale/Fox Hills transition shown in Fig. 55) crops out in NW, Sec. 19, T2S, R16E. Buried slump beds are exposed in cutbank at the base of the hill. Above the slump at least twenty-seven thin, southward-dipping sand beds with intervening mudstone were counted in a ten meter section below the "bench." The bench marks the location of the unconformity between the Lower Unit of the Fox Hills and deeply weathered strata of Upper Unit of the Fox Hills. A trace of red Chamberlain Pass Formation containing pods of fresh water limestone and possible termite mound structures were recognized in the vicinity by Dennis Terry (personal communication, 1997); this is overlain by basal Chadron Formation sandstone which caps the knob.

(described earlier), most likely representing an unconformity within the Fox Hills Formation. This unconformable surface is equivalent to the base of the small "yellow mounds" in the Roberts Prairie Dog Town locality (described above).

As in the previous locality, this upper unit of Fox Hills is roughly 5 meters thick, orange-red due to limonite stains, with the same thin-to-thick, even-bedded sand and mudrock layering. The difference in this location is the occurrence of several cross bedded shaley sandstone beds near the top of the interval. The cross bedding in this upper unit occurs locally in opposing directions, suggesting that sediments at the top of the Fox Hills were locally reworked a by migrating channel-type drainage, either by streams or tidal creeks. Unfortunately, the uppermost beds of this interval are also most heavily weathered by processes attributable to the Yellow Mounds-style weathering.

The relationship between the top of the Fox Hills and the overlying Chamberlain Pass Formation is unclear at this site, but it appears to be unconformable. Retallack (1983) originally named this interval the "Interior Red Clay" in exposures along a drainage in the Pinnacles area, east of the Sage Creek Wilderness and just west of the Dillon Pass area along the Badlands Loop Road; he attributed it to a period of heavy leaching associated with a hot, wet climate that existed in the region prior to deposition of the basal Chadron Formation. However, the discovery of conglomeratic stream deposits, freshwater limestone lenses, fossil wood, and land mammal remains described by Evans & Terry (1993), Terry & Evans (1994), and Dennis Terry (personal communication, 1997) clearly demonstrates that this unit, named the Chamberlain Pass Formation, is an Early Tertiary terrestrial unit. Without fossils, unfortunately, the age of the channels beneath the Chamberlain Pass and on top of the Fox Hills remains unclear. It may represent tidal creeks or stream channels similar to terrestrial facies in the uppermost Fox Hills Formation or Hell Creek Formation elsewhere in the region.

### 6.3.8 Dillon Pass Area, North Unit, Badlands National Park

In the Dillon Pass area, the Badlands Loop Road dips southward to the intersection with Conata Road; it then follows a narrow ridge northwestward along the general trend of the Sage Creek Anticline before climbing to the high Pinnacles Overlook area. The stratigraphic and structural relationship between the Pierre Shale, Fox Hills, and overlying Tertiary beds are fairly complex in the Dillon Pass area. Several NW-SE-trending faults cut across the area.

A measured section for the Dillon Pass area is presented in Fig. 57. The gray shale of the uppermost *Baculites clinolobatus* Zone is exposed along the bottom of ravines south of the "Seabed Jungle" Overlook, along the Badlands Loop Road near the intersection of Conata Road in SW, Sec. 27, T 2 S, R 16 E. Gray shale exposures occur sporadically along the intermittent creek bed that extends northwest

# BADLANDS NATIONAL PARK
## Dillon Pass/Conata Basin Area
## Badlands Loop Road
## Measured Section

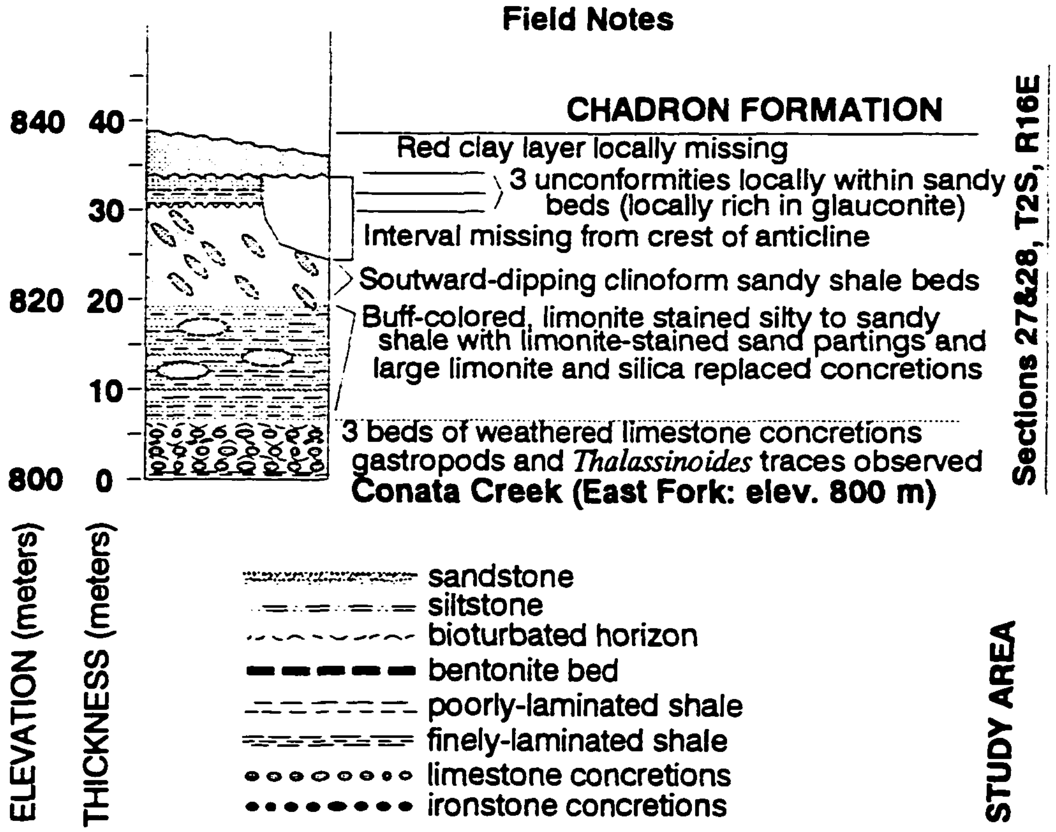


Fig. 57. Measured section for the Dillon Pass and eastern Pinnacles Area near the intersection of Conata Road and the Badlands Loop Road, Badlands National Park, North Unit.

along the south side of the Badlands Loop road. The ravine turns westward into a deep ravine penetrating the "Pinnacles," high white bluffs of the type reference area for the White River Group in NW, Sec. 20, T 2 S, R 16 E (Retallack, 1983; Retallack, 1985). Between the gray shale of the upper Pierre Shale and the base of the Chadron in this locality is the type area for Retallack's "Yellow Mounds Weathering Profile." Retallack's weathering profile is imprinted on the upper Pierre Shale/Fox Hills transition interval.

The headwaters of Conata Creek have exhumed the uppermost Pierre Shale, exposing several closely spaced beds of large limestone concretions bearing unidentified gastropods and the traces of *Thalassinoides, Planolites,* and *Chondrites.* These concretions, exposed in the core of the Sage Creek Anticline, most resemble concretions in the *Baculites clinolobatus* Zone along the South Fork of Sage Creek (NW, Sec. 28, T 2 S, R 16 E). The uppermost concretion beds are heavily altered by Yellow Mounds-style weathering. They display massive rinds of cone-in-cone crusts, and show dissolution replacement of calcite with limonite and silica. Some concretions have been completely replaced by white opalaceous silica. In general, the original sedimentary structures and fossils were completely destroyed in the interval affected by Yellow Mounds-style weathering.

Within the overlying Interior Zone, the dissolution and re-precipitation of iron minerals (due to Yellow Mounds-style weathering) resulted in the impregnation of thin sand sheets with limonite, highlighting the bedding structures. On the east side of the Badlands Loop Road in SW, Sec. 21, T 2 S, R 16 E, limonite-cemented sand-sheets stand out on the side of a creek bed, revealing a large-scale clinoform-style bedding geometry consistent with sediments deposited on a southward prograding mudbank (Fig. 58). Sand-sheets, probably representing storm-generated turbidity flow deposits, dip southward and pinch out down-slope. The dip angle of approximately 10° is exaggerated by structural warping along the crest of the Sage Creek Anticline.

In NW, Sec. 20, T 2 S, R 16 E, many sand sheets up to 6 inches thick are exposed along the bottom and the sides of a ravine draining from the high Pinnacles area to the west. These sand sheets appear to unconformably overlie the sandy shale of the upper Interior Zone along the creek bed on the east side of the Badlands Loop Road in NE, SE, Sec. 20, T 2 S, R 16 E. Traveling northward along the creek bed the sand sheets become more massive and increasingly coarser-grained before disappearing beneath younger sedimentary cover. These units most likely represent the Fox Hills Formation, although no fossils were observed to demonstrate this. The sand sheets display bright colors of red, orange, and pink, except for some fresh (unweathered) exposures of the structure's core which reveals a composition of mostly pelloidal grains of glauconite. The glauconite gives the sand a bright green color (similar to "greensands" mined in Maastrichtian age sediments in central New Jersey).

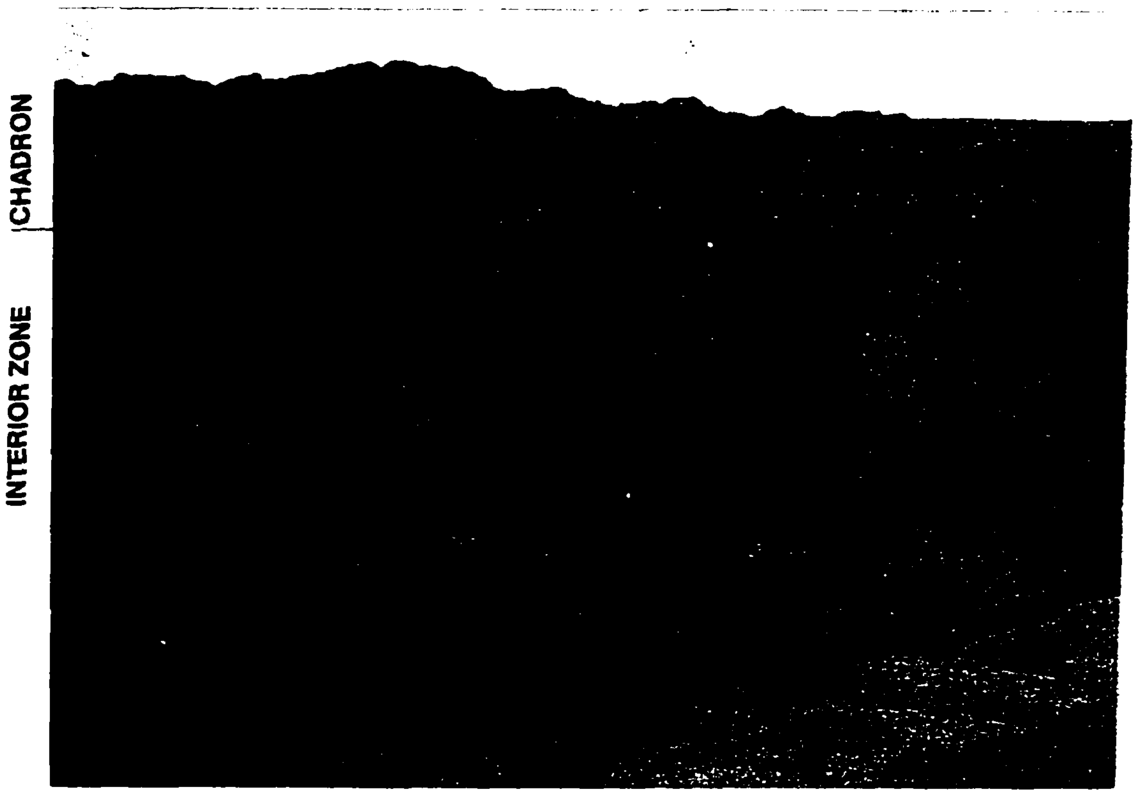


Fig. 58. Dillon Pass/Pinnacles area, Badlands National Park, North Unit. Gently southward-dipping clinoform beds of the Interior Zone are consistent with an interpretation of a southward prograding mudbank. Banding of layers represent glauconitic sand sheets that are affected by meteoric dissolution and cemented with limonite and silica. The Fox Hills and younger units are missing beneath overlying Chadron Formation. A red band along the base of the Chadron represents a paleosol. The height of the small bluffs in the foreground are about 20 meters.

The surfaces of these sand beds are weathered to a tan to reddish-brown color characteristic of limonite. Throughout the mudrocks and sand sheets small grains of limonite give the rock a speckled appearance. These dark brown grains probably represent weathered glauconite pelloids. These glauconitic sand beds provide evidence that the coloration of the sediment in the "Yellow Mounds Weathering Profile" are derived, in part, from the leaching of glauconite from sand beds in the Interior Zone and the Fox Hills Formation.

Fig. 59 shows perhaps the best exposure of the Fox Hills Sandstone in Badlands National Park. This exposure is in a ravine on the west side of the Badlands Loop Road in the Dillon Pass/Conata Basin area in NW, NE, SE, Sec. 20, T 2 S, R 16 E. Approximately 3 meters of sandy shale of the Interior Zone may be found near the creek bed. Immediately above the unconformable boundary is an intermittent bed of glauconitic sandstone (almost pure glauconite). This basal sand sheet is overlain by about three meters of fine-grained, thick-bedded to massive glauconitic sandstone. For correlation purposes this massive glauconitic sandstone is referred to the "Lower Unit" of the Fox Hills Formation. This is overlain by a 4 meter thick interval of thin to thick-bedded tuffaceous sandstone and mudstone, referred to here as the "Upper Unit" of the Fox Hills Formation. This is overlain by a thin Interior Red Clay layer (Retallack, 1985) (or a remnant of a paleosol equivalent to the Chamberlain Pass Formation after Terry & Evans, 1994). Yellow Mounds-

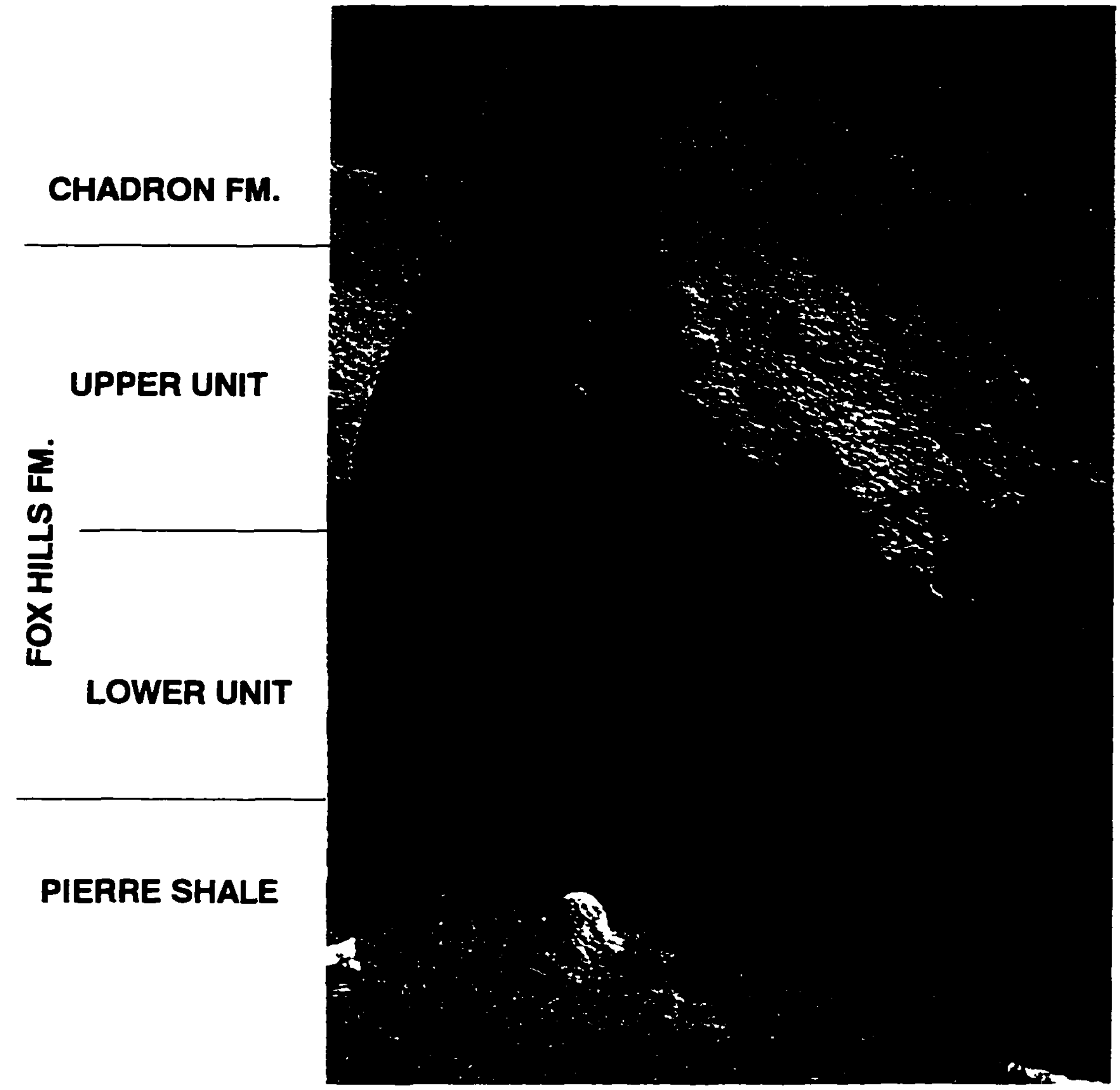


Fig. 59. This outcrop in a ravine on the west side of the Badlands Loop Road in the Dillon Pass/Conata Basin area in NW, NE, SE, Sec. 20, T 2 S, R 16 E is perhaps the best exposure of the Fox Hill Sandstone in Badlands National Park. Near the creek bed is approximately three meters of sandy shale of the Interior Zone. Immediately above the unconformable boundary is a thin intermittent bed of glauconitic sandstone (almost pure glauconite). This basal sand sheet is overlain by about three meters of fine-grain, thick-bedded to massive glauconitic sandstone. For correlation purposes this is the "Lower Unit" of the Fox Hills Formation. This is overlain by a four meter thick interval of thin to thick-bedded tuffaceous sandstone and mudstone, or the "Upper Unit" of the Fox Hills Formation. This is overlain by a thin Interior Red Clay layer (Retallack, 1985)(or a remnant of a paleosol equivalent to the Chamberlain Pass Formation after Terry & Evans, 1994). Yellow Mounds-style weathering has affected both the Interior Zone and the overlying Fox Hills, whereas the Chadron Formation is unaffected by Yellow Mounds-style weathering. The Jacobs staff is 1.5 meters for scale.

style weathering has affected both the Interior Zone and the overlying Fox Hills, whereas the Chadron Formation is unaffected by Yellow Mounds-style weathering.

Raymond and King (1985) mapped a fault system which trends west-northwest across the Dillon Pass/Conata Basin area. Numerous small faults were observed displaying offset in the range of several meters, with the greatest offset along a fault near the "Seabed Jungle" Overlook (SW, NW, Sec. 27, T 2 S, R 16 E) (Fig. 60). This fault is exposed in the area where the Badlands Loop Road dips southward toward its intersection with the Conata Road. This structure is an exceptional example of "growth faulting," that is, faulting contemporaneous with sedimentation of the White River Group. This normal fault is down-thrown on the south side, putting Chadron Formation adjacent to sediments of the Interior Zone. South of the fault, the beds appear to have rotated, resulting in a gentle northward dip, consistent with the rotation along glide planes typical of large slumps. However, the character of the fault in the subsurface is unknown. The general NW-SE trend of the fault system in the Conata Basin/Dillon Pass area parallels the general trend of the larger Sage Creek Anticline. This large anticline (or perhaps more accurately - a monocline because there is little dip on the north side) extends southeastward from the Cheyenne River Valley area, and extends south towards the confluence of Sage Creek (to the west) and the White River Valley east of Interior, South Dakota (to the east). The large extent of the Sage Creek anticline/fault system suggests that it is related to the

Fig. 60. Dillon Pass/Pinnacles area, Badlands National Park, North Unit. A view near the "Seabed Jungle Overlook" shows normal faults displaying offset of the uppermost Cretaceous units along with offset of beds in the overlying White River Group. The extent of faults beneath the surface are unknown. Most of the faults we observed in the Badlands area affecting Cretaceous rock are normal faults with east-to-west strike with the down-thrown hanging wall on the south side. These faults may be reactivated structures associated with buried slumps in the underlying Cretaceous beds and/or older basement structures. Reactivated Cretaceous slumps and faults during Eocene time may be responsible for the springs and ponds associated with the location of bone beds in the overlying Chadron Formation. Total height of the bluff is approximately 50 meters.

reactivation of a large basement structure in the area.

In NE, SE, Sec. 20, T 2 S, R 16 E, a small normal fault borders its down-thrown block to its north (which is atypical of this area). On the north side of the fault (down-thrown block) weathered glauconitic sandstone of the Fox Hills is exposed beneath a thin layer of red clay (Chamberlain Pass Formation). On the south side of the fault, both the Fox Hills and Chamberlain Pass formations are missing beneath the Chadron Formation. This indicates that faulting was active prior to deposition of the Chadron Formation.

## 6.4 CHEYENNE RIVER VALLEY

Selected exposures of the upper Pierre Shale were examined along the Cheyenne River Valley between Wasta, SD on Interstate 90 northward to the confluence with the Belle Fourche River and eastward to the confluence of the Cheyenne and the Missouri rivers. This is a vast region encompassing approximately 200 kilometers along the Cheyenne River. Access to fresh cutbank exposures is generally difficult due to lack of roads and private land ownership.

The Cheyenne River Valley is not easily accessible by car; attempts to navigate lines shown as roads on maps resulted in many dead ends, and private roads often posted "no trespassing zones." No attempts were made to investigate outcrops north of the Cheyenne River on Indian reservation land. Nevertheless, exceptional exposures were found at numerous localities in this region (discussed below). These localities were adequately spaced to provide a general description of sedimentary facies change within the study interval along the Cheyenne River valley. Permission was granted to gain access to outcrops along the valley of the Cheyenne River on the Jensen Ranch, the Tom Trask Ranch, and the Gabriel Ranch (Fig. 61). Additional Cheyenne River hillside sections were studied along excavations for an unnamed country road built to provide access to powerline towers in Pennington County, and along SD Highway 73 in Haakon and Ziebach Counties, South Dakota. The strata and structure along the Cheyenne River between SD Route 73 and the town of Cherry Creek, and between Cherry Creek and the Missouri River were not examined because of inaccessibility on the south side of the river, and Indian reservation holdings on the north. Future investigations might include a canoe trip down this section of the river in the late spring when water levels are higher and insect levels are lower! Another good investigation would be to travel by power-boat up stream on the lower portion of the Cheyenne River flooded by Lake Oahe Reservoir.

Strata in the region north and west of Wasta, South Dakota dip gently to the northwest toward the Williston Basin. The AAPG Highway Map of this region shows several northward plunging synclines and anticlines (see Fig. 8, p. 28). Except for a relatively small exposure of the upper Pierre Shale along the crest of the Cedar Creek Anticline (SD-MT boarder), the Pierre Shale and Fox Hills formations vanish under

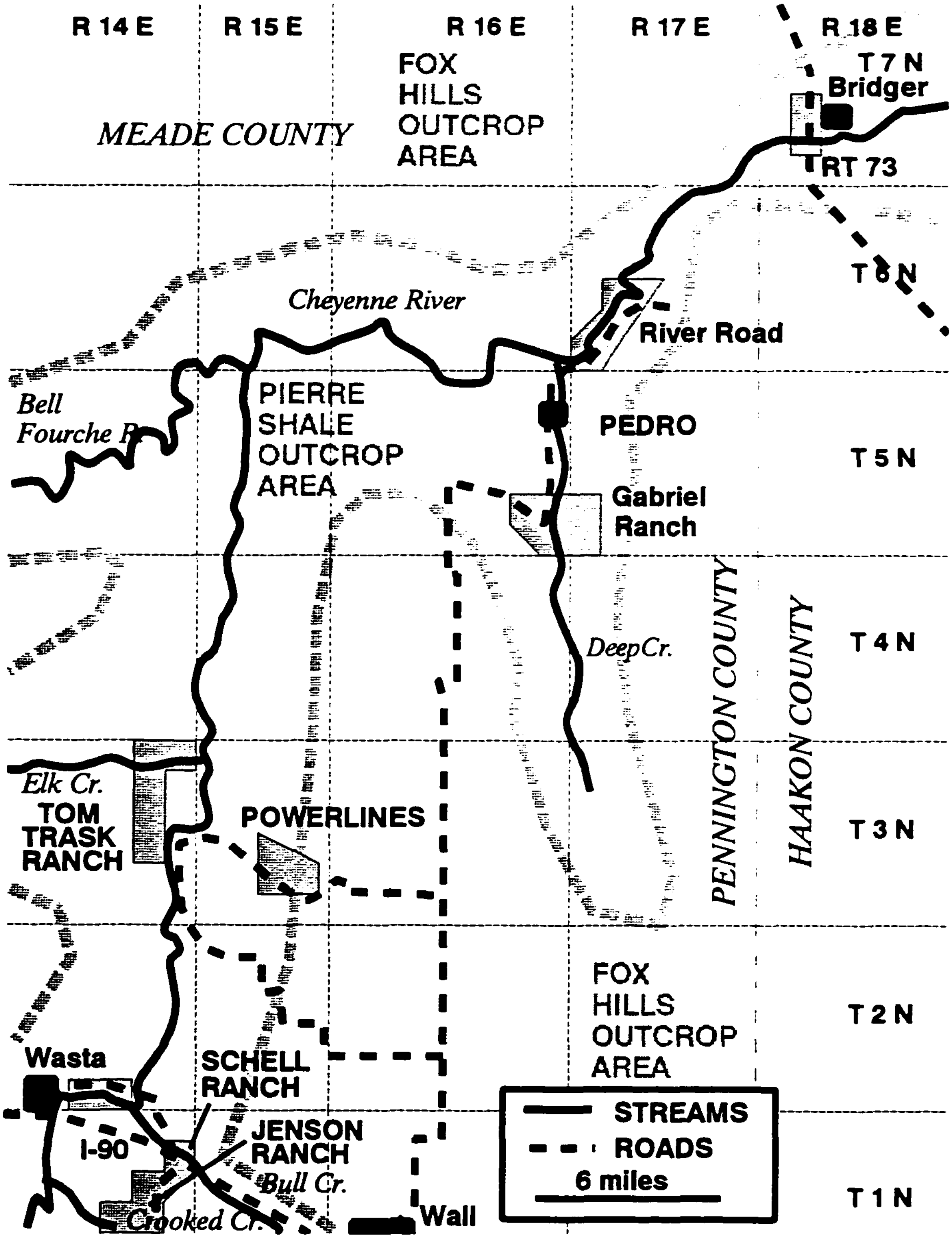


Fig. 61. Map of localities in the Cheyenne River Valley where sections were measured and studied on private land.

the sedimentary cover in the Williston Basin region. Bishop (1975) mapped the Pierre Shale stratigraphy demonstrating that the massive sandstones of the Fox Hills Formation sit conformably on top of the *Baculites grandis* Zone in the Pierre Shale. According to Gill & Cobban's (1973) model for the eastward progradation of the Sheridan Delta during Early Maastrichtian time, the basal Fox Hills in the Cedar Creek Anticline area is equivalent in age to the *Baculites clinolobatus* Zone. Gill & Cobban's report, however, made no attempt to resolve the stratigraphic relationships of the Pierre Shale and Fox Hills formations associated with the progradation of the Sheridan Delta into the Badlands National Park and Cheyenne River Valley region.

The region west of the Cheyenne River and north of the Black Hills was investigated by Robinson, Mapel, & Cobban (1959), and W. A. Cobban (personal communication, 1996). In general, the upper Pierre Shale is very poorly exposed in this area except at cutbanks along the Belle Fourche River and in the drainage of Elk Creek. Cobban assigns the names "Lower" and "Upper" unnamed shale members to this area, and illustrates that erosion and/or non-deposition has resulted in the absence or the *Baculites eliasi* and *Baculites jenseni* Zones in this region. In addition, Cobban indicated that the Kara Bentonitic Member is missing in the region north of the Black Hills. The missing Kara Bentonitic Member is consistent with an interpretation that an unconformity exists, defining the boundary between sediments of Campanian and Maastrichtian age in the Badlands National Park region.

### 6.4.1 Jensen Ranch (AMNH Localities 3208 & 3209)

The Jensen Ranch borders the south side of Interstate 90 along the hills on the eastern bank of the Cheyenne River. With permission from the landowner, specimens were collected and outcrop sections were measured on ranch property along County Road 50A. County Road 50A (Jensen Road) intersects I-90 approximately 3 miles east of Wasta, South Dakota. The road crosses the Jensen Ranch and eventually winds to Badlands National Park. South of the Interstate exit ramp, the road climbs upward through exposures of a full section of the upper Pierre Shale (Fig. 62). Strata throughout this portion of the Cheyenne River Valley appear to be essentially flat-lying to very gently dipping toward the north-northwest, based on the appearance of the change in slope and shale character between the Verendrye Member and the Virgin Creek Member on the lower hillsides, and occurrence of the Yellow Mounds Weathering Profile along the hilltops throughout the valley. The lowermost sandy units of the Fox Hills Formation are exposed along the hilltops north of Interstate 90 on the east side of the river on the land of Schell Ranch. The interval is very poorly exposed and displays heavy alteration by Yellow Mounds-style weathering. It consists of yellow-brown mudrock with large ironstone pedogenic concretions, and thick-bedded bioturbated sandstone that is orange-brown in color due to limonite stain. Unfortunately, a Schell Ranch employee would not grant permission for study of, or collection from these exposures. The Fox Hills Formation does not appear to crop

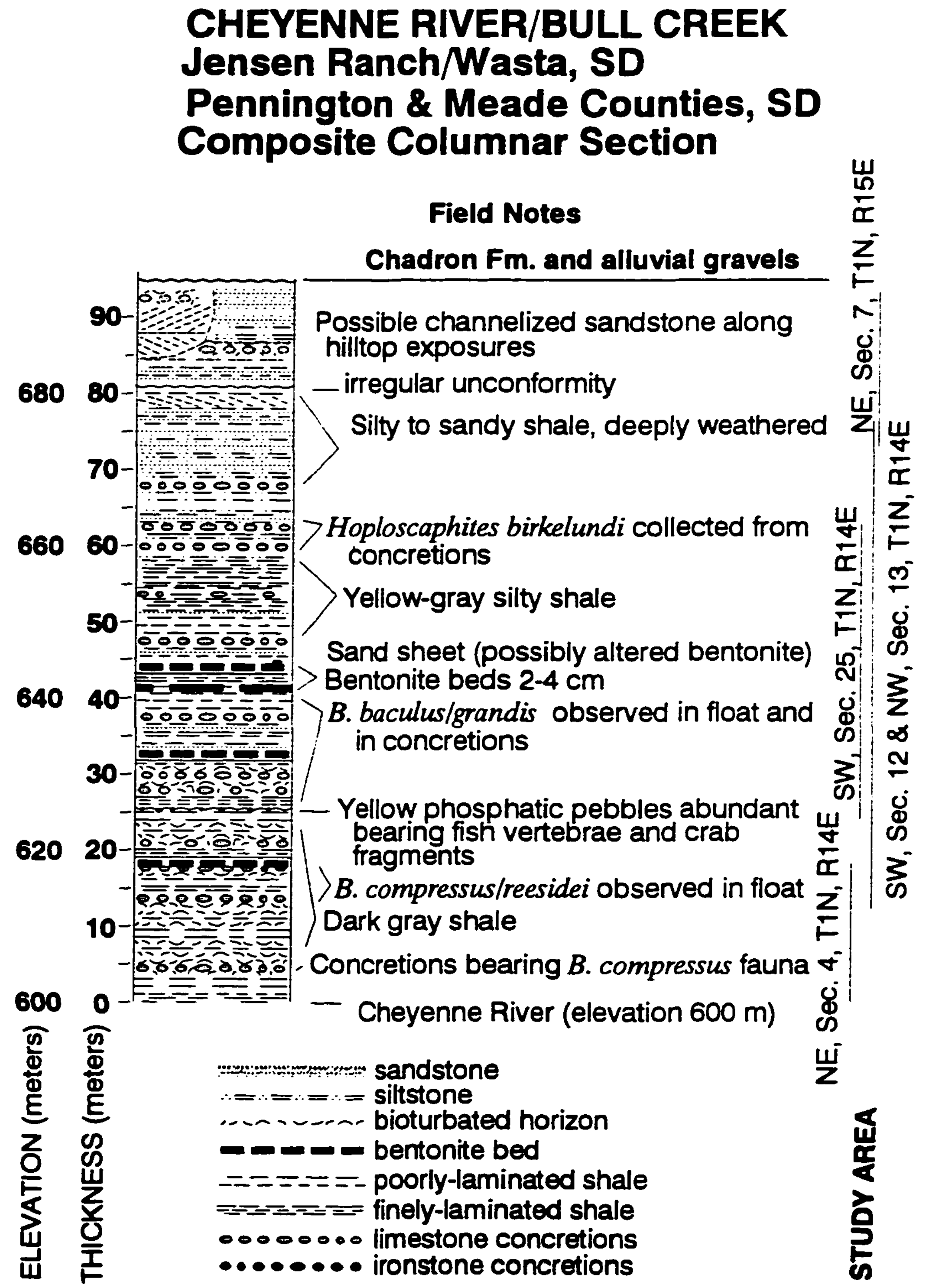


Fig. 62. Composite measured section for road cuts and cutbanks in the Wasta, SD area along Jenson Road (on Jensen Ranch) and in the valleys of Bull Creek and Crooked Creek, Pennington & Meade Counties, SD.

out along the hilltops on the south side of the Interstate, yet the hilltops are about the same elevation. This suggests that the strata dip very gently northward or northeastward in the Wasta area.

The *Baculites compressus* Zone is poorly exposed along the base of the hill along the Cheyenne River floodplain. Several body chamber fragments were observed in float along railroad cuts next to the northwest side of the Cheyenne River approximately one mile east of Wasta, South Dakota in NW, Sec. 4, T 1 N, R 14 E.

The intersection of Interstate 90 and County Road 50A (Jensen Road) is about 5 kilometers west of Wasta. South of the Interstate, the county road climbs through a complete section of the upper Pierre Shale. The Fox Hills Formation is missing below Quaternary alluvium at the top of the hill. The uppermost Pierre Shale is heavily altered by Yellow Mounds-style weathering.

Traveling southward along County Road 50A in NE, Sec. 4, T 1 N, R 14 E specimens resembling *Baculites cuneatus* were observed in large, gray, septarian limestone concretions on either side of the road at an elevation of approximately 717 m (approximately 17 meters above the river elevation of 700 m in nearby Wasta, South Dakota). At an elevation of about 725 m an abundance of small, yellow phosphatic nodules (1-5 cm) with black cores were collected. Many specimens contain the carapaces of small crab-like crustaceans, and many have the shape of coprolites. Several nodules were observed to contain small fish vertebrae. This zone of yellow phosphatic pebbles probably correlates with the Campanian/Maastrichtian boundary unconformity observed in Badlands National Park where yellow phosphatic pebbles were observed in this horizon. This interpretation is also supported by the observed occurrence of *Baculites compressus* below, and *Baculites grandis* above, this interval. Therefore, this unconformity separates the darker gray shale of the Verendrye Member (below) from the lighter gray shale of the Virgin Creek Member (above). The phosphatic pebble zone possibly represent a lag deposit along the unconformable boundary.

The Virgin Creek Member (above the phosphatic pebble zone) is very poorly exposed along County Road 50A. This is consistent with the observed poorly exposed occurrence of the Virgin Creek Member practically everywhere in the Badlands and Cheyenne River Valley region. This is probably a reflection of the weathering character of the member. However, several hundred meters west of County Road 50A locality (discussed above) is a less weathered exposure of the Virgin Creek Member. This locality located in SW section 12, T 1 N, R 14 E contains a dried, abandoned pond: remains from an old dam wash-out. Along either side of this dam and southward along the walls of two steep-sided ravines many large limestone concretions were observed bearing specimens resembling *Baculites grandis*. These concretions occur in at least two laterally continuous beds at an elevation of about 728 m and 730 m. Within many of the concretions the shells of numerous baculites occurred stacked together and were possibly current-oriented.

Along the easternmost ravine above the washed-out dam (closest to the road) between 740 m and 745 m in elevation, two prominent bentonite beds occur. Above these bentonite beds small baculite body chamber fragments were found lying loose in float. These specimens resembled the smaller compressed form of *Baculites clinolobatus* from the Sage Creek area. No other fossils were found in the Pierre Shale section upward through the transition into the buff-colored beds of the Interior Zone along County Road 50A. At the crest of the hill along the same road (in NE, SW, Sec. 13, T 1 N, R 14 E), no Fox Hills Sandstone is exposed beneath a cover of Quaternary alluvium.

Approximately 7 kilometers south of the Interstate, County Road 50A dips into the valley carved by Crooked Creek. Near the creek in SW, Sec. 25, T 1 N, R 14 E, an abundance of yellow phosphatic nodules with a similar appearance to those described above were collected. This site is at an elevation of 775 m whereas the site along County Road 50A mentioned above where the "yellow phosphatic pebble layer" occurs is at 725 m. This observation is supporting evidence that the strata is dipping very gently to the north at approximately 10 meters per kilometer.

Above the pebble layer the shale displays the typical yellowish brown weathering character typical of shale affected by Yellow Mounds-style weathering. At an elevation of about 780 m a thin cone-in-cone (calcite) layer crops out on the road-cut on the east side. A more prominent cone-in-cone layer crops out about 4 meters higher in the same outcrop. Both cone-in-cone layers display a yellowish appearance suggesting that they probably represent heavily altered and calcite-cemented bentonite layers. Approximately 4 meters above the upper cone-in-cone layer are two prominent beds of yellow limestone concretions that yield a specimen resembling *Holoscaphites birkelundi* (see Fig. 22A, p. 68). Based on the occurrence of this fossil in Badlands National Park, the altered bentonite beds probably occur in the upper *Baculites grandis* and *Baculites clinolobatus* zones. These concretions occur in the transition at the top of the Mobridge Member into sandier beds showing the yellow weathering typical of the Interior Zone, except here the Mobridge Member has been heavily altered by Yellow Mounds-style weathering.

### 6.4.2 Trask Ranch (AMNH Localities 3186-3189)

The Tom Trask Ranch covers many sections of land along the western side of the Cheyenne River south of the confluence of Elk Creek in section 9, T 3 N, R 14 E (see Fig. 61). The upper Pierre Shale is exposed in numerous cutbanks and in barren hilly exposures through the ranch property (Fig. 63). Fossils were collected from several localities on the ranch during the summer of 1995. Core samples were collected in two localities during the summer of 1996: 1) cutbanks along Elk Creek in SE section 9, T 3 N, R 14 E, and 2) along a steep, deeply incised ravine in NW

Fig. 63. The "Breaks of the Cheyenne" on the Tom Trask Ranch, Meade County, SD. This photograph was taken from the east side of the Cheyenne River looking westward toward bluffs of the upper Pierre Shale on Tom Trask Ranch. The Cheyenne River is just below the center of the photograph. The hill beyond is approximately 100 meters high. The Verendrye Member is covered on the lower forested slopes. The break in slope about halfway up the slope (about 50 meters) corresponds to the transition between the Verendrye and Virgin Creek Members. The Virgin Creek is gradational upward into the Mobridge Member. The light gray, more calcareous shale of the Mobridge Member forms the steepest slopes just below the ridge line. The top 10 meters of the hill is sandy shale facies equivalent to the Elk Butte Member.

section 23, T 3 N, R 14 E. A measured section for these exposures is presented in Fig. 64.

Large limestone concretions typical of the *Baculites compressus* Zone are exposed along the banks of Elk Creek (shown on bottom of the measured section on Fig. 64). Concretions yielded numerous fossils of baculites and displayed large bioturbation networks typical of a well-oxygenated benthic environment. Specimens of *Baculites cuneatus* were observed in a concretion approximately 10 meters above creek level. At approximately 20 meters above the stream a specimen of *Jeletzkytes nodosus* was collected just below a prominent bentonite bed. According to Dr. Neil Landman (personal communication, 1996) *Jeletzkytes nodosus* is a species that occurs in the *Baculites reesidei* Zone. The bentonite bed displays heavy cone-in-cone development due to an abundance of calcite cement. The bentonite also contains abundant small cannon-ball shaped limestone concretions with weathering rinds packed with grainy barite and calcite crystals. Approximately a meter above the bentonite was a zone of small yellow-weathering phosphatic nodules. The phosphatic pebbles bed probably represents a lag deposit along the unconformity separating sediments of Campanian and Maastrichtian age. The sediments immediately below the unconformity displayed brown limonite staining in abundant small fractures. Within a couple meters above the Campanian/Maastrichtian Boundary specimens most resembling *Baculites grandis* were collected.

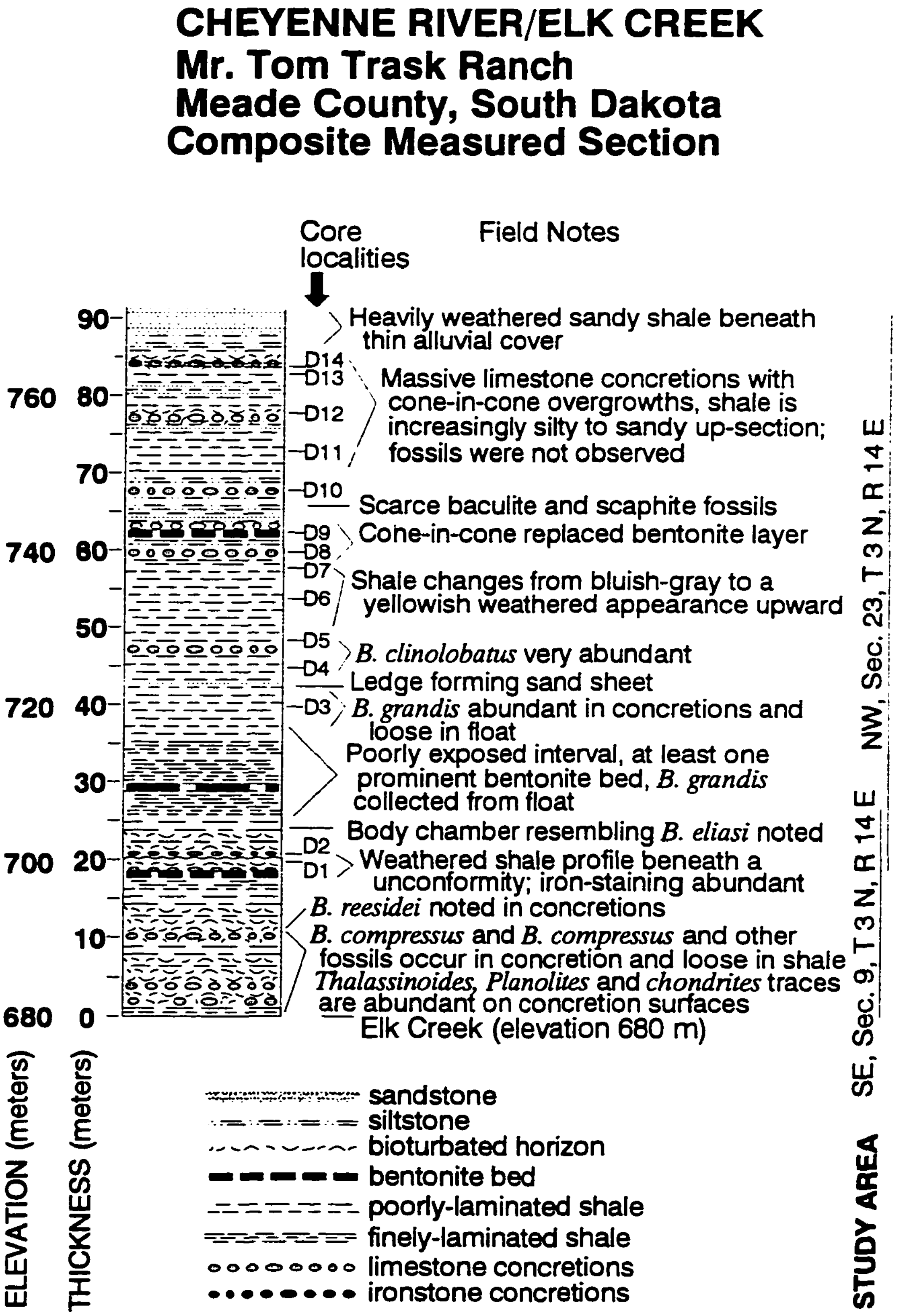


Fig. 64. Composite measured section for the Tom Trask Ranch, Meade County, South Dakota.

The upper portion of the Pierre Shale was sampled along the upper hillsides of the Cheyenne River Valley in Sec. 23, T 3 N, R 14 E, the measured section for this area is shown on the upper part of the measured section (Fig. 64). In section 23 the lower, western hill slopes bordering the river are overgrown with shrub forests and deep grasses. Small baculite body chambers most closely resembling *Baculites eliasi* were collected in float from the ravine at the base of the hill. The unconformity between the Verendrye and Virgin Creek members is not exposed, but is implied by a general change in color of the weathered soil from a dark gray below (the Verendrye Member) to a lighter gray above (the Virgin Creek Member); further evidence includes an abundance of small, yellow-weathering phosphatic nodules scattered on the surface in the vicinity of a break in slope at the base of the hill.

Specimens of *Baculites grandis* are abundant on the middle to upper slopes of the east-facing hillside below a USGS benchmark marking the NW corner of Sec. 23, T 3 N, R 14 E. Thin, ledge-forming sand sheets occur in the upper *Baculites grandis* Zone. One sandy bed approximately 10-15 cm thick creates a distinct ledge in several ravines in section 23. These sand ledges possibly represent a distal fan-type sand sheet formed along the front of the Sheridan Delta as it prograded eastward along the Wyoming/Montana border during *Baculites grandis* to *Baculites clinolobatus* time (Gill & Cobban, 1973).

The *Baculites clinolobatus* Zone contains many large limestone concretion beds. Scaphites resembling *Hoploscaphite birkelundi* occur near the top of the *Baculites clinolobatus* Zone approximately 30 meters below the benchmark. These fossils occur in a bed of concretions just above a 6-8 cm thick bentonite bed that displays intense cone-in-cone cementation. The original mud or shale above and below this bentonite was probably highly calcareous, perhaps a marl, however, dissolution processes have leached much of the calcite (from shells and microfossils) and precipitated it in beds of massive concretions and in cone-in-cone beds. The light gray color of the sediment, the abundance of large limestone concretions, and the occurrence *Baculites clinolobatus* demonstrates that the name Mobridge Member can be applied to this interval below the top of the hillside, although it has been heavily altered by Yellow Mounds-style weathering.

Above the zone bearing *Hoploscaphites birkelundi,* fossils are scarce or absent, and the shale grows increasingly silty and yellow to buff-colored, similar to the Interior Zone beds in Badlands National Park. Two beds of massive limestone concretions occur near the top of the hill. These concretions are up to 3 meters in diameter and 1 meter thick. They display massive overgrowth crusts of cone-in-cone (Fig. 65). No fossils are preserved in the concretions, however ghosts of bioturbation networks on the underside of several concretions indicate that marine life still flourished at the time that these upper sediments were deposited. The top of the hill is a covered with rusty, sandy sediment beneath alluvial terrace deposits.

Fig. 65. The Tom Trask Ranch, Pennington County, SD. A large limestone concretion with a thick crust of cone-in-cone calcite crops out in shale in the fossil barren interval above the *Baculites clinolobatus* Zone and the base of the Fox Hills Formation. Meteoric water penetrating from the surface is responsible for late-stage degradation of concretions, the formation of crusts, and probably the dissolution of fossil remains from this uppermost Pierre Shale unit (in NE, Sec. 22, T3N, R14E). The hammer is approximately 1 foot for scale.

From the hilltops on the Tom Trask Ranch the Fox Hills can be seen cropping out along ridge-tops on the east side of the Cheyenne River Valley. Based on this observation, a hilltop exposure near some powerlines that cross the Cheyenne River were investigated (discussed below).

### 6.4.3 Power Lines - Fox Hills Outcrop, Pennington County

The hilltops on the east side of the Cheyenne River are about 60 meters higher in elevation than the hilltops on the Tom Trask Ranch across the valley. Outcrops of Fox Hills Formation make up the difference in elevation on the east side of the river, where it forms a recessed bench along the hilltops. The bench is quite apparent when looking northward along the eastern side of the Cheyenne River Valley from a hilltop vista along a county road in SE, Sec. 5, T 2 N, R 15 E. This vista stop is approximately 2 miles south of the powerlines locality discussed below. The bench perhaps represents the same resistant unconformable surface marking the top of the Pierre Shale in the Sage Creek Wilderness Area in the North Unit of Badlands National Park. The bench probably represents a difference in the weathering character of the sandstone-dominant lithology of the Fox Hills juxtaposed on the underlying Pierre Shale.

Fox Hills Sandstone is well exposed in several hilltop excavations for a road and powerlines on the eastern side of the Cheyenne River Valley opposite the Tom

Trask Ranch in NE, Sec. 33, and NW, Sec. 34, T 3 N, R 15 E (see Fig. 61). These exposures are along a gravel ranch access road that climbs from the floodplain to the hilltops on the eastern side of the valley. Many exposures of the Pierre Shale occur throughout the valley in this area, however, no one could be found to get permission to gain access to posted property.

In the locality at the top of the hill the road passes beneath the power lines. Approximately 200 meters east of where the powerlines cross the road, poorly exposed outcrops of the gray shale of the upper *Baculites clinolobatus* Zone are indicated by the presence of large limestone concretions displaying large bioturbation networks. Unfortunately, no fossils were observed, but the shape and size of the concretions and the elevation where they occur are similar to those of the concretions at the top of the section on the Tom Trask Ranch directly across the valley. A measured section is shown in Fig. 66.

Within a 5 meter interval the gray shale observed among the limestone concretions grades upward to the buff-colored, limonite-stained sandy sediments typical of the lower Interior Zone. Sandstone talus covers the base of the hillsides below the Fox Hills Formation making it impossible to determine whether an unconformable surface exists between the Pierre Shale and the Fox Hills formation. In fresh road cuts on either side of the road below the powerlines, thick sand sheets form ledges that stand out from the faster weathering sandy shale above and below.

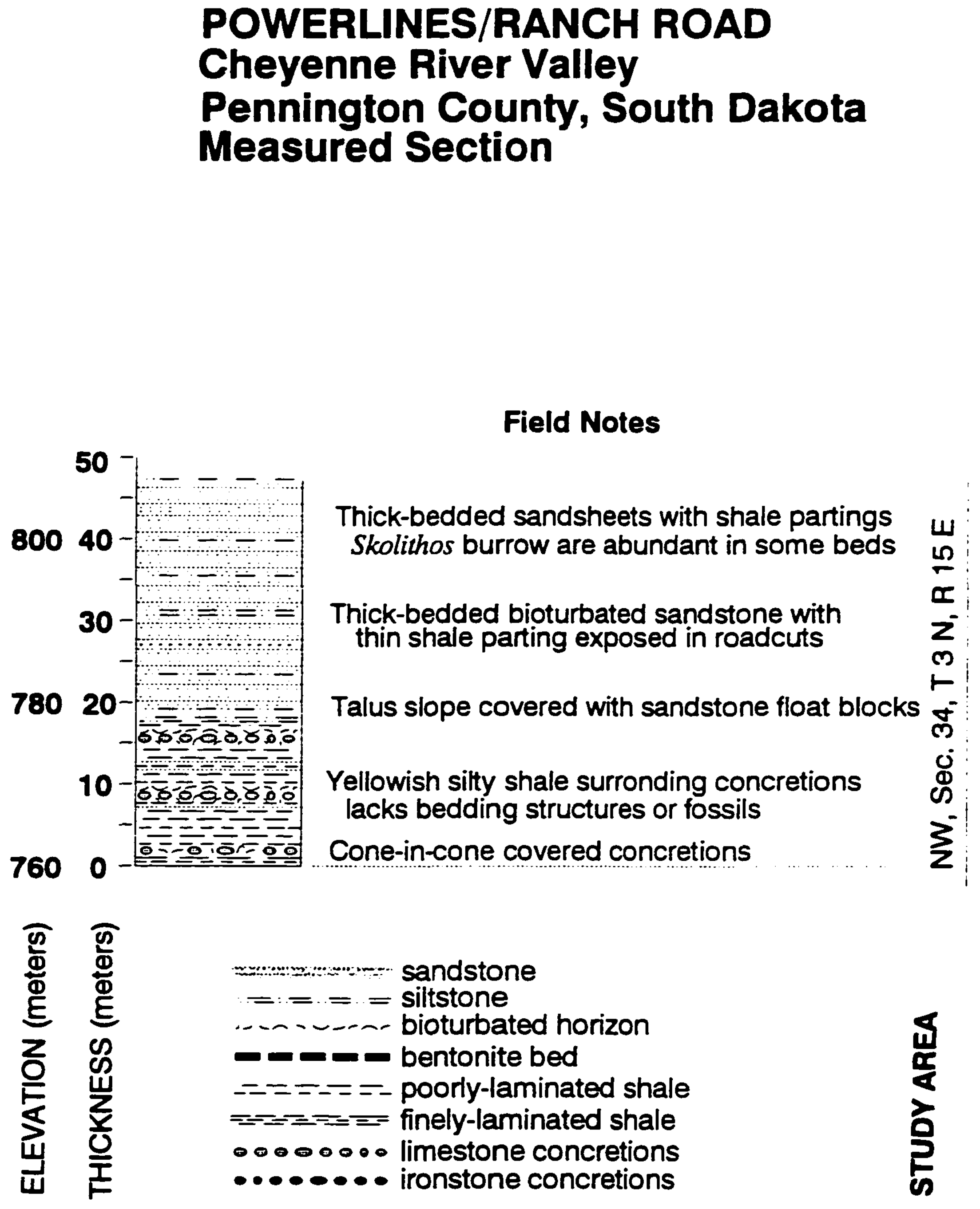


Fig. 66. Measured section of exposures beneath powerlines on the hilltop on the east side of the Cheyenne River Valley, Pennington County, South Dakota.

The thick-bedded sandstone layers display marine bioturbation networks typical of crustaceans, and display "starved-ripples" bedding structures on the surfaces and cross-sections of the sand sheets. *Skolithos*-type burrows are abundant, indicating that these sediments were deposited in a shallow, nearshore marine setting. The upper part of the section consists of massive bluffs of brown, even-bedded sand sheets and mudstone that were probably deposited in tidal flat-type sedimentary environments. In NW, NE, Sec. 34, T 3 N, R 15 E, the measured thickness of the interval between the limestone concretions at the base of the section and the top of the hilltop exposure beneath the powerlines is approximately 45 meters. Talus cover, unconsolidated terrace gravels and alluvium mask most of the slopes and the hilltop top.

### 6.4.4 Pedro, South Dakota (AMNH Localities 3221, 3184-3185)

Pedro, South Dakota is shown as a town on road maps, but in reality it represents a small cluster of widely spaced ranch homes along the valley of Deep Creek, a small tributary of the Cheyenne River (see Fig. 61). Several exposures of the Pierre were examined in the vicinity of Pedro including river bank bluffs along the Cheyenne River in SE, Sec. 31, T 6 N, R 17 E. A measured section for the Pedro area is illustrated in Fig. 67. Large, gray limestone septarian concretions along the river bottom yielded specimens of *Baculites compressus* and *Baculites cuneatus* from float on a gravel bar. Similar concretion were observed weathering from fresh

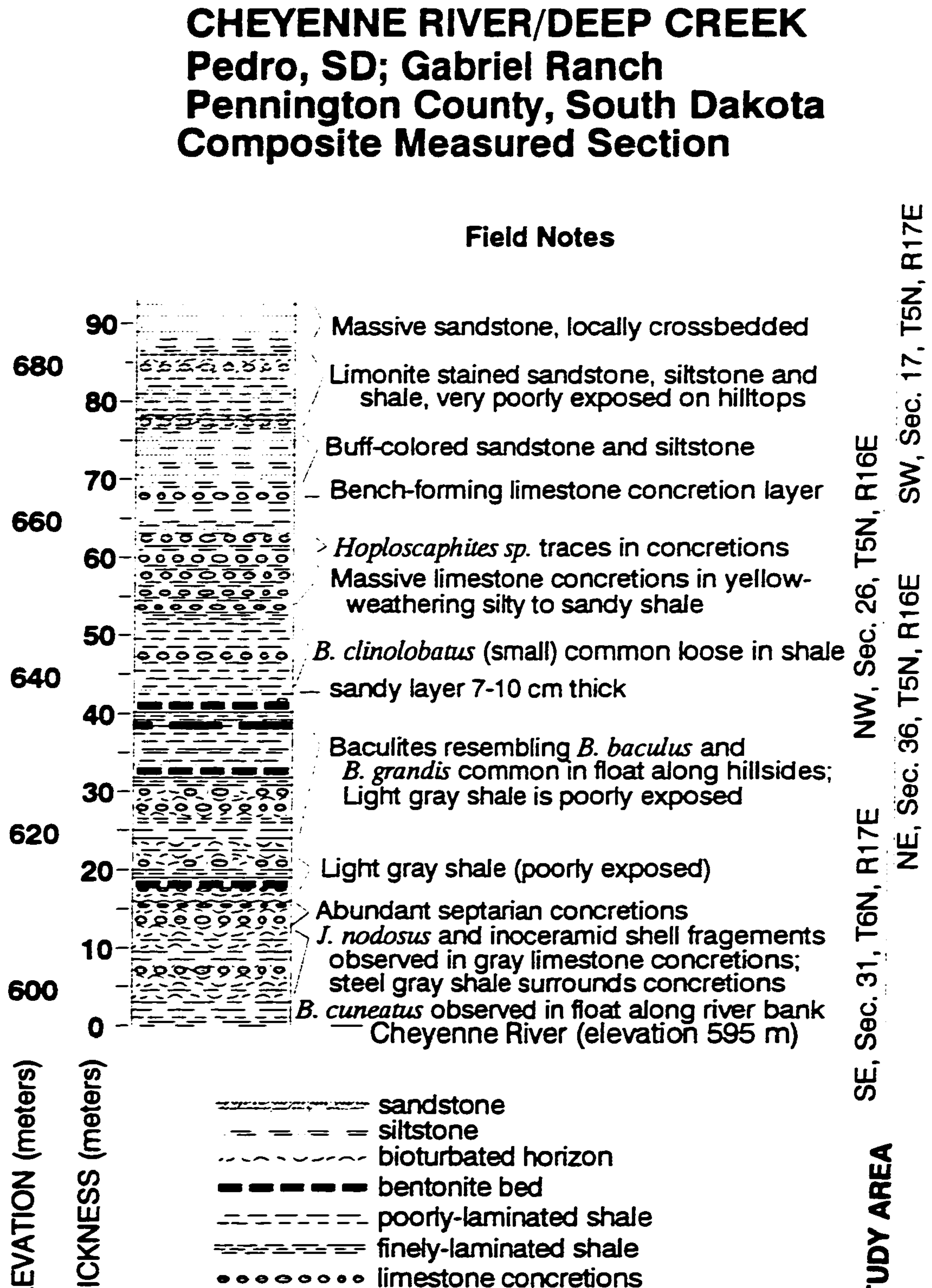


Fig. 67. Composite measured section for the Pedro area along Deep Creek on the Gabriel Ranch and along the Cheyenne River Road, Pennington County, South Dakota.

shale in small cutbanks along the river.

The road-cuts along the hillsides above the river road in section 31 yielded abundant specimens of *Baculites grandis*. These exposures are only about 15 meters above the river. If the ammonite zones of *Baculites reesidei* through *Baculites baculus* are present in this location, then they are very thin. The unconformity observed between sediments of Verendrye Member and Virgin Creek Member in the Badlands area is not exposed and is not apparent in this location. However, the close proximity of concretions bearing *Baculites cuneatus* and *Baculites grandis* suggests that the unconformity is present.

The strata seem to dip gently to the east in the vicinity of Pedro. This gentle structure was confirmed by the discovery of specimens most closely resembling *Baculites grandis* in weathered outcrops along the Cheyenne River, about 12 kilometers east of Pedro at an elevation of about 595 m. This zone occurs at about 700 m on the western hillsides of Gabriel Ranch about 7 kilometer north of Pedro.

A massive cutbank along Deep Creek was examined with permission behind the ranch house on the Gabriel Ranch in NW, Sec. 36, T 5 N, R 16 E. The upper *Baculites grandis* Zone is juxtaposed with sediments of the *Baculites clinolobatus* Zone, along a normal fault that cuts across this outcrop. The *Baculites grandis* Zone contains numerous bentonite beds typical of the Virgin Creek Member. The bentonite beds contain cone-in-cone type cement overgrowth. A prominent sand bed cuts across the outcrop near the top of the zone. This sand sheet in the middle of the *Baculites grandis* Zone is possibly the equivalent of a similar sand bed observed in the Tom Trask Ranch locality (approximately 26 kilomters to the southwest). The small, compressed variant form of *Baculites clinolobatus* are very abundant at this locality (see Fig. 21A). Near the top of the outcrop large limestone concretions occur in several discrete horizons approximately 2-3 meters apart. These concretions occur in laterally continuous horizons throughout the Deep Creek Valley. The bottom surfaces of these concretions display intense bioturbation patterns of *Chondrites, Planolites,* and *Thalassinoides* burrows. Poorly preserved casts of *Hoploscapites* sp. are common in the lower concretion beds in this interval (between 50 and 70 meters above the Cheyenne River elevation).

The top-most concretion bed is a ledge-forming unit. Concretions in this ledge range between 0.5-1.5 meters in diameter. This ledge forming unit was examined in SW, Sec. 17, T 5 N, R 17 E. Above this concretion bed the character of the sediment becomes sandier. This uppermost interval displays abundant limonite staining typical of Yellow Mounds-style weathering (similar in appearance to the Interior Zone in Badlands National Park). In general, the sediments above the uppermost ledge-forming concretion layer are very poorly exposed. If an unconformity exists along the boundary between the Pierre Shale and the base of the Fox Hills it is not apparent due to surface cover.

Bluffs consisting of massive cross-bedded sandstone similar to the upper Timber Lake Member in the Grand River Valley crop out in hilltop exposures about 2 kilometers east of the ranch house in Sec. 31, T 5 N, R 17 E. This massive sand unit of the upper Fox Hills creates steep-sided bluffs and a distinct break in slope along the steeper, uppermost hillsides along the west side of Deep Creek Valley. This interval is missing on hilltops on the west side of the valley. This difference is an indication of the gentle eastward dip of the strata into large synclinal trough that exists between Pedro on the west and the town of Bridger, South Dakota approximately 15 kilomters to the east.

### 6.4.5 SD Route 73 Bridge/Bridger, South Dakota

Exposures of the upper Pierre Shale and Fox Hills formations were examined along SD Highway 73 in the vicinity of the Cheyenne River Bridge (see Fig. 61). A measured section for this locality is presented in Fig. 68. Bluffs along the south side of the river are easily accessible from a pull-off that leads to a parking area under the bridge. The Indian reservation settlement of Bridger, South Dakota is to the north and east of the bridge.

Specimens of *Baculites cuneatus* were recovered from concretions on the river bar at the base of the bluffs. Poorly preserved specimens of *Baculites reesidei* in "baculite hash" were observed in float along the base of the bluff. The lower ten

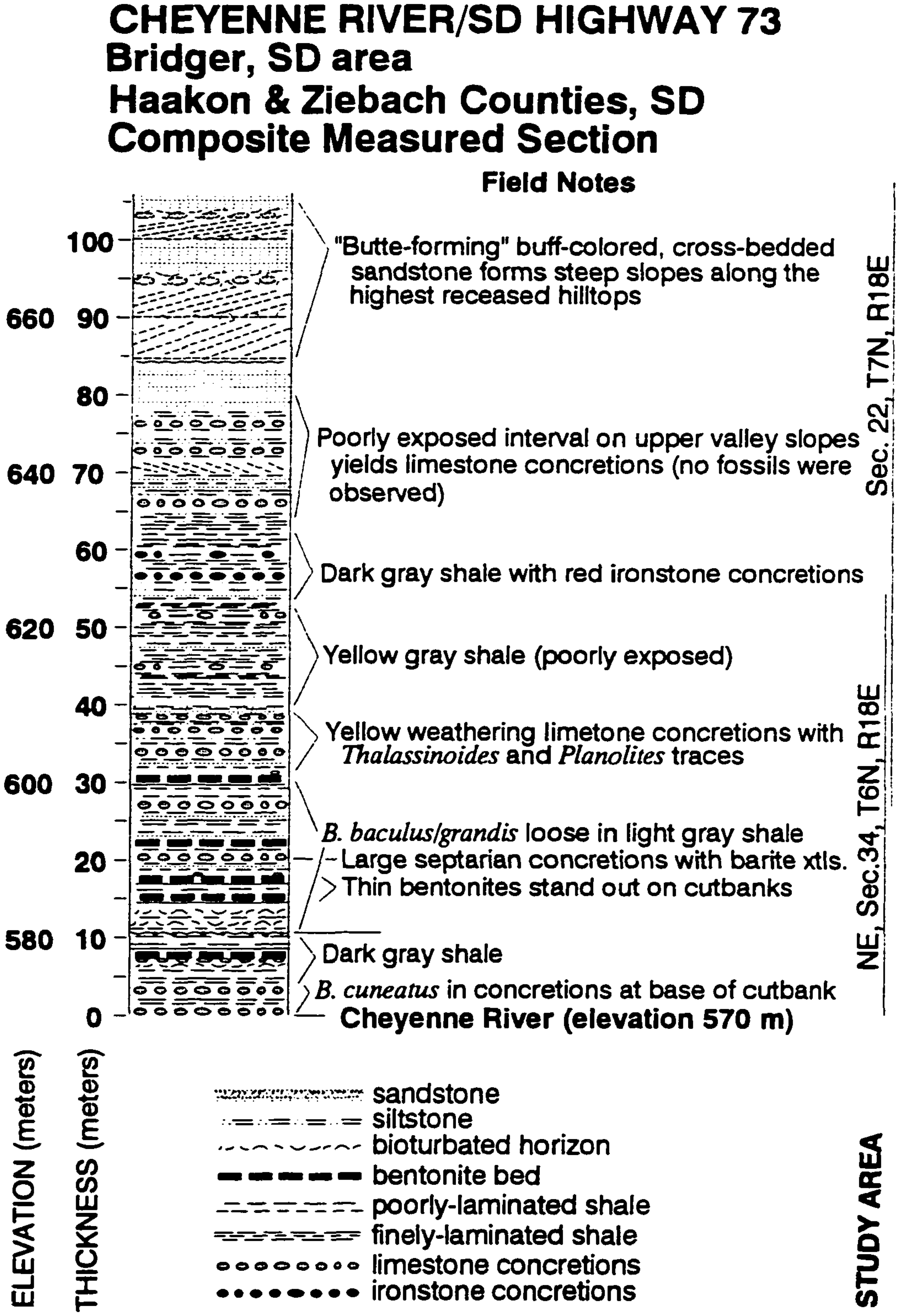


Fig. 68. Composite measured section for the Cheyenne River valley from cutbanks and road cuts near the SD Route 73 river bridge near the town of Bridger in Haakon and Ziebach counties, South Dakota.

meters of the section are a dark gray shale bearing large, cavernous septarian limestone concretions with barite- and calcite- filled fissures. Bentonite layers stand out as thin white stripes across the fresher exposures of the river cutbanks. The dark color of the shale, and the presence of *Baculites cuneatus* and *Baculites reesidei* indicate that this lower section is the upper portion of the Verendrye Member.

A change in color from dark gray to light gray occurs about 10 meters above river level. This is perhaps the only physical evidence to define the boundary between the Verendrye Member (below) and the Virgin Creek Member (above). The boundary between the Verendrye and the Virgin Creek members is perhaps more gradational here than in the Badlands National Park.

Several prominent bentonite beds and concretion horizons occur in the interval between 10 and 30 meters above river level. At the top of the river cutbanks the slope of the hillsides becomes less steep and the shale becomes a lighter gray color typical of the Virgin Creek Member observed in the Mobridge area. Pieces of large baculites, possibly *Baculites grandis*, crushed and covered with selenite crystals, were observed weathering from the shale. The occurrence of bentonite beds and the light gray appearance of the shale and the baculites indicate that this interval represents the Virgin Creek Member.

Several massive limestone concretion beds occur in the upper exposures of the river bank outcrops. The light color of the shale, the abundance of limestone concretions, and the ability to make the shale fizz when weak acid is applied indicates that this interval (between 32 and 52 meters above river level) is the equivalent of the Mobridge Member. However, no specimens of *Baculites clinolobatus* were observed in this outcrop area.

Roadside exposures of the uppermost Pierre Shale along SD Highway 73 north of the river yielded red ironstone concretions from two concretion horizons in an interval approximately 55 to 60 meters above river level. The shale encasing these concretions is dark gray, non-calcareous and fine-grained, similar to the Elk Butte Member in the Mobridge region. By comparison, however, this interval is very thin, no more that 5 to 10 meters thick before the shale changes to the buff, weathered silty shale similar to the transition interval to the overlying Fox Hills Formation in the Mobridge region. Massive limestone concretions with thick rinds of cone-in-cone crusts with septarian cracks mark the transition to the overlying sandier Fox Hills Formation. Poorly exposed bioturbated sandstone and shale beds containing concretions were observed in this area by Waage (1968) who assigned the name "Little Eagle" facies to this interval below the massive sand beds of the upper Fox Hills in the Moreau River valley region. Waage's "Little Eagle" facies are possibly equivalent to the Interior Zone in the Badlands National Park in the Bridger area. Unfortunately, no fossils were observed to support correlation. The occurrence of ironstone concretions in dark, fine-grained shale in the interval above the Mobridge facies suggests that water depths were greater, and the supply of coarser-grained sediments were not being transported into the Bridger area. It is possible that the southward dipping sandy clinoform beds in the Sage Creek Wilderness Area were deposited by nearshore current transport processes. Sediments were perhaps carried southward by currents along the western shoreline of the seaway, thereby starving the Missouri Valley region of coarser-grained sediments. The progradation of the Sheridan Delta had not yet reached the Bridger area when the sediments of the Interior Zone in the park were being deposited. These correlation problems are addressed in greater detail in the "Regional Correlation" section (Chapter 8).

# CHAPTER 7

## GEOCHRONOLOGY

A discussion of geochronology is essential for resolving problems relating to the age of units and to determine the significance of the unconformity observed between the Verendrye and Virgin Creek Members in the Badlands National Park region. Previously published reports discussed in this chapter establish a foundation for a geochronology for the Campanian through Maastrichtian strata in the Western Interior region. Early reports focused on interpretation of stratigraphic relationships along the western margin of the seaway, followed by the establishment of a chronology of biozonation (introduced in Chapters 1, 2, and 5). Perhaps the most important work is the establishment of a chronology of ammonite biozonation for the Western Interior region (Gill & Cobban, 1966; Gill & Cobban, 1973; Scott & Cobban, 1986; and Cobban, 1993)(see Fig. 2, p. 7). Additional confirmation of Cobban's ammonite biozonation sequence for the upper Pierre Shale include studies in the Wyoming region by Perman (1988), Roehler (1990) and Roehler (1993).

The integration of biozonation into a standard geologic time scale involve refinements in geochronology. This includes the determination of absolute ages of selected intervals in the Late Cretaceous section using radiogenic methods and strontium isotope geochronology methods, magnetostratigraphic determinations, and global correlations of microfossils and macrofauna. Such data can serve as a foundation to high resolution correlation and reconstruction of geologic history (sequence stratigraphy), both locally and globally. Unfortunately, not all of these methods have been integrated into a single report for the Western Interior. However, a framework for geochronology has been established for the Late Campanian through Early Maastrichtian strata in the Western Interior region which incorporates many lines of evidence. Current understanding of the geochronology of the Campanian-Maastrichtian boundary in the Western Interior is discussed below.

## 7.1. CAMPANIAN/MAASTRICHTIAN BOUNDARY GEOCHRONOLOGY

A discussion of the geochronology of the Campanian/Maastrichtian stage boundary is significant to this study because the Pierre Shale section in Badlands National Park encompasses this boundary. Because the type locality for this latest Cretaceous stage boundary was first established in Europe it has been difficult to translate the boundary to other locations around the world, and to the Western Interior in particular as this discussion will demonstrate. Many biologic and stratigraphic changes apparently occurred at the close of the Campanian stage, and these changes are recognized in outcrop sections around the world, and within the Western Interior.

For instance, previous research has demonstrated that a global eustatic fall in sea level occurred at the end of Campanian time, followed by a eustatic rise in early Maastrichtian time (Haq et al., 1987, Hancock, 1993; and Barrera et al., 1997). This resulted in lithostratigraphic facies changes as well as changes in biological communities preserved in representative sediment in the Campanian/Maastrichtian boundary section in every published locality. Difficulty arises in using microfossils, macrofossils, and/or lithostratigraphic variables to define the boundary, since no single event, such as an asteroid impact ash layer, occurred to mark this boundary. The mild mass extinction associated with the transition from Campanian to Maastrichtian time may not have occurred around the globe at the same time. In addition, the migration of species and sedimentary facies relevant to the establishment of the boundary probably occurred over a fairly lengthy interval of time. The discussion below illustrates the difficulties deriving from using different methods to correlate chronostratigraphic boundaries from different locations around the world, particularly by biostratigraphic means.

Obradovich (1993) stated that the micropaleontological definition of the Campanian/Maastrichtian boundary is the extinction horizon of the foraminifera *Globotruncana calcarata*. This assignment is the source of micropaleontology correlation problems between Europe and the Western Interior region of North America. The top of the Campanian was defined by Dalbiez (1959) as the top of the

*Bostrychiceras polylocum* Zone in northwestern Europe. Pessagno (1969) correlated this to the *Globotruncana calcarata* Zone in the Gulf Coast region. Bergstresser (1981) pointed out that the *Globotruncana calcarata* corresponds to a Western Interior foraminifer *Rugotrucana subcircumnodifer.* He added, however, that this species corresponds to the top of the Niobrara Chalk, so that the use of these species to defines the Campanian - Maastrichtian boundary places it somewhere in the lower Pierre Shale.

Obradovich (1993) reported that more recent work with global magnetostratigraphy methods indicate that the extinction horizon of the foraminifera *Globotruncana calcarata* most closely corresponds to the Late Cretaceous R32-N33 isochron. Obradovich reported that in the Western Interior region this isochron falls within the *Exiteloceras jenneyi* Zone (two zones below *Baculites compressus*). Bergstresser (1981) stated "it is unlikely that the discrepancy in ages indicated by planktonic foraminifera and ammonites will be readily resolved."

Using correlation with European and North American ammonites to define the boundary, Obradovich & Cobban (1975) initially placed the Campanian/Maastrichtian Boundary at the base of the *Baculites reesidei* Zone. But based on refinements in ammonite correlation to European reference sections, Kennedy, Cobban & Scott (1992) moved the placement of the boundary to the top of the *Baculites jenseni* Zone (or base of the *Baculites eliasi* Zone). They moved the boundary to this location based on the occurrence of the ammonite *Jelezkytes nodosus* in association with *Nostoceras hyatti* at the top of the Campanian in Poland. They found *Jelezkytes nodosus* within the *Baculites jenseni* Zone in Colorado. Baardsgaard et al., (1993) suggested that Campanian/Maastrichtian boundary should be placed at the top of the *Baculites reesidei* Zone citing that the *Nostroceras hyatti* probably spans the Campanian/Maastrichtian boundary in Spain, and that *Jelezkytes nodosus* is not found in the *Baculites jenseni* Zone in Canada. Baardsgaard et al., (1993) presented an absolute date of 72.5 ± .4 Ma using a variety of radiogenic methods for a bentonite bed at the top of the *Baculites reesidei* Zone in Alberta. Baardsgaard et al., cited unpublished data by McArthur that the *Baculites jenseni* Zone corresponds to previously established interpolated date for a type Campanian/Maastrichtian boundary section in northeastern Germany based on strontium isotope stratigraphy. However, Baardsgaard *et al.*, remained undecided whether the boundary should be placed above or below the *Baculites jenseni* Zone.

Hancock and Kauffman (1989) and Hancock (1993) suggested changing the Campanian/Maastrichtian boundary to correspond to a global eustatic rise in sea level that corresponds with the base of the *Baculites baculus* Zone in Colorado. Using this method to define the boundary works well in areas where facies changes mark the boundary, which, as Hancock (1993) was able to demonstrate occurred for sections throughout Europe, eastern and southeastern North America, and in the Western

Interior. Although Hancock (1993) placed the beginning of the eustatic rise in sea level at the base of the *Baculites baculus* Zone it may have occurred earlier (discussed below).

We collected *Jeletzkytes nodosus* from the top of the *Baculites reesidei* Zone just below an unconformable surface exposed in the cutbank along Cedar Creek in the South Unit of Badlands National Park. We also observed *Baculites baculus* Zone fossils a short distance above the unconformity (which we suggest defines the boundary between the Verendrye and Virgin Creek Members of the Pierre Shale). The thin or missing zones of *Baculites jenseni* and *Baculites eliasi* in the Badlands National Park region corresponds to a eustatic fall and rise in sea level. However, since these zones are apparently missing in the Badlands region, the Campanian - Maastrichtian boundary cannot be defined more precisely in the Badlands National Park area of South Dakota than the interval missing along the unconformity.

Gill & Cobban's (1966) description of the upper portion of the Lower unnamed shale member presents some problems which, unfortunately, we were unable to verify or resolve. They described the *Didymoceras cheyennense*, *Baculites compressus*, and *Baculites cuneatus* Zones as either missing or very thin in the Redbird section, but added that nothing about a six foot thick shale interval between the *Exiteloceras jenneyi* and the *Baculites reesidei* Zones (where the missing zones belong) hint of an unconformity or a period of non-deposition. They suggested that the thinness of the strata probably is related to a widespread unconformity at the base of the Teapot Sandstone Member of the Mesa Verde Formation in central and western Wyoming, and that submarine erosion may have removed these zones from the Redbird area. They acknowledged, however, that these zones occur on the eastern flank of the Black Hills.

Gill & Cobban (1966) report the occurrence of *Baculites eliasi* in the Redbird, Wyoming type section. They reported that a portion of the stratigraphic section below the Kara Bentonitic Member as a poorly resolved "*Baculites jenseni-eliasi*" interval (they could not resolve any differences between the two species beyond stratigraphic location, below and above).

In the Osage Oil Field area we observed concretions bearing fossils resembling *Baculites compressus*. This interval was overlain by a poorly exposed fossil-barren interval with thin, heavily iron-stained bentonites. This interval was overlain by the "*Baculites jenseni-eliasi*" Zone. (We also could not resolve a difference between the two species.) We observed an abundance *Baculites eliasi* starting slightly below the Kara Bentonitic Member and extending upward to the probably conformable transition to the *Baculites baculus* Zone in the Osage Oil Field, Wyoming study area.

In the Osage Oil Field section we collected a number of unidentified lobster-like crustaceans from yellow-weathering phosphatic concretions in an interval approximately 10 meters below the massive lowermost, ridge-forming bentonite layer of the Kara Bentonitic Member (see Fig. 25A, p. 71). These lobsters occurred in association with *Jelezkytes plenus* and *Baculites eliasi*. The size and abundance of these crustaceans suggests that water depths and oxygen availability was high enough to support a bottom community. However, above this interval, no bottom-dwelling organisms were observed until inoceramids and the bivalve *Protocardium* sp. appear in the *Baculites eliasi/baculus* transition zone. The abundance of *Baculites eliasi* fossils, yet a lack of inoceramids and bivalves through the Kara Bentontic Member, suggests that bottom fauna was insignificant, and that bottom currents were not strong enough to rework bentonite layers into the sediment. This would be consistent with an interpretation that water depths increased significantly during *Baculites eliasi* time, and that episodes of regression or uplift were already proceeding during *Baculites baculus* time in the Black Hills region. This is consistent with the interpretation by Winn, Bishop & Gardner (1987) who suggest that sea level rose during *Baculites eliasi* time and continued to rise to progressively higher levels culminating during *Baculites grandis* time, after which the seas began to progressively recede from their central Wyoming study area region during *Baculites clinolobatus* time. The occurrence of *Protocardium* sp. and other "shallow water" benthic fauna (including incrusting corals and scaphopods) on the western flank of the Black Hills during *Baculites baculus* through *Baculites clinolobatus* time suggest the possibility the tectonism may have elevated the Black Hills region relative to Winn, Bishop, &

Gardner's study area in central Wyoming. This hypothesis of tectonism in the Black Hills region might also explain the thinning of units, missing ammonite zones, and the occurrence of the unconformity between the Verendrye and Virgin Creek Member in the Badlands National Park region (and possibly in the Redbird section as well).

Because so many reasons have been given for establishing the placement of the Campanian - Maastrichtian boundary around the globe, argument will no doubt continue. The correspondence of the base of the *Baculites eliasi* Zone with the beginning of a eustatic rise in sea level may significantly help to resolve many aspects relating to the geologic history of the seaway. In any case, the placement of the Campanian - Maastrichtian boundary based on a eustacy curve would correspond to the chronostratigraphic equivalent horizons associated with a peak lowstand. In the Western Interior, based on ammonite biozonation and lithostratigraphic considerations in the Osage Oil Field study area, this would be within the *Baculites jenseni/eliasi* Zone, or just below the base of the *Baculites eliasi* Zone. This horizon corresponds to the horizon of phosphatic concretions about 10 meters below the boundary between the top of the Lower Unnamed Shale Member and the Kara Bentonitic Member in Wyoming. In the Badlands region, however, the unconformity between the top of the Verendrye and the base of the Virgin Creek conveniently serves as a reference to a major regression and transgression episode that occurred in the South Dakota region of the Western Interior Seaway, and is the most practical stratigraphic location to use in placing the Campanian - Maastrichtian boundary. Additional support for a hypothesis of concurrent changes in sea-level and tectonism in the vicinity of the Campanian - Maastrichtian transition in the Badlands National Park region comes from the study of strontium isotopes from selected samples of ammonite shell material discussed below.

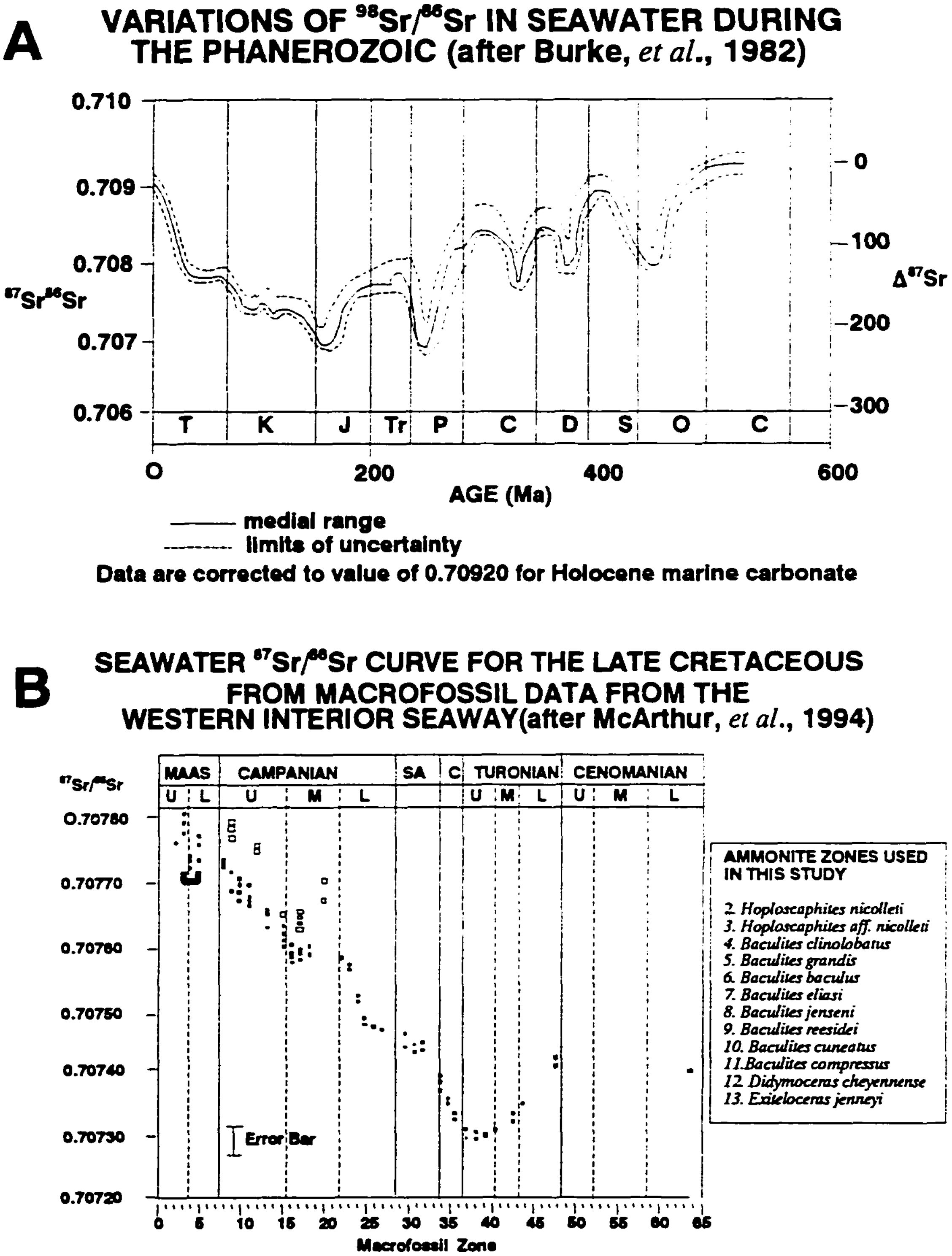
## 7.2. ABSOLUTE AGES AND $^{87}Sr/^{86}Sr$ DATA FROM AMMONITE ZONES

A growing body of data suggests that stable isotopes of strontium can be used for precise measurement of absolute ages for marine shell material when the general geologic age has already been determined (DePaolo & Ingram, 1985; Koepnick, Denison, & Dahl, 1988; Chaudhur & Clauer, 1986; Veizer, 1989; Denison et al., 1993). It is a numerical method with quantifiable uncertainties and high resolution, and, at least in the marine environment, it is independent of facies (Emery & Robinson, 1984). The general philosophy behind the method strontium isotope geochronology is as follows.

In the modern ocean the $^{87}Sr/^{86}Sr$ ratio of dissolved in seawater is constant at 0.70920. This is because the residence time of Sr in seawater is long ($\sim$4 million years) in relation to the time it takes the global oceans to mix ($\sim$1,000 years)(Palmer & Edmond, 1989). Marine organisms that secrete calcareous material (bone or shell) take up strontium in the $Sr^{87}/Sr^{86}$ ratio of seawater at the time that the organism lived.

Because the Rb concentration is carbonate and shell material is extremely low, radiogenic decay is not a significant source of $Sr^{87}$. The fossil will record the ratio of $^{87}Sr/^{86}Sr$ of the seawater in which the organism lived as long as the fossil had not been altered during diagenesis of the encasing sediment, or the seawater was not diluted by meteoric waters which tend to be enriched in $^{86}Sr$ (Bryant, Jones, & Mueller, 1995). A growing body of data from throughout the sedimentary record demonstrates that the strontium isotopic values (reported as a ratio of $^{87}Sr/^{86}Sr$ of ocean water has shifted back and forth between higher and lower values through time (Fig. 69A)(Burke et al., 1982). Once a seawater reference curve has been established it can be used for chronostratigraphic dating. For the purpose of this investigation, detailed $^{87}Sr/^{86}Sr$ curves have been established for the Late Cretaceous using deep sea foraminifera from the Pacific Ocean (Barrera et al., 1994), planktonic foraminifera from the Atlantic Ocean (Sugarman et al., 1991), from the English Chalk (McArthur et al., 1993), and with greatest significance to this research, from mollusks from the Western Interior Seaway (McArthur et al., 1994)(Fig. 69B).

Data for seawater reference curves are established from unaltered marine carbonate or phosphate specimens compared with other means of absolute dating of sediments (i.e., radiometric dates on bentonite beds, magnetochrono-stratigraphy, high resolution biostratigraphy, etc.)(Emery & Robinson, 1982). Precision and accuracy of dates derived from a Sr sea-level curve depend on several factors: 1) the accuracy



A VARIATIONS OF $^{98}$Sr/$^{86}$Sr IN SEAWATER DURING THE PHANEROZOIC (after Burke, *et al.*, 1982)

——— medial range
--------- limits of uncertainty

Data are corrected to value of 0.70920 for Holocene marine carbonate

B SEAWATER $^{87}$Sr/$^{86}$Sr CURVE FOR THE LATE CRETACEOUS FROM MACROFOSSIL DATA FROM THE WESTERN INTERIOR SEAWAY(after McArthur, *et al.*, 1994)

AMMONITE ZONES USED IN THIS STUDY

2. *Hoploscaphites nicolleti*
3. *Hoploscaphites aff. nicolleti*
4. *Baculites clinolobatus*
5. *Baculites grandis*
6. *Baculites baculus*
7. *Baculites eliasi*
8. *Baculites jenseni*
9. *Baculites reesidei*
10. *Baculites cuneatus*
11. *Baculites compressus*
12. *Didymoceras cheyennense*
13. *Exiteloceras jenneyi*

(after McArthur, *et al.*, 1994)

Fig. 69. $^{87}$Sr/$^{86}$Sr curves for seawater derived from marine shell material. A: Burke, *et al.*, (1982) curve for Phanerozoic time. B: McArthur, *et al.*, (1994) for the Late Cretaceous ammonite zonation in the Western Interior Seaway.

of the measurements (which is generally negligible with modern analytical methods); 2) the gradient of the curve - the steeper the curve the greater the resolution; and 3) accuracy of the curve itself. The main problems with defining the curve include: 1) inter-laboratory analytical bias in published results; 2) contamination of marine carbonates with Sr from non-marine sources (from minerals in the encasing sediment or from post-depositional alteration); 3) uncertainty in the biostratigraphic dating of the samples. The laboratory analytical bias is minimalized by normalizing sample $^{87}Sr/^{86}Sr$ data to a reference standard for modern seawater, and by having analyses conducted by a laboratory dedicated to stable isotope research. The second problem is reduced by analyzing large numbers of "screened" specimens - the greater the number, the greater the accuracy of the curve. Screened specimens are samples that have been closely scrutinized for diagenetic alteration or contamination. For instance, the examination of $\delta^{13}C$ and $\delta^{18}O$ can demonstrate whether the shelled organism lived in waters diluted by meteoric input (Palmer & Edmond, 1992; Bryant & Jones, 1995). The third problem is perhaps of greatest significance, for without other means of chronostratigraphic correlation the Sr curve dates are disputable. Fortunately, for the Western Interior Seaway region absolute age data and biostratigraphic data are available.

As mentioned above, age resolution is dependent on the steepness of the curve and its accuracy. McArthur et al., (1994) demonstrates that certain portions of the curve for the late Cretaceous show "inflections," that is, sudden shifts in Sr values away from the general trend of the curve. These inflections render the age determinations for samples from the "inflection interval" to a greater range of uncertainty. McArthur et al., suggests that inflections may represent "markers" or event horizons where either a global, regional, or local "event" cause a very rapid shift in Sr values. These inflections are either real or errors in sample data. For instance, McArthur et al., (1994) record an inflection in the *Baculites clinolobatus* Zone in the Western Interior Seaway. The cause of this inflection, if it is real, is unknown.

Radiometric dating of bentonite horizons within Cobban's ammonite zones establish as an important framework for systematic revision of the geologic history of the Western Interior region. A number of absolute dates derived from volcanic ash material have been published for three ammonite range zones in the study interval from localities throughout the Western Interior region. These include dates for $^{40}Ar/^{39}Ar$ ages for bentonite beds in the *Baculites compressus* Zone (73.35 ± 0.39 Ma) and the *Baculites clinolobatus* Zone (69.42 ± 0.37 Ma) by Obradovich (1993). A third date by Baardsgaard et al., (1993) for the upper *Baculites reesidei* Zone is discussed below. Obradovich's absolute dates were used by McArthur et al., (1994) to calibrate a strontium isotope curve for the Western Interior (discussed below).

McArthur's Sr curve was an attempt to establish ages for ammonite range zones in the Western Interior. McArthur's interpolated numeric dates for the middle of ammonite range zones in the study interval are reproduced below in Table II. This table includes McArthur et al.'s, (1994) complete data set, as well as age data obtained from ammonite specimens collected in Western Interior region. Species identification and collection sites for our specimens are given in the footnotes to Table II.

Baardsgaard et al., (1993) reported ages for a single bentonite bed near the top of the *Baculites reesidei* Zone. These ages and the methods used are as follows: 72.5 ± 0.2 (Rb-Sr analysis of a zircon grain), 72.4 ± 0.4 ($^{206}Pb/^{238}U$ analysis of a zircon grain), 72.6 ± 0.4 Ma ($^{207}Pb/^{235}U$ analysis of a zircon grain), 72.5 ± 0.2 Ma ($^{40}Ar/^{39}Ar$ analysis of a sanidine grain), and 72.6 ± 0.2 Ma ($^{40}Ar/^{39}Ar$ analysis of a biotite grain). Combining these data they establish the age of the bentonite at 72.5 ± 0.4 Ma. This is good confirmation for the use of the Sr Curve method for the Campanian-Maastrichtian interval because McArthur et al., (1994) reported the interpolated age for the middle of the *Baculites reesidei* Zone to be 72.2 Ma.

## 7.3. $^{87}Sr/^{86}Sr$ ANALYSES OF SELECTED AMMONITE SAMPLES

Confirmation of ammonite age designations is supported by strontium isotope analyses ($^{87}Sr/^{86}Sr$) on selected specimens from the study area compared with data for ammonite shell by McArthur et al., (1994).

Seven analyses were conducted on ammonite shells: six baculite shells and one *Didymoceras* shell. Specimens selected all showed a bright, iridescent nacreous sheen. Analyses were conducted by mass spectrometry using facilities at M.I.T. under supervision of Krueger Enterprises, Inc. Results of analyses are presented along with McArthur et al.'s (1994) data in Table II.

Strontium isotope data for samples of *Baculites reesidei*, *Baculites eliasi*, *Baculites grandis*, and *Baculites clinolobatus* collected in this study fell within data ranges presented by McArthur et al., (1994). However, data for a single sample of *Baculites compressus* shell from Sage Creek indicated a value significantly lower (and therefore "older") than McArthur's data. The reason for this disparity is unclear. Additional testing of samples from the *Baculites compressus* Zone might help resolve problem by providing a basis for distinguishing between sampling error, experimental error, and diagenetic alteration. In this regard, the idea of simple diageneitical alteration seems unlikely for two reasons. The *Baculites compressus* shell sample was taken from the center of a concretion (similar to the specimen in Fig. 15B, p. 61). This specimen was selected because it appeared to be in pristine condition, having a brightly iridescent nacreous layer without visible fractures or deformations. McArthur's discussion demonstrates that the testing error encountered with samples of mollusk shell in their study of the Western Interior region tended to provide dates that were *younger* because of diagenetic alteration of shell material was the result of the

# TABLE II

## $^{87}$Sr/$^{86}$Sr DATA, ABSOLUTE DATES AND NUMERIC AGES FOR WESTERN INTERIOR AMMONITE ZONES

| BIOSTRAT. AGE[1] | AMMONITE ZONE[2] | SAMPLE DATA[3] MCARTHUR | SAMPLE DATA[4] STOFFER | MEAN[5] $^{87}$Sr/$^{86}$Sr | Ar/Ar Date[6] Ma | Numeric Age[7] Ma |
|---|---|---|---|---|---|---|
| Late Maastrichtian | *Hoploscaphites nicolletii* | .707759±07<br>.707797±07 | | .707778 | | 68.8 |
| Late Maastrichtian | *Hoploscaphites* aff. *nicolletii* | .707775±07<br>.707790±07<br>.707802±07 | | .707789 | | 69.3 |
| Early Maastrichtian | *Baculites clinolobatus* | .707720±09<br>.707730±11<br>.707729±11<br>.707738±07 | .707739±16 | .707729 | 69.4 | 69.7 |
| Early Maastrichtian | *Baculites grandis* | .707733±08<br>.707752±10<br>.707756±09<br>.707759±07<br>.707766±11<br>.707770±08 | .707746±08 | .707757 | | 70.2 |
| Early Maastrichtian | *Baculites baculus* | .707731±08<br>.707747±08 | | .707739 | | 70.7 |
| Early Maastrichtian | *Baculites eliasi* | .707733±09<br>.707734±09 | .707730±11 | .707734 | | 71.2 |
| Late Campanian | *Baculites jenseni* | .707723±10<br>.707726±07<br>.707727±09<br>.707730±07<br>.707734±07 | | .707728 | | 71.7 |
| Late Campanian | *Baculites reesidei* | .707685±08<br>.707710±07 | .707679±10<br>.707705±11 | .707697 | | 72.2 |
| Late Campanian | *Baculites cuneatus* | .707667±09<br>.707669±09<br>.707679±07<br>.707683±07<br>.707693±08<br>.707695±08<br>.707703±12 | | .707688 | | 72.6 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Late Campanian | *Baculites compressus* | .707661±10<br>.707668±07<br>.707674±08<br>.707675±08<br>.707692±08 | .707578±16 | .707679 | 73.4 | 73.1 |
| Late Campanian | *Didymoceras cheyennense* | | .707686±11 | | | 73.9 |
| Late Campanian | *Exiteloceras jenneyi* | .707625±09<br>.707626±07<br>.707648±09<br>.707651±08 | | .707637 | 74.8 | 74.8 |

Notes on superscripts:

[1] Biostratigraphic Age: Age reported by McArthur et al., (1994) after Obradovich, (1993).

[2] Ammonite Zone Names used by McArthur et al., (1994) after Cobban (1993).

[3] Sample Data reported by McArthur et al., (1994, p. 100).

[4] Sample Data prepared for this report by *Geochron Laboratories, Krueger Enterprises, Inc.*, 1996.

*Baculites clinolobatus*: From Tom Trask Ranch, Pennington County, SD (AMNH3186)
*Baculites grandis*: Osage Oil Field, Weston County, WY (AMNH3194)
*Baculites eliasi*: Osage Oil Field, Weston County, WY (AMNH3194)
*Baculites reesidei*: Cedar Creek, Badlands National Park, South Unit (AMNH3212)
*Baculites reesidei*: Cedar Creek, Badlands National Park, South Unit (AMNH3212)
*Baculites compressus*: Wasta, SD (AMNH3183)
*Didymoceras cheyennense*: collected from above the unconformity above the *Baculites reesidei* Zone at Cedar Creek, Badlands National Park, South Unit (AMNH3212)

[5] Mean $^{87}$Sr/$^{86}$Sr reported for samples from each zone by McArthur et al., (1994, p. 105).

[6] Absolute dates for $^{40}$Ar/$^{39}$Ar reported by Obradovich (1993).

[7] Numeric interpolated ages of the middle of zones based on an adjusted $^{87}$Sr/$^{86}$Sr curve by McArthur et al., (1994, p. 105).

influx of isotopically lighter meteoric water. Our sample is isotopically *heavier* (reported as 0.707578±16, which according to McArthur's data would be about 6 million years older than his estimate 73.1 Ma for the *Baculites compressus* Zone). However, an unusaual diagenetic process may be at work. The sample was collected from the location at the base of a cutbank where a large normal fault, associated with the Sage Creek anticline/fault system, displays as much as 20 meters of offset. The fact that our $^{87}Sr/^{86}Sr$ is heavier (by .0001) than McArthur's $^{87}Sr/^{86}Sr$ data for the *Baculites compressus* Zone is possibly a reflection of shell modification by water enriched in $^{87}Sr$ that may have migrated upward from older strata through the fault zone in the vicinity where the concretion formed in which the fossil was preserved. Additional testing of *Baculites compressus* from throughout the region are essential to resolve this question.

Two specimen of baculites from the Cedar Creek cutbank in the South Unit of Badlands National Park fell within the McArthur's et al., (1994) sample means of *Baculites compressus* and *Baculites reesidei*, respectively. The two samples were collected from concretions approximately five meters below the unconformity at the top of the Verendrye Member. This interval is unusual because fossils resembling *Baculites compressus/cuneatus/reesidei* appear to be mixed together, most are only fragments. Their occurrence together suggest the possibility that they were reworked and deposited together during *Baculites reesidei* time as part of a lowstand systems tract that accumulated as seas withdrew from the region (as indicated by the overlying unconformity).

A specimen of a *Didymoceras* shell collected from a concretion collected above the unconformity on top of the *Baculites reesidei* Zone in the Badlands National Park, Cedar Creek locality (AMNH 3213). The *Didymoceras* showed a $^{87}Sr/^{86}Sr$ value of 0.707686±11, a value very closed to what McArthur et al, (1994) reported for the mean for the *Baculites reesidei* Zone. This specimen is particularly intriguing because it presents several possibilities. First, this specimen (the largest body chamber illustrated in Fig. 13, p. 59) could be a new, unidentified species of *Didymoceras* (based on its unusual stratigraphic position high in the section). Second, this specimen could represent *Didymoceras cheyennense*, an ammonite range zone fossil assigned to exist below the *Baculites compressus* Zone. (This would mean that either the range of this fossil is much longer than previous published, or that the zone had been incorrectly identified by Mr. Cobban.) However, A third possibility is perhaps the best explanation. The specimen, along with other fossils in concretions were reworked from older Campanian deposits and redeposited in the sediments on top of the unconformity above the *Baculites reesidei* Zone. Of the choices mentioned above, the final hypothesis is supported by a variety of other evidence.

The concretion that contained the *Didymoceras* was extracted directly from the host shale in the upper cutbank in the *Baculites reesidei* zone in the Cedar Creek locality. The shell did not display a bright, iridescent luster, rather it appeared slightly chalky, indicating that strontium isotope values were probably "reset" to the age of the younger sediment. When the concretion was dug out of the outcrop it was found already broken with a piece missing, an indication that it probably had been reworked. Also, the concretion did not occur in a "horizon" or continuous layer typical of concretions beds. Rather, it occurred in a zone of reddish-colored sediment along with other concretions displaying awkward orientations, some with their long axis oriented in a vertical direction. Other concretions in the interval consisted of ironstone concretions bearing inoceramids. These concretions occur within a five meter interval above the unconformity. Since the massive bentonitic unit of the Kara Bentonitic Member and fossils of *Baculites eliasi* were not observed, the concretions bearing the *Didymoceras* represent lag material associated with a transgressive systems tract in the base of the *Baculites baculus* Zone. The specimen was probably derived from submarine erosion in the vicinity of the southern Black Hills erosion, and was exhumed as sea level was falling at the end of Campanian time.

Three specimens from the Osage Oil Field area in Wyoming showed results consistent with McArthur's *et al*, (1994) data. A specimen resembling *Baculites eliasi* from a concretion collected from below the Kara Bentonitic Member was closer to the value of *Baculites jenseni*, an observation consistent with Gill & Cobban's (1966) description of this interval as the *Baculites jenseni/eliasi* Zone in the Redbird, Wyoming area. A specimen resembling *Baculites grandis* yielded a value intermediate between McArthur's et al., (1994) mean sample values for *Baculites baculus* and *Baculites grandis*. Compared with their data, our sample of *Baculites clinolobatus* yielded a value within the reporting range for the same species.

# CHAPTER 8

## STRATIGRAPHIC CORRELATION

Correlation between outcrops in the upper Pierre Shale and Fox Hills Formation is based on lithological characteristics and estimated thicknesses of fossil teilzones. (A teilzone, or range zone, designates the local duration of existence of a species.) Correlation reveals information about eustatic cycles in the Western Interior Seaway and the influence of tectonism on the geometry of sedimentary sequences and the occurrence of preserved fauna they contain. This section integrates information from field observations, geochronology, and correlation information from previous investigations by other authors.

Not all outcrops yield essential information. For instance, a single fossil from one outcrop may be the only representative specimen observed in the region (such as a single specimen of *Jelezkytes crassus* found in the Cedar Creek locality). Yet if the fossil occurs within zone a identifiable lithology that is laterally continuous (such as the occurrence of multiple bentonite beds, sand sheets, or ledge-forming limestone concretion beds, etc), then correlation of the range of that fossil may be assumed, particularly if other index fossils are identified in strata above or below. In this manner, for each of the stratigraphic sections teilzones of ammonites were inferred and member formation boundaries were selected. Regional correlation is the foundation for interpretation of the chronological order of the Campanian and Maastrichtian sequence of facies preserved as mudrocks and sandstones at the top of the Cretaceous section in the Western Interior study area. Conversely, interpretation of the origin of units is essential for defining the significance of sequence boundaries in the hierarchy of sequence stratigraphy. These sequence boundaries, where they can be interpreted, mark the logical placement of member and formation boundaries. Therefore, this correlation discussion includes aspects of sequence stratigraphic interpretation in order to explain or justify the placement of stratigraphic boundaries, particularly where they are associated with unconformities. A thorough review of the sequence stratigraphy of Badlands National Park is presented in Chapter 10.

## 8.1 CORRELATION WITHIN THE BADLANDS NATIONAL PARK AREA

Stratigraphic nomenclature used in the Missouri River Valley is applied to outcrops in Badlands National Park region for several reasons. First, fauna and lithologies, and stratigraphic boundaries in the Missouri Valley can be correlated to the Badlands National Park area (discussed in section 8.2). The correlation to the Wyoming localities is also possible (discussed in section 8.3). However, the use of South Dakota nomenclature is logical for several reasons: 1) the disparity in correlatable stratigraphic boundaries between South Dakota and Wyoming (i.e., Campanian/Maastrichtian boundary unconformity), 2) the significant differences in the thickness of units between South Dakota and Wyoming, 3) the lack of continuity of outcrops between Badlands National Park and the Wyoming localities, and 4) the separation of localities by political (state) boundaries. Younger sedimentary cover by White River Group and alluvium covers the Cretaceous beds throughout the region south and west of Badlands National Park and the region north of the Black Hills. In addition, structural uplift of the greater Black Hills region and along the Chadron Arch (in northwestern Nebraska) have resulted in either the non-deposition of Cretaceous sediments or their removal by erosion.

Fig. 70 is a map of localities used for correlation in the Badlands National Park Area. Figs. 71 through 78 are columnar sections showing interpretations of range zones of index fossils and the interpretation of stratigraphic boundaries of named stratigraphic units for each field locality in the Badlands National Park area. Fig. 79 illustrates correlation of strata represented by ammonite range zones from section to section through the park area.

### 8.1.1 The Verendrye Member

In the Missouri Valley region Searight (1937) originally included the Verendrye beds within his upper Sully Member. His lower Sulley Member included

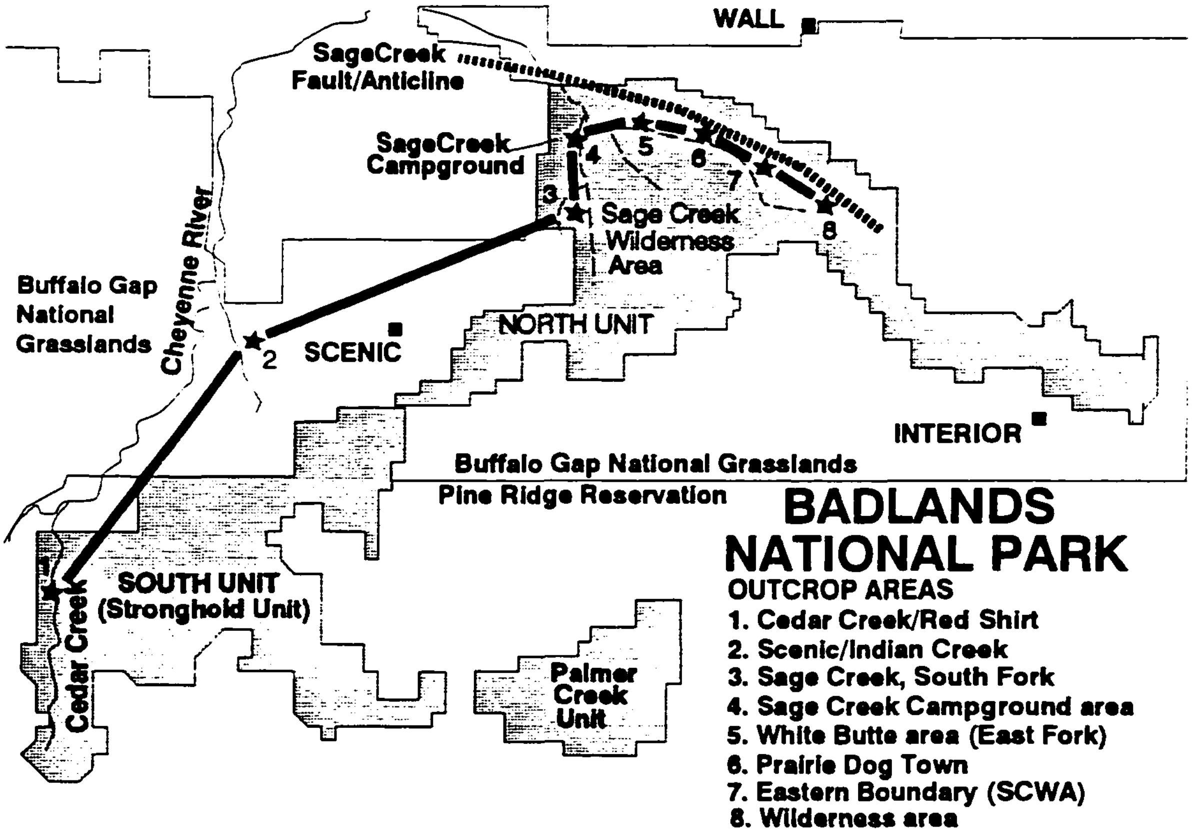
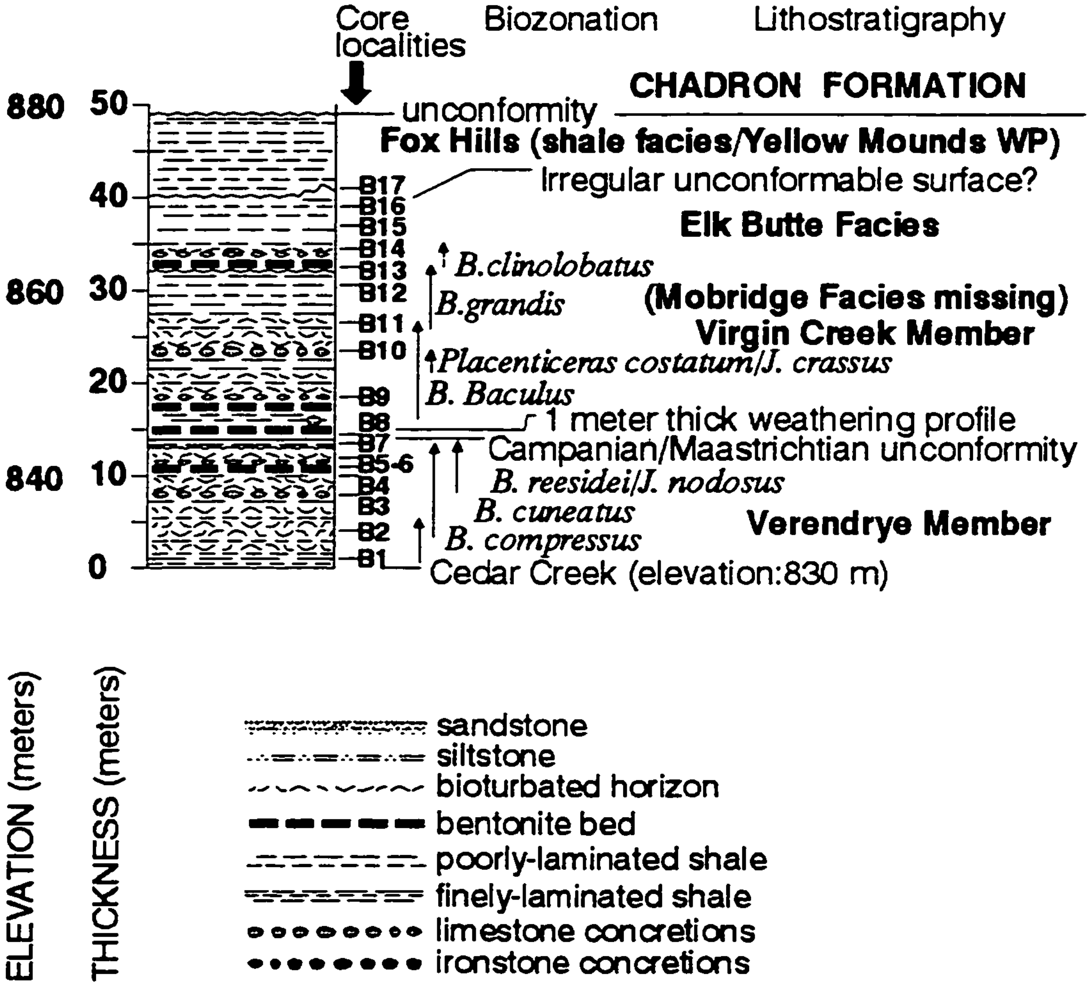
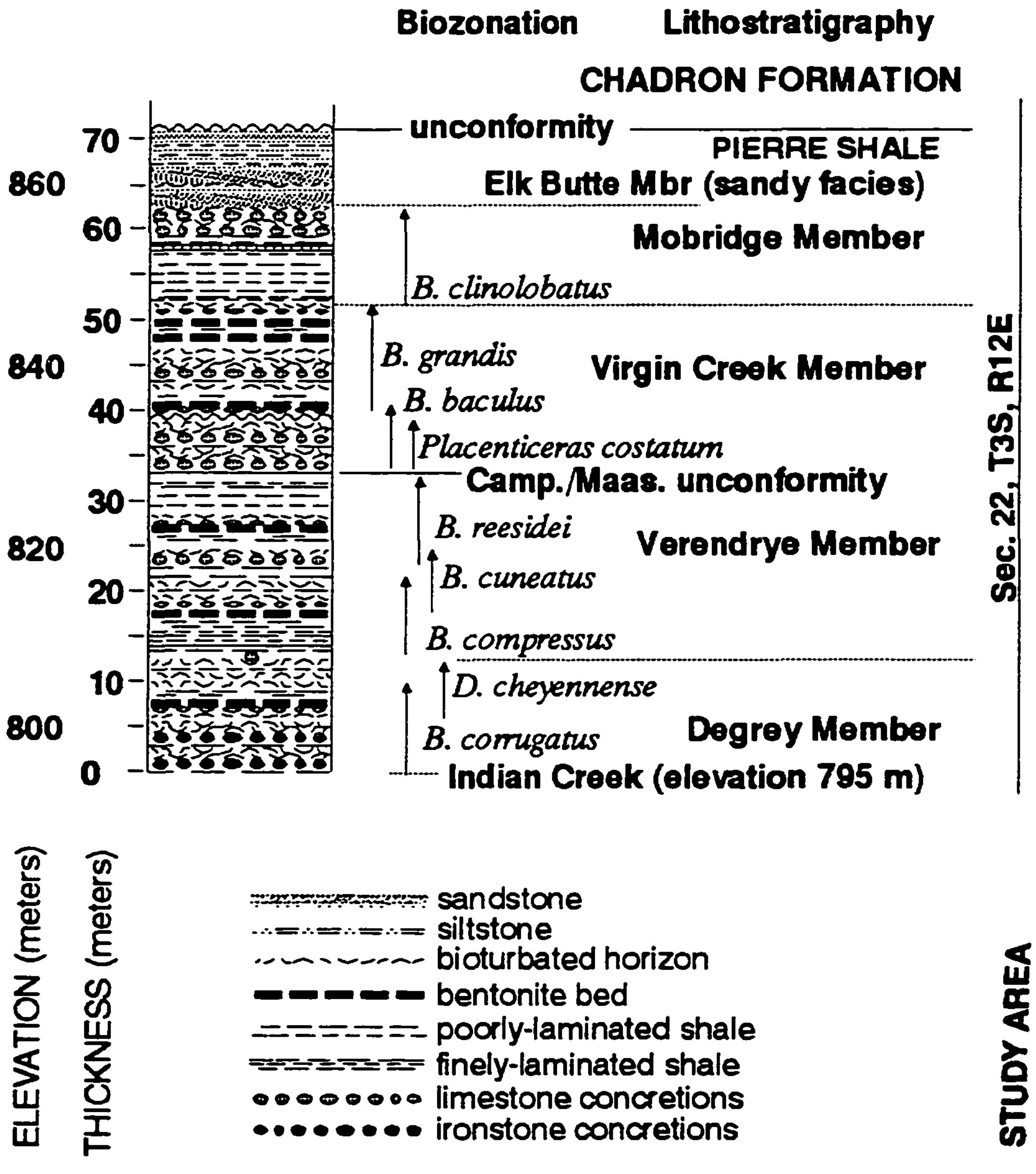


Fig. 70. Location of columnar sections in the Badlands National Park area. Note the location of the crest of the Sage Creek Anticline. The north side of this anticline is very poorly exposed, but appears to be very gently dipping to the northeast. The strata on the south side dips gently southwest at about 10-15° and is broken in places by small normal faults with displacements in the range of 2-50 meters. South of the East Fork of Sage Creek the strata is essentially flat-lying to very gently dipping to the south. The character of the faults in the subsurface is unknown.



BADLANDS NATIONAL PARK
South Unit - Cedar Creek Area
Columnar Section
SE, Sec.11, T 5 S, R 10 E

Fig. 71. Cedar Creek cutbank locality near Redshirt, South Dakota, Badlands National Park, South Unit.



BUFFALO GAP NATIONAL GRASSLANDS
Scenic, SD/Indian Creek Area
Columnar Section

Fig. 72. Indian Creek area, Buffalo Gap National Grasslands west of Scenic South Dakota.

BADLANDS NATIONAL PARK
Sage Creek Wilderness Area
South Fork of Sage Creek
Columnar Section

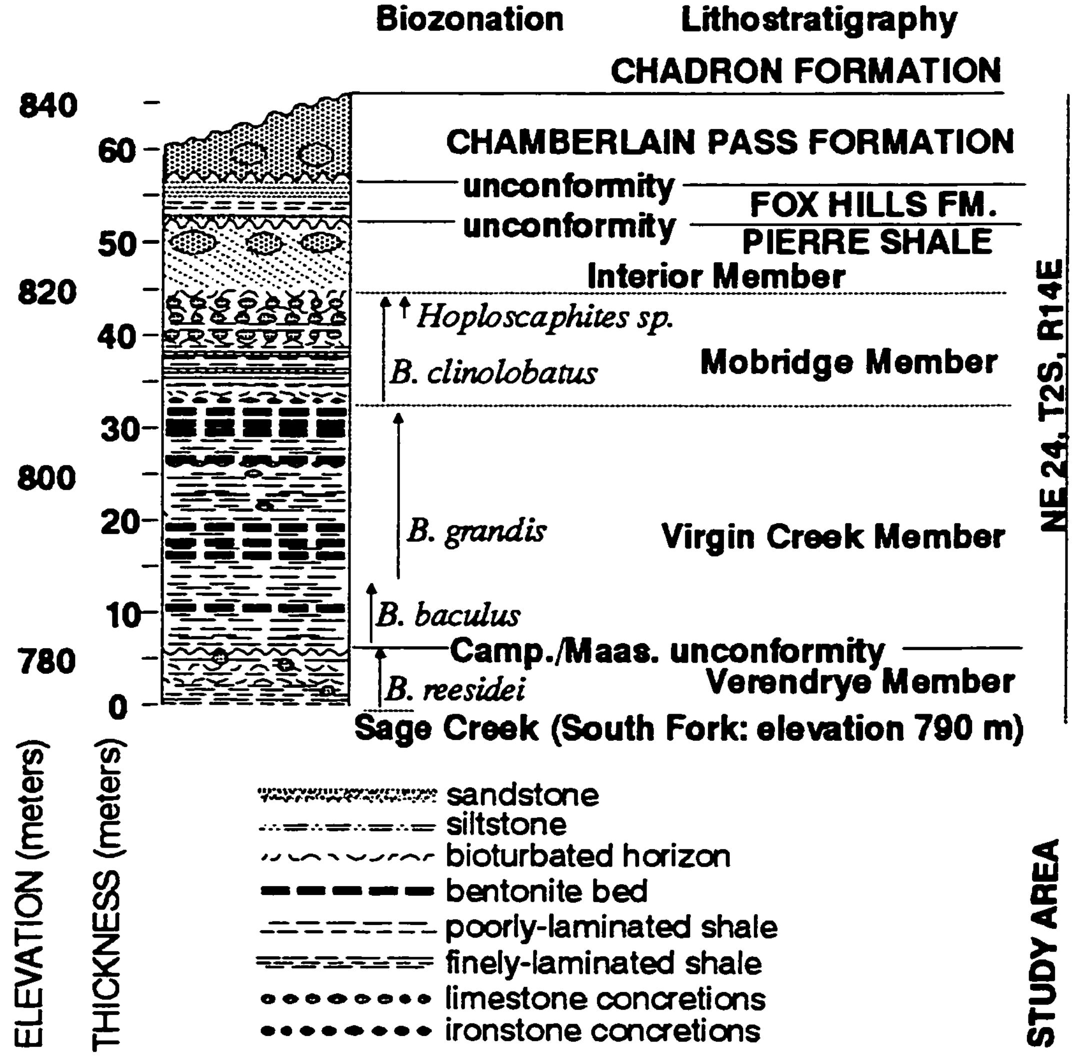


Fig. 73. South Fork of Sage Creek, Sage Creek Wilderness Area, Badlands National Park, North Unit.

# BADLANDS NATIONAL PARK
## Sage Creek Campground Area Columnar Section

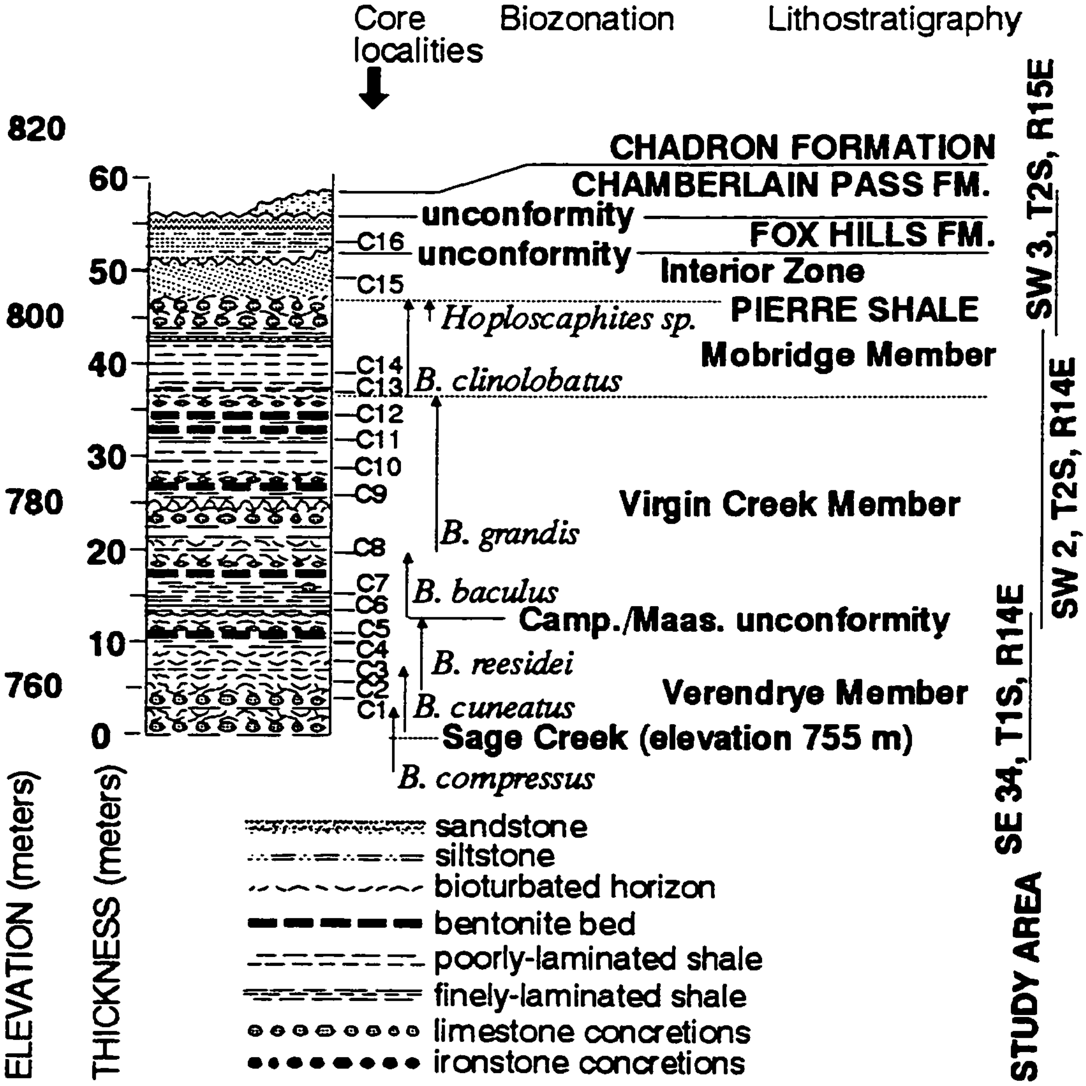


Fig. 74. Sage Creek Campground area, Badlands National Park, North Unit.

# BADLANDS NATIONAL PARK
## Sage Creek Wilderness Area
## White Butte
## Columnar Section

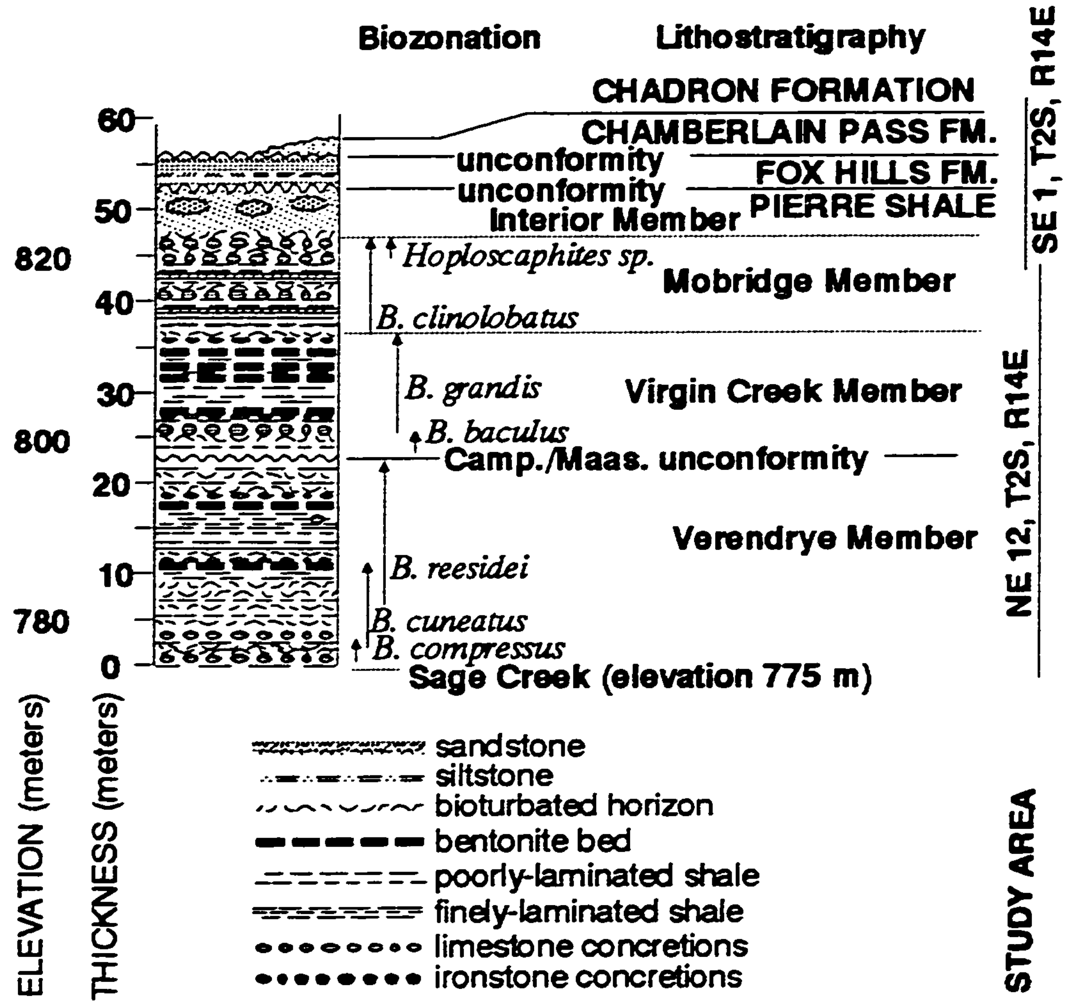


Fig. 75. White Butte along the East Fork of Sage Creek, Sage Creek Wilderness Area, Badlands National Park, North Unit.

# BADLANDS NATIONAL PARK
## Sage Creek Wilderness Area
## Roberts Prairie Dog Town Area
## Measured Section

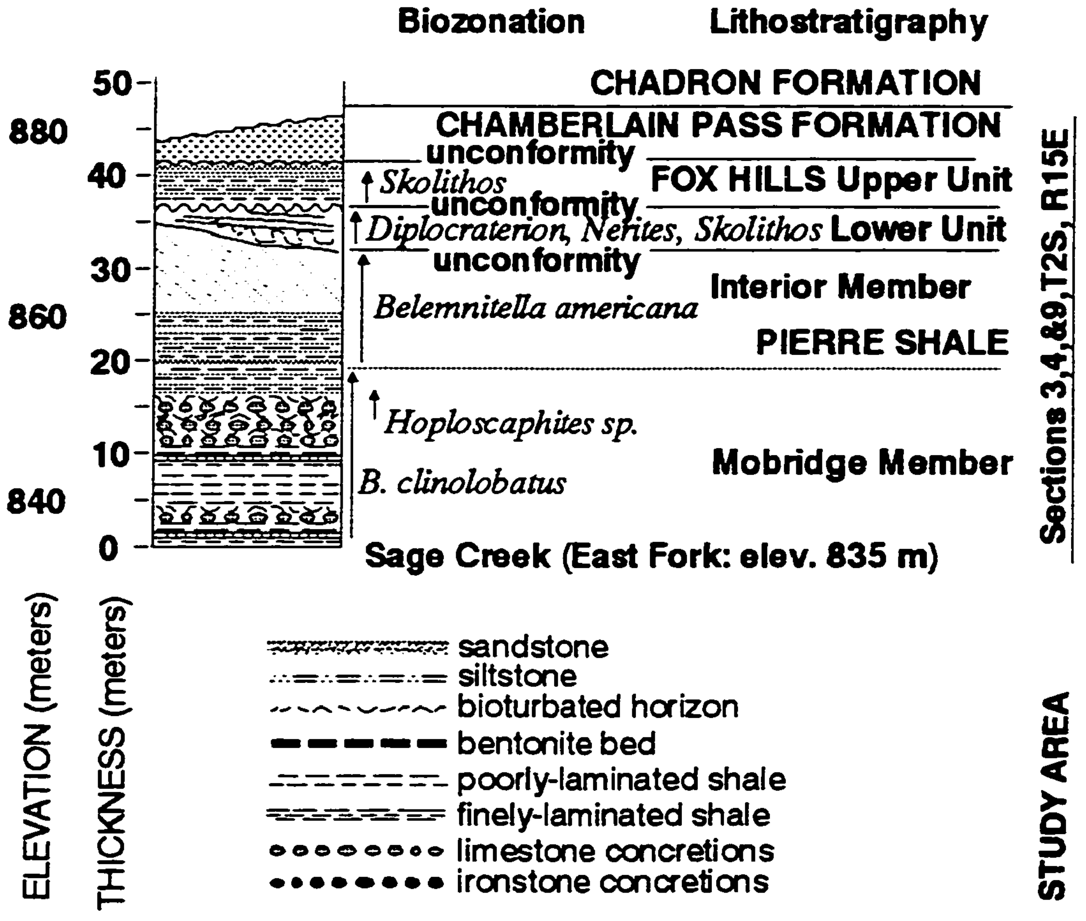
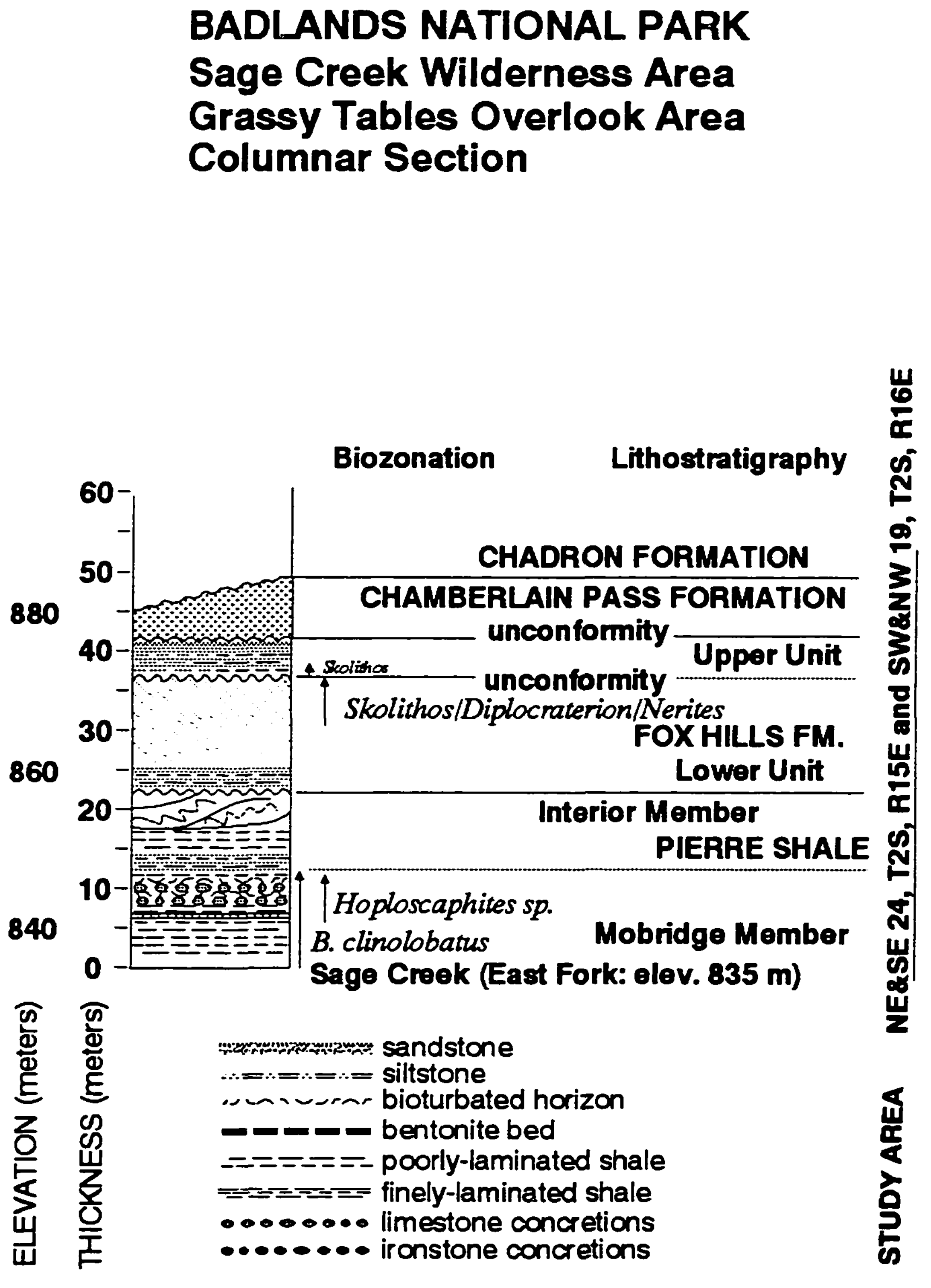


Fig. 76. Roberts Prairie Dog Town area, Sage Creek Wilderness Area, Badlands National Park, North Unit.



BADLANDS NATIONAL PARK
Sage Creek Wilderness Area
Grassy Tables Overlook Area
Columnar Section

Fig. 77. Grassy Tables Overlook Area, Sage Creek Wilderness Area, Badlands National Park, North Unit.

**BADLANDS NATIONAL PARK**
**Dillon Pass/Conata Basin Area**
**Badlands Loop Road**
**Measured Section**

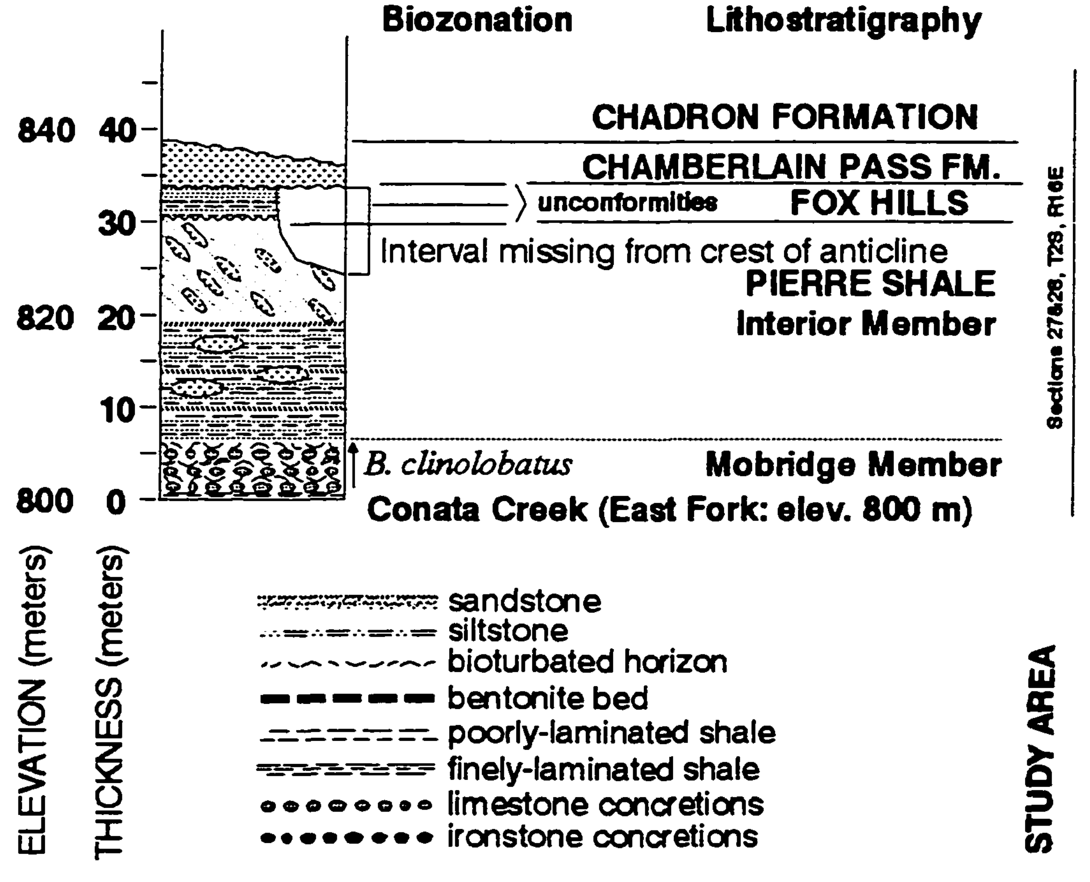


Fig. 78. Dillon Pass/Conata Basin area, Badlands National Park, North Unit.

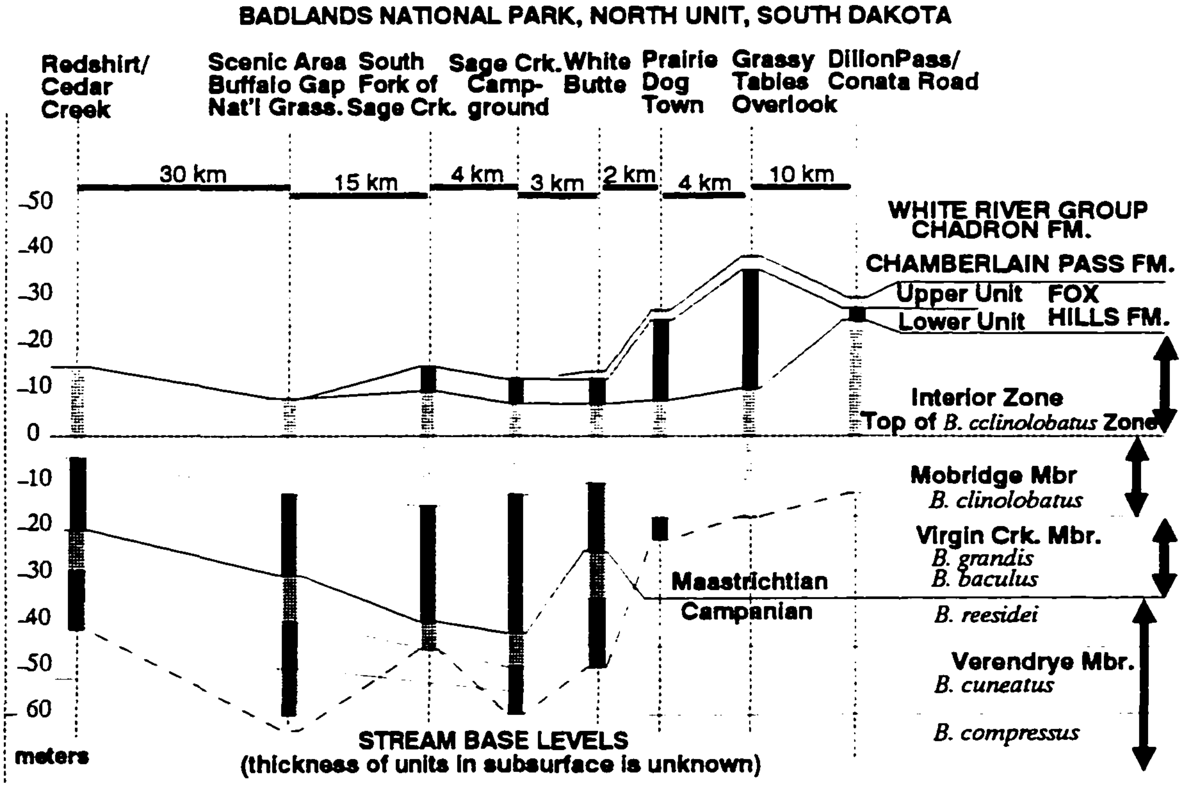


Fig. 79. Correlation of ammonite range zones and stratigraphic units through the Badlands National Park area.

his "magniferous Oacoma beds." Crandall (1958) revised Searight's stratigraphic names as follows. The Verendrye beds, which yielded fossils of *Baculites compressus*, was raised to Member status. Crandall also combined the underlying Oacoma beds were combined with an underlying unit, the Agency Siliceous beds, and assigned the name DeGrey Member. The type locality is presumably under the Verendrye Monument at Fort Pierre, Stanley County, South Dakota (Agnew & Tychsen, 1965). Crandall (1958) defined the top of the member as occurring beneath the basal bentonite beds of the overlying Virgin Creek Member. He noted that the base of the member yielded concretions impregnated with iron oxide locally which make a continuous bet that forms a resistant ledge in gullies cut into the contact. He also noted that springs frequently are observed at or near the boundary between the two members.

In the Badlands National Park area the zones of *Baculites compressus, Baculites cuneatus*, and *Baculites reesidei* (representing the Verendrye Member) crop out along creek level along the lower drainage basin of Sage Creek. The zones appear to overlap, but this could reflect concretions bearing these fossils were either reworked upward into younger sediments during periods of erosion and redeposition, or by younger concretions migrated downward into older zones by surface creep and slumping on modern outcrops. The *baculites reesidei* Zone, however, is generally barren of fossils in the north unit of the park and in the national grasslands area along

Indian Creek west of the town of Scenic, South Dakota (see Fig. 72) and in the North Unit of Badlands National Park (see Figs. 73-75). The upper portion of this interval yields abundant large limestone concretions that display well-developed septarian cracks filled with vein calcite and surface dissolution features, such as cone-in-cone crusts and encrustation with mineral salts such as jarosite and selenite. The lack of fossils and the abundance of large septarian nodules suggests that the upper *Baculites reesidei* Zone experienced early diagenetic alteration by fresh groundwater during a period of possible subaerial exposure perhaps during an interval represented by the occurrence of an unconformity on the top of the Verendrye Member. Meteoric water may have penetrated the muddy sediments of the *Baculites reesidei* Zone and dissolved calcareous shell material and re-precipitated it as concretion material (similar to a model for concretion formation in the Greenhorn Formation proposed by Ludvigson et al., 1994). Along the South Fork of Sage Creek, a one meter thick interval of shale impregnated with abundant limonite at the top of the Verendrye Member may represent a paleosol beneath the unconformable surface. In addition, the general lack of fossils in the upper Verendrye Member probably represents another pulse of high-standing seas with anoxic bottom conditions during *Baculites reesidei* time prior to a withdrawal of the seas during *Baculites jenseni* through *Baculites eliasi* time. The occurrence of bentonite beds in the lower *Baculites reesidei* Zone in the North Unit suggests that sedimentation occurred for a period below wave base.

In the Cedar Creek area of the South Unit of Badlands National Park, the *Baculites reesidei* Zone yields an abundance of *Protocardium* sp. preserved along with broken ammonite shells, and evidence of massive bioturbation networks (see Fig. 37, p. 121). These factors indicate that shallower water condition prevailed in the region around the South Unit of Badlands National Park. Bedding geometry along Cedar Creek indicates that the *Baculites reesidei* Zone was deposited in association with a northeastward prograding clinoform-style mudbank typical of a lowstand wedge-prograding complex of a lowstand systems tract (Vail, 1987). The top of this mudbank appears to be truncated by submarine erosion (representing the Campanian/Maastrichtian boundary unconformity). The shale interval above the unconformity displays a reddish color (indicative of oxidation conditions during possible subaerial exposure) and contains reworked concretions bearing fossils from older Campanian deposits (i.e., *Didymoceras cheyennense*).

The only locality where the Verendrye Member is completely exposed is in the Indian Creek area west of Scenic, South Dakota. The boundary between the DeGrey and the Virgin Creek Members appears gradational. The DeGrey is represented by dark gray silty shale bearing irregular-shaped, red-weathering ironstone concretions containing inoceramids and the ammonite *Didymoceras cheyennense*. The base of the Verendrye is perhaps best represented by the first occurrence of gray limestone concretions bearing fauna of the *Baculites clinolobatus* Zone. The Verendrye also encompasses the zone of *Baculites cuneatus* and *Baculites reesidei*. The top of the Verendrye Member is well-defined where an unconformity is well-exposed separating the medium-gray silty shale of the Verendyre from the lighter colored, gray to olive-drab or reddish sediments of the overlying lower Virgin Creek facies. Where the member is poorly exposed it is expressed as a general change in color, with the darker colored sediments represented by the underlying Verendrye Member. In most localities studied the overlying Virgin Creek is very poorly exposed due to grass cover on gentle rolling slopes. Using the section along Indian Creek, the Verendrye Member is approximately 22 meters thick, and is possibly thinner toward the south in the Cedar Creek area.

### 8.1.2 The Virgin Creek Member

Searight (1937) originally defined the type locality in the valley of Virgin Creek, about 1.5 miles south of Promise, Dewey County, South Dakota. He observed that the base of the unit contained an abundance of thin but conspicuous bentonite beds. The upper portion of his Virgin also yielded bentonite beds, but were more widely spaced. He reported *Baculites grandis* as an index fossil for this member. He also observed that the contact between the Virgin Creek and the overlying Mobridge Member was gradational.

The Virgin Creek Member in the Badlands National Park area is bounded at the base by the unconformity (discussed above). The lowermost strata contains reworked material. The reworked Campanian fossils in concretions in the Cedar Creek area of the South Unit are perhaps the most apparent confirmation of the lower boundary (see Fig. 71). In the North Unit concretions found in the Sage Creek Campground area along the unconformity preserve mud intraclast and shell hash (see Figs. 73-75). There is also an abundance of small, yellow-weathering phosphatic nodules, possibly preserved as a lag deposit along the boundary. Therefore, the lowermost meter to several meters represents a transgressive systems tract (Vail, 1987). Within several meters from the base of the member, the strata preserves many thin bentonite beds, some ranging up to 10 cm in thickness. These are perhaps best exposed along the South Fork of Sage Creek (see Fig. 44, p. 137). The shale within the interval where the bentonite beds occur is dark colored, lacks indication of benthic fauna, but yield specimens of baculites with well developed flank ribbing and an elliptical body chamber most resembling *Baculites baculus*. These sediments represent a highstand systems tract (Vail, 1987). Seas were probably deeper (in the range of about 100 meters) and well stratified with anoxia affecting the deeper water, hence the lack of benthic fauna. The bentonite beds were preserved due to lack of bioturbation or currents in the deeper water environment that were strong enough to rework the sediment.

The upper Virgin Creek Member also yields bentonite beds, inoceramids, and *Baculites grandis*. Large gray, limestone concretions are common, particularly in association with bentonite layers. The transition to the overlying Mobridge Member is represented by a subtle change in lithology (discussed below). The Virgin Creek Member varies in thickness in the Badlands National Park Area between about 15 meters in the Cedar Creek area in the South Unit to about 25 meters in the Sage Creek Campground area of the North Unit. Local variation between 15 to 25 meters between measured sections in the North Unit possibly suggests that contemporaneous movement may have occurred along faults associated with the Sage Creek Fault anticline/fault system during Maastrichtian time while sediments representing the Virgin Creek Member were being deposited.

### 8.1.3 The Mobridge Member

Searight (1937) assigned the name to a succession of highly calcareous shale and chalk that crops out along the Missouri River Valley. His type locality was defined along the western side of the Missouri River near Mobridge, South Dakota along a road cut in the vicinity of Sitting Bull's Grave. Although the original section locality is completely overgrown, the Mobridge Member is evident as a white to light blue-gray colored resistant steep slope-forming unit along the shoreline bluffs of Lake Oahe Reservoir. Searight (1937) and Mello (1969) both observed the the contacts between the underlying Virgin Creek Member and the overlying Elk Butte Member were gradational. Searight reported that *Baculites clinolobatus* is an index fossil for the Mobridge Member.

The Mobridge Member is perhaps best exposed in cutbanks along the South Fork of Sage Creek. In fresh cutbank exposures the calcareous shale of the Mobridge Member appears light bluish-gray, and contains thin to thick-bedded concretionary limestone beds (micrite) that yields shells of *Baculites clinolobatus*. One, possibly two, discontinuous bentonite layers occur in the upper Mobridge Member, locally replaced by cone-in-cone calcite. The upper part of the member yields large septarian limestone concretion typically 0.5-1.0 m in diameter and occurring in at least three laterally continuous beds. These concretions display evidence of bioturbation, particularly on their bottom surfaces (where they have not been affected by Yellow Mounds-style weathering). The top of the Mobridge Member yields a fauna which includes a compressed, smaller variant of *Baculites clinolobatus*, body chambers of scaphites including specimens resembling *Hoploscaphites birkelundi*, unidentified arthropod fragments, a chondricthyan tooth, *Scapanorhynchus texanus*, and abundant traces, dominantly *Thalassinoides*. These fossils occur in greatest abundance along the South Fork of Sage Creek in the transition interval with the overlying Interior Zone.

In the Badlands National Park region, the facies of the Mobridge Member represents a period of high-standing seas in the Western Interior Seaway. The Mobridge Member is 15-20 meters thick in the throughout the Sage Creek Wilderness area, and may be slightly thicker on the south side of the Sage Creek Anticline. Along the East Fork of Sage Creek in the Dillon Pass/Conata Basin area large limestone concretions of the upper *Baculites clinolobatus* Zone occur in abundance along creek beds, but the surrounding shale has been heavily altered by Yellow Mounds-style weathering. In this area the upper boundary of the Mobridge Member is best indicated by the occurrence of the uppermost, laterally continuous bed of limestone concretions. Throughout the region encompassing the North Unit of Badlands National Park most concretions of the upper Mobridge Member display effects of dissolution due to Yellow Mounds-style weathering. As a result many concretions display replacement by limonite, hematite, opalaceous silica, and microcrystalline quartz.

### 8.1.4 The Interior Zone

The sequence of mudrocks above the Mobridge Member (above the *Baculites clinolobatus* Zone) displays the greatest variability of units within the National Park region. Details about the history of stratigraphic nomeclature problems related to the Interior Zone are presented in Badlands National Park discussion in Chapter 6 (beginning on p. 111). It is with considerable difficulty that this unit can be assigned to either the Pierre Shale or Fox Hills Formation. Because of its stratigraphic location above the *Baculites clinolobatus* Zone it is equivalent to the Fox Hills Formation in northern Wyoming and is equivalent to the Elk Butte Member of the Pierre Shale in the Missouri Valley region. In the North Unit of the Badlands National Park, a well developed unconformable surface serves as a logical placement for a boundary between the top of the Pierre Shale and the base of the overlying Fox Hills Formation [see Figs. 46 (p. 142), 49 (p. 153), 50 (p. 154), and 55 (p. 163)]. To the interval between the top of the Mobridge Formation and the base of this unconformity the name **Interior Zone of the Pierre Shale** is recommended (after Raymond & King, 1976 who used the term "Interior Zone of local usage" for this interval). The *AGI Dictionary of Geologic Terms* states that a zone is "a belt or strip of earth materials, however disposed distinguished from surrounding parts by some particular property or content, e.g., fault zone..." Facies of the Interior Zone seem to be limited to the North Unit of Badlands National Park area, specifically to the vicinity on the south side of the Sage Creek anticline/fault system. Elsewhere it is recognizable as the shaley Elk Butte Member, or a sandy phase of the Elk Butte Member. North and west of Badlands National Park these sediments are transitional to the pro-delta and deltaic sediments of the Sheridan Delta of Gill & Cobban (1973) and are probably equivalent to lower Fox Hills Formation in northwestern South Dakota (Bishop, 1975).

Within the North Unit of Badlands National Park the Interior Zone varies from as little as five meters thick along the South Fork of Sage Creek (see Fig. 73), to as much as twenty five meters thick in the Dillon Pass/Conata Basin area (see Fig. 78). The Interior Zone represents marine shale-dominated facies deposited in as a southward prograding clinoform-style mudbank typical of a lowstand wedge-prograding complex of a lowstand systems tract (Vail, 1987). Sediments of the Interior Zone may have been in-part derived from the erosion of the crest of the Cedar Creek anticline. The Interior Zone yields marine fossils including belemnites, arthropod fragments, and very poorly preserved ammonites, none of which could be identified positively due to their heavily weathered condition. Whether these fossils are reworked from older deposits from the crest of the Sage Creek anticline is unclear. One vertebrae from the tail of a mosasaur near the top of the Interior Zone. It was collected by Rachel Benton (July, 1997) and added to the collections at the Museum of Geology in Rapid City.

The Interior Zone displays characteristics indicative of a southward prograding clinoform-style mudbank including buried slumps which preserve roll-type bedforms and glide plains showing movement toward the south, Bouma cycle graded-bedding, and southward dipping bedding surfaces that preserve flute and drag marks formed submarine turbidity flows. These features are apparent in most outcrops of the Interior Zone in the Sage Creek Wilderness area and in the Dillon Pass/Conata Basin area. The Interior Zone facies may represent delta foreset beds or an offshore mudbank associated with the regressive facies of a prograding strand-line, similar to modern nearshore depositional environments along the Gulf Coast of Mississippi (Friedman et al., 1992). A stacked succession of slumps approaching 20 meters thick in the Interior Zone and affects sediments in the overlying Fox Hills Formation in the Grassy Tables Overlook area. The occurrence of these slumps suggests that deposition was probably influenced by contemporaneous movement along the Sage Creek anticline/fault system. The occurrence of clinoform bedding structure in the Interior Zone may perhaps be best explained by the proximity of the crest (and trough on the south side) of the Sage Creek Anticline in relation to the southward prograding shoreline of the Sheridan Delta system. In any case, the cross-beds indicate that the sediment supply was from the north. The top of the Interior Zone is very difficult to correlate from one outcrop to the next because of the variation in facies, the affects of submarine slumping, and by poor exposure.

Weimer & Land (1975) recognized contemporaneous (growth) faulting, slumping and deformation in transitional sediments between the Pierre Shale and the Fox Hills Formation in Colorado near Denver and on the margins of the Rock Springs uplift in Wyoming. They demonstrated that sandstone facies of the Fox Hills grade toward the basin into fine-grained mudrocks of the Pierre Shale in the deeper water setting. Their interpretation is that strand-line and deltaic facies of the Pierre

Shale/Fox Hills transition were influenced by the proximity to active structural uplifts. In the Badlands National Park area the sandy facies of the Fox Hills Formation are not recognized east, south or west of the North Unit. In the South Unit of Badlands National Park the top of the Pierre Shale is fine-grained mudrock (with the overprint of the Yellow Mounds-style weathering) most similar to the Elk Butte Member. There is no indication of Fox Hills Sandstone in the Cedar Creek locality, however, throughout the region south and west of the South Unit of Badlands National Park on the Pine Ridge Indian Reservation there are abundant large sandstone concretions weathering from the Yellow Mounds Weathering Profile beneath the unconformity at the base of the White River Group. Whether Fox Hills Formation was not deposited, or was removed by erosion prior to the formation of the weathering profile is unclear.

### 8.1.5 The Fox Hills Formation

The Fox Hills Formation is widespread throughout the Western Interior region. It was first described by Meek & Hayden (1862) for exposures near the mouth of the Moreau River along the Missouri River Valley, in the foothills of the Bighorn Mountains in central Wyoming, and along tributaries of the Platte River in Colorado. Robison, *et al.*, (1959) examined the Fox Hills within the study area region, and recognized the occurrence of the uppermost Pierre Shale ammonite zones on the northern flank of the Black Hills. Waage (1964) and Waage (1968) established the type area for the Fox Hills in South Dakota in the Dewey/Corson County area west of Mobridge. As discussed in Chapter 6, Pettijohn (1965) first clearly recognized the Fox Hills Formation in Badlands National Park.

Fig. 59 (p. 174) shows perhaps the most useful exposure of the Fox Hill Sandstone in Badlands National Park for purposes of correlation. It is exposed in a ravine on the west side of the Badlands Loop Road in the Dillon Pass/Conata Basin area in NW, NE, SE, Sec. 20, T 2 S, R 16 E. Near the creek bed is approximately three meters of sandy shale of the top of the Interior Zone. Immediately above an unconformable boundary at the top of the Interior Zone is an intermittent bed of glauconitic sandstone (almost pure glauconite). This basal sand sheet is overlain by about three meters of fine-grained, thick-bedded to massive glauconitic sandstone. This is the "Lower Unit" of the Fox Hills Formation (shown on the columnar sections). According to Tucker (1995) glauconite tends to form in marine-shelf environments starved of sediment, and is likely to occur in association with facies between a transgressive system tract and a high stand system tract. The basal glauconitic sandstone unit therefore probably represents a transgressive systems tract of a Late Maastrichtian sedimentary cycle represented by the Fox Hills Formation. The Lower Unit is overlain by a four meter thick interval of thin- to thick-bedded, quartz-rich sandstone and mudstone, referred to here as the "Upper Unit" of the Fox Hills Formation. The boundary between the two units is an unconformity that is perhaps most apparent in the Roberts Prairie Dog Town locality and throughout Grassy Tables Overlook area (discussed below).

Perhaps the toughest correlation in Badlands National Park is the job of correlating the unconformity between the Lower and Upper Units of the Fox Hills throughout the park and beyond. The pinkish massive lower unit in the Dillon Pass/Conata Basin area displays contorted bedding, similar to the Bouma-style beds in the Roberts Prairie Dog Town Area (see Fig 52, p. 158). The sand beds in this unit contain *Diplocraterion, Nerites*, and *Skolithos* traces. These same traces also occur in equivalent beds in the Grassy Tables Overlook area (see Figs 76 and 77). In the Grassy Tables Overlook area, olive-gray silty and sandy beds which bear these traces overly the scoured upper surface of the slumped unit in the upper Interior Zone. This is illustrated in Fig. 55, (p. 163). These beds are probably equivalent to the base of the massive Lower Unit in the Dillon Pass/Conata Basin area (see Fig 78). This correlation is based on similarities in the stratigraphic position, the similar trace fossils in each location, the occurrence of glauconite in the sand, and the general color and texture of the sediments on close inspection.

In the Grassy Tables Overlook area the Lower Unit of the Fox Hills reaches its maximum thickness, approaching 12 meters. It consists of a stacked succession of gently southward inclined sand sheets and shale beds that become less sandy in a southward direction. The geometry of the beds suggest that the Lower Unit of the

Fox Hills represents a lobe of a clinoform-style mudbank that filled in accommodation space created by movement along the Sage Creek anticline/fault system. The Lower Unit of the Fox Hills is recognizable in the region between the Sage Creek Campground and the Dillon Pass/Conata Basin area. South of the East Fork of Sage Creek and west of the Sage Creek Campground it is not possible to differentiate the Lower and Upper Units of the Fox Hills. In the southernmost exposures in the Grassy Tables Overlook area the sand sheets seem to pinch out completely in a southward direction. In addition, the sandy beds in the Fox Hills also tend to pinch out as they are traced southward along the South Fork of Sage Creek. In the southernmost exposures along the South Fork of Sage Creek it is practically impossible to differentiate between the weathered silty shales of the Interior Zone and the overlying Fox Hills. In exposures along the White River 2-7 miles west of Interior the Fox Hills-equivalent strata consists of thick-bedded mudstone. The unconformity between the Pierre and the Fox Hills is indicated only by a subtle change in sediment color and texture, and slump fractures in the top of the Interior Zone are truncated by the overlying Fox Hills. Beyond the Sage Creek drainage area there is no apparent distinction between the Lower and Upper Units of the Fox Hills. This suggests that the unconformity between the two units is an expression of active tectonism of the Sage Creek anticline/fault system during Fox Hills time.

The more variegated sequence of sand and shale beds of the Upper Unit in the

Dillon Pass/Conata Basin area is most similar to the variegated strata in the Roberts Prairie Dog Town area exposed in the small "yellow mounds" that overlie a more resistant underlayer of the unconformable boundary between the two units of the Fox Hills Formation (see Fig. 51, p. 156). In the Grassy Tables Overlook area a resistant irregular surface on top of the Lower Unit is well exposed and is visible throughout the lower rolling hills in the Sage Creek Valley along the East Fork of Sage Creek. The Upper Unit is very distinct in the Grassy Tables Overlook area in that it is poorly consolidated and a darker color than the underlying Lower Unit (shown as the upper portion of the small hill in Fig. 56, p. 165). In the Grassy Tables Overlook area the top of this Upper Unit locally displays cross-bedding, possibly of tidal channel or stream channel origin. This sedimentary facies appears to be restricted to the area on the crest of the Sage Creek anticline. Unfortunately, the Upper Unit of the Fox Hills Formation is problematic in that it does not yield fossils. The presence of channelized cross-bedded units and intermittent sand and shale beds in the Upper Unit suggests that the unit possibly represents floodplain deposits, and therefore may represent Fox Hills or possibly Hell Creek Formation. Yellow Mounds-style weathering has affected both the Interior Zone and the overlying Fox Hills. The Upper Unit is unconformably overlain by a thin Interior Red Clay layer (Retallack, 1985)[which Terry & Evans, (1994) include as a remnant of a paleosol equivalent to the Chamberlain Pass Formation after Terry & Evans, (1994)]. The overlying

Chadron Formation is unaffected by Yellow Mounds-style weathering.

It is difficult, however, to correlate the two unconformities (between the Pierre Shale and the Lower Unit of the Fox Hills, and between the Lower Unit and the Upper Unit) beyond the boundary of the North Unit of Badlands National Park. Neither of the unconformities were recognized in the Indian Creek locality west of Scenic, or in the South Unit of Badlands National Park. The Yellow Mounds Weathering Profile probably masks these unconformities in these localities. In the region between the North Unit and the South Unit of Badlands National Park the Basal Chadron Formation unconformably lies on top of the Yellow Mounds Weathering Profile or on top of the Pierre Shale where paleo-valleys were carved by ancient streams through the weathering profile, and later filled in by sediments of the White River Group (Raymond & King, 1976).

## 8.2 CORRELATION FROM BADLANDS NP TO THE MISSOURI VALLEY

Correlation of ammonite zones and lithologic units are possible between the Badlands National Park area and Missouri Valley along the valleys of the Cheyenne River and the White River. Fig. 80 is a map of locations of measured sections along the Cheyenne River Valley. Fig. 81 through Fig. 86 are columnar sections representing each field locality showing biozonation and lithologic boundaries. Fig. 87 illustrates correlation of strata represented by ammonite range zones from section

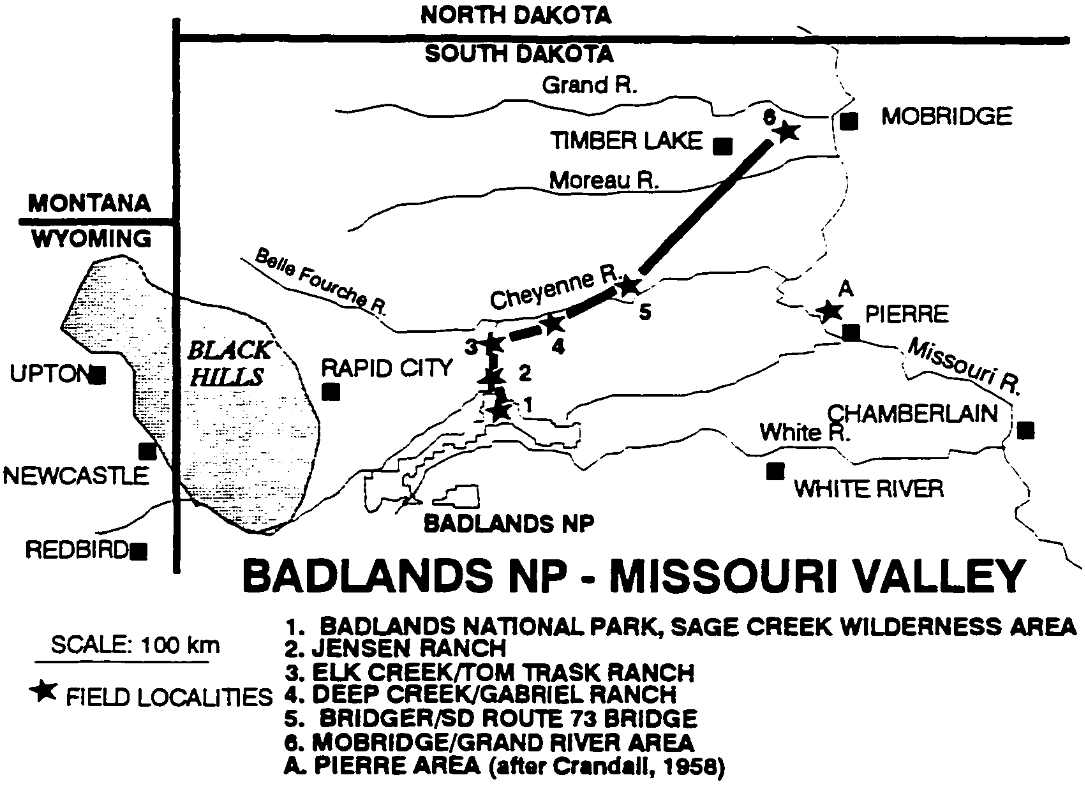


Fig. 80. Location of measured sections used for correlation between Badlands National Park and the Missouri River Valley, including sites in the Cheyenne River Valley, and the Mobridge and Pierre, South Dakota areas.

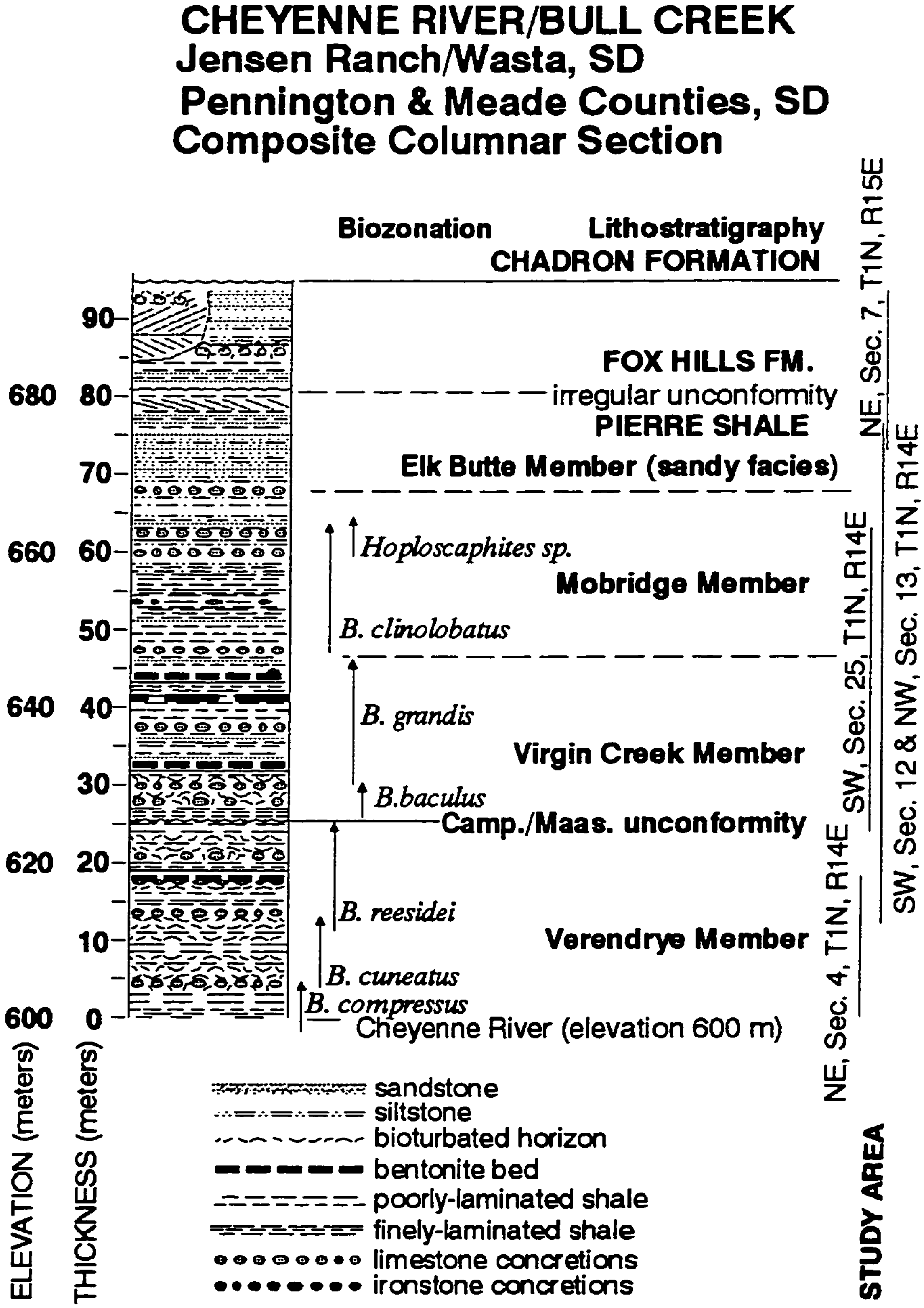


Fig. 81. Jensen Ranch, Bull Creek/Cheyenne River Valley area near Wasta, Meade & Pennington Counties, South Dakota.

# CHEYENNE RIVER/ELK CREEK
## Mr. Tom Trask Ranch
## Meade County, South Dakota
## Composite Columnar Section

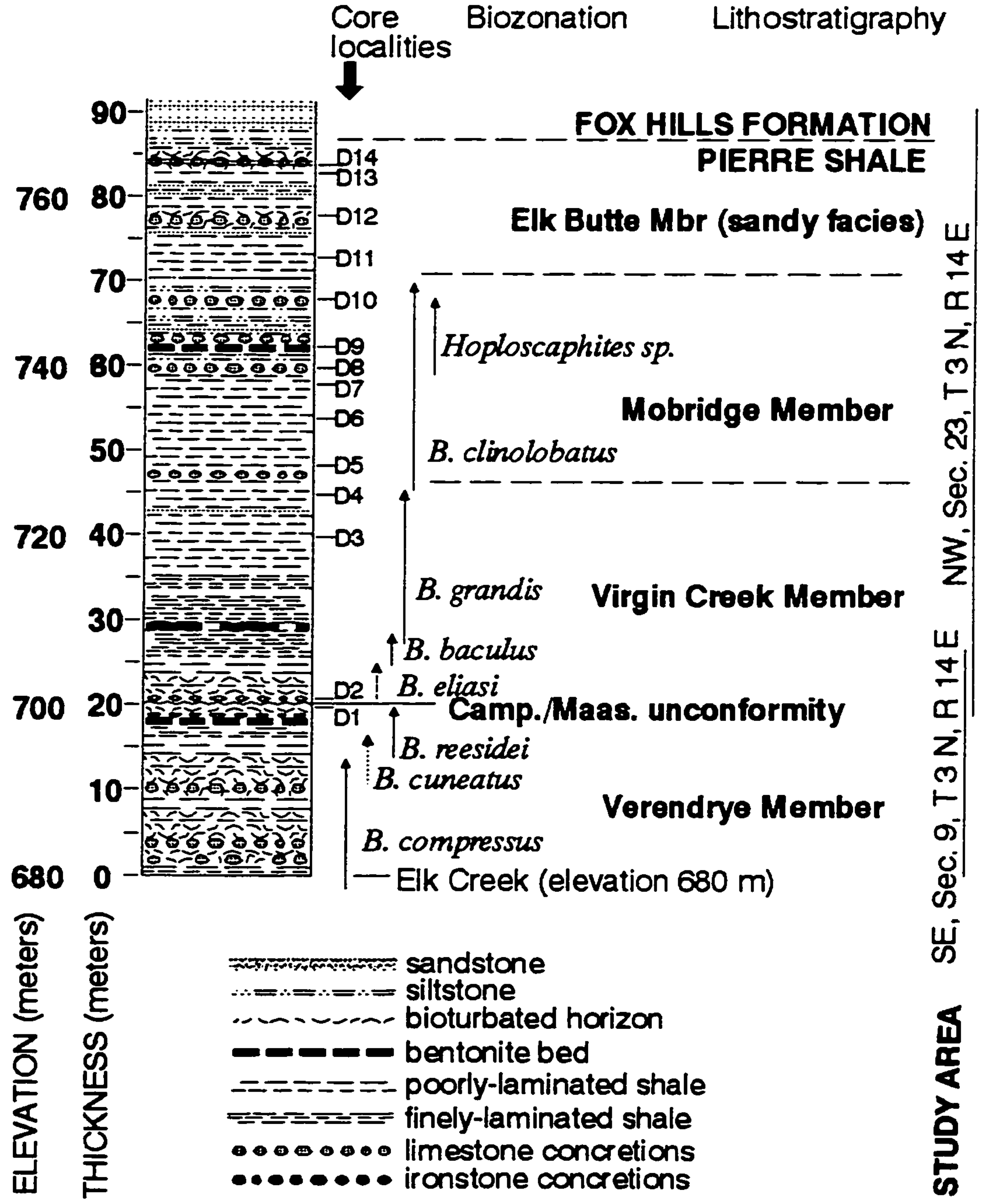


Fig. 82. Tom Trask Ranch, Cheyenne River Valley, Meade County, South Dakota.

**POWERLINES/RANCH ROAD**
**Cheyenne River Valley**
**Pennington County, South Dakota**
**Columnar Section**

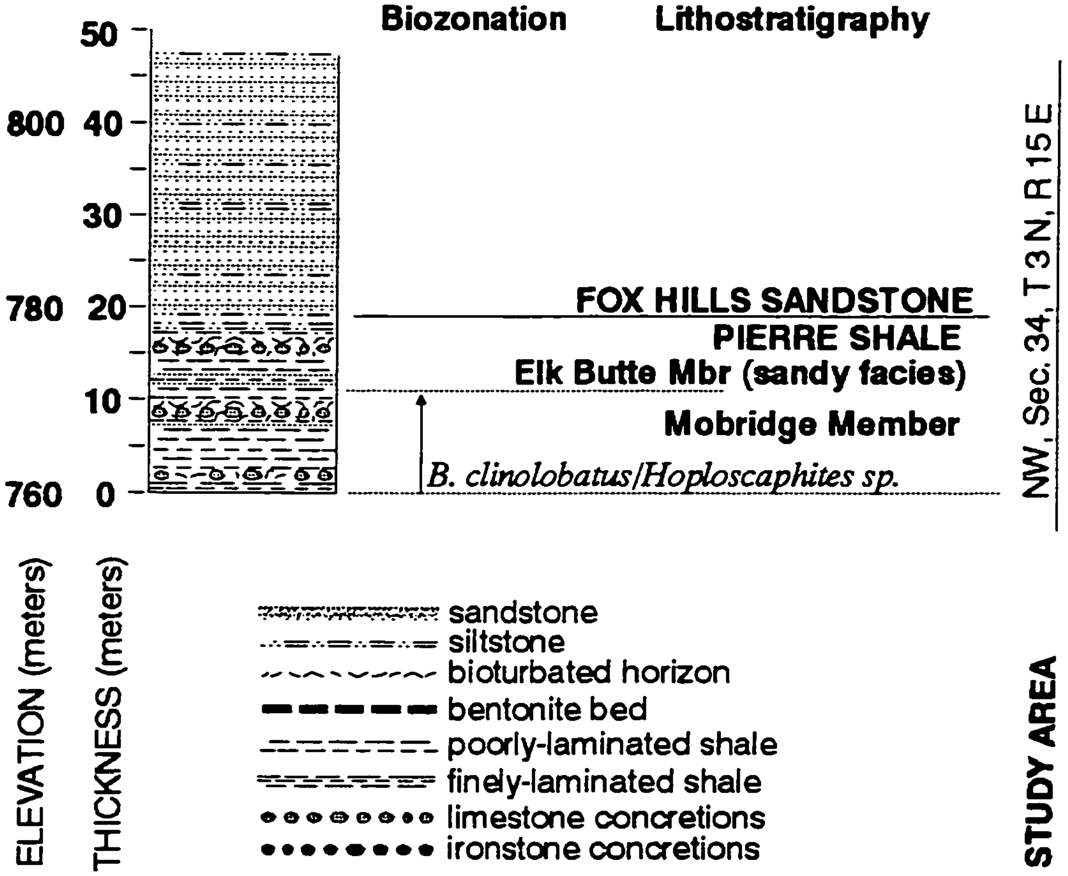


Fig. 83. Powerlines/Fox Hills Outcrop,east side of the Cheyenne River Valley, Pennington County, South Dakota.

**CHEYENNE RIVER/DEEP CREEK**
**Pedro, SD; Gabriel Ranch**
**Pennington County, South Dakota**
**Composite Columnar Section**

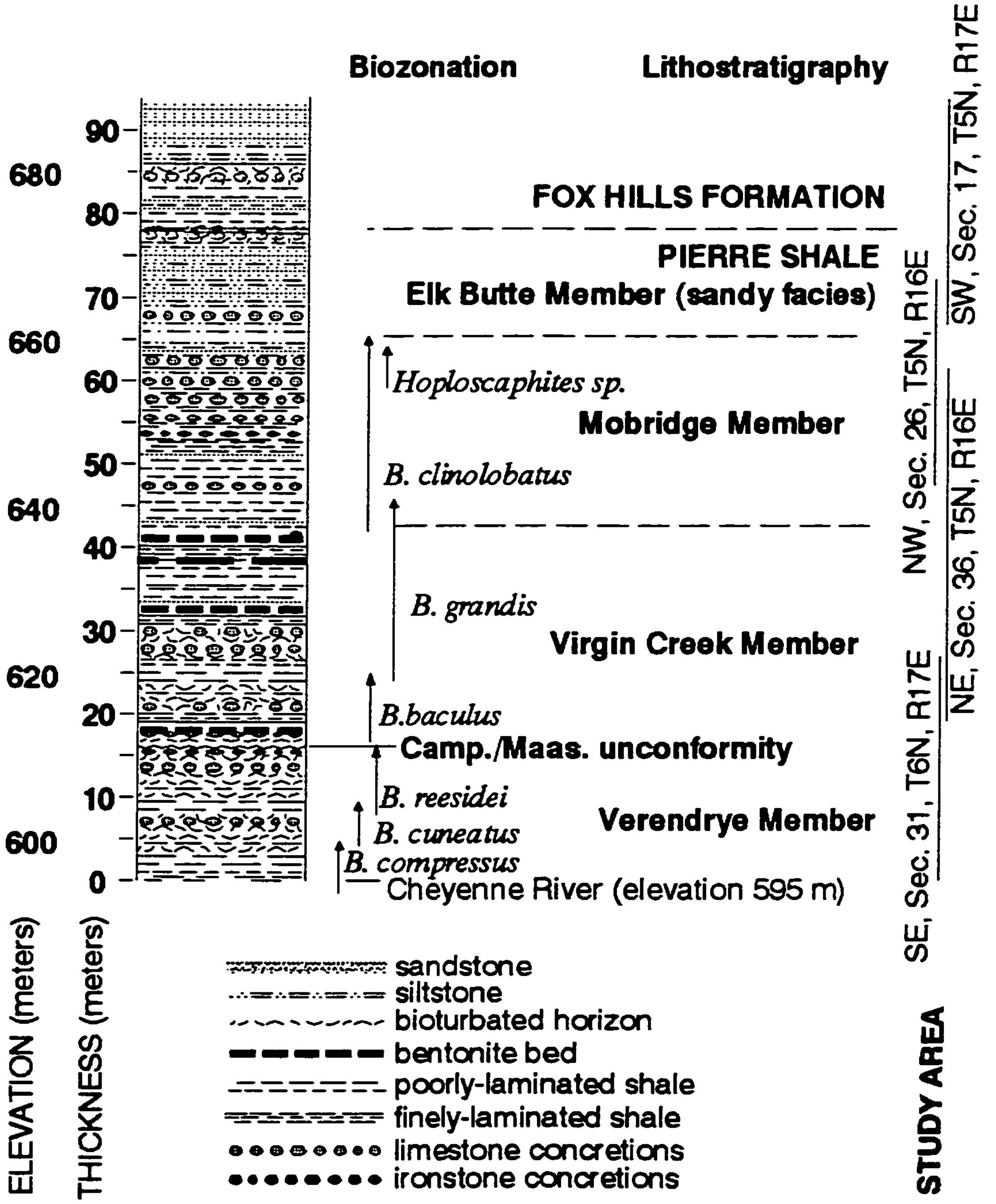


Fig. 84. Pedro/Gabriel Ranch area, Pennington County, South Dakota.

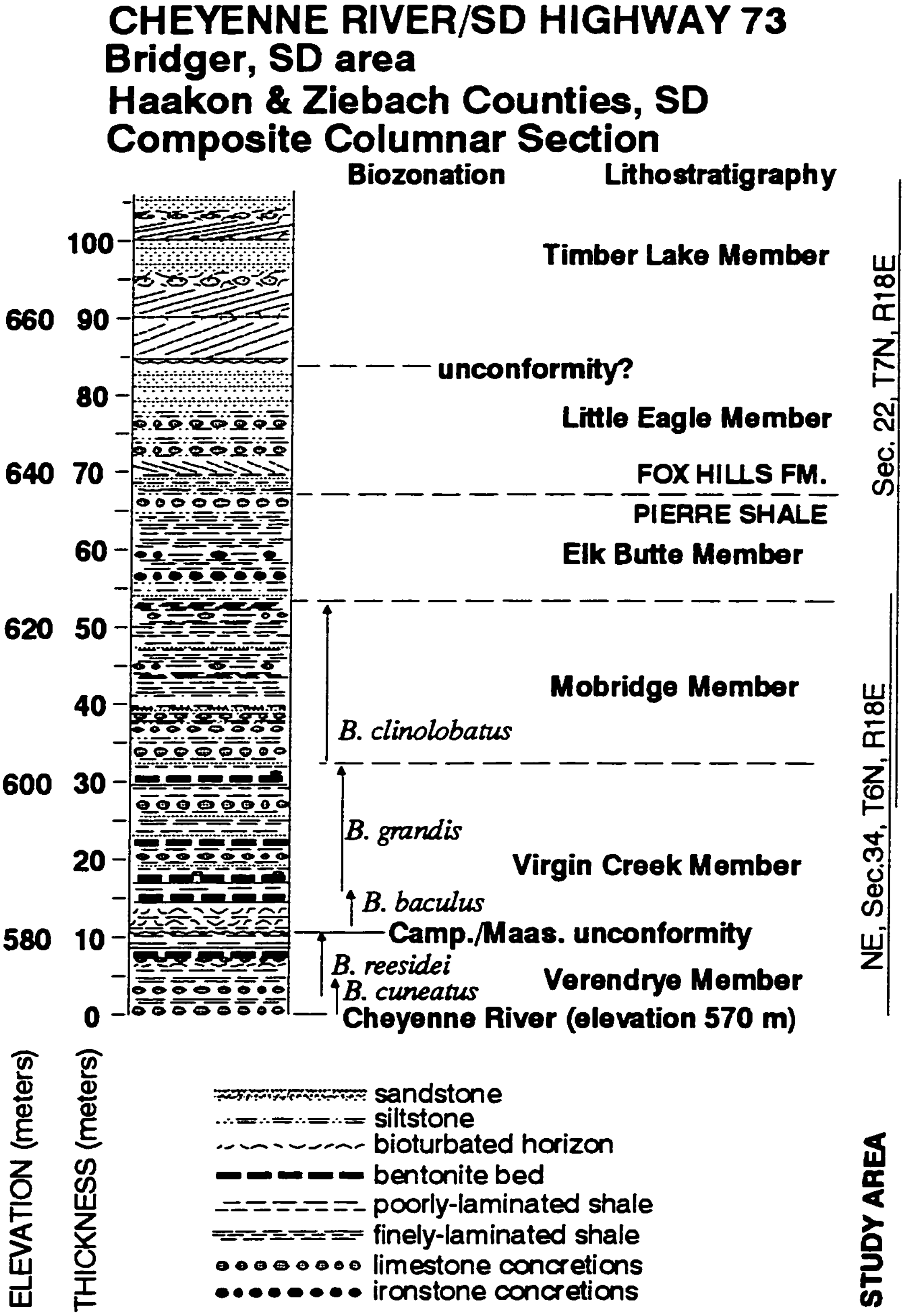


Fig. 85. Bridger area/Rt. 73 Bridge over the Cheyenne River, Haakon and Ziebach Counties, South Dakota.

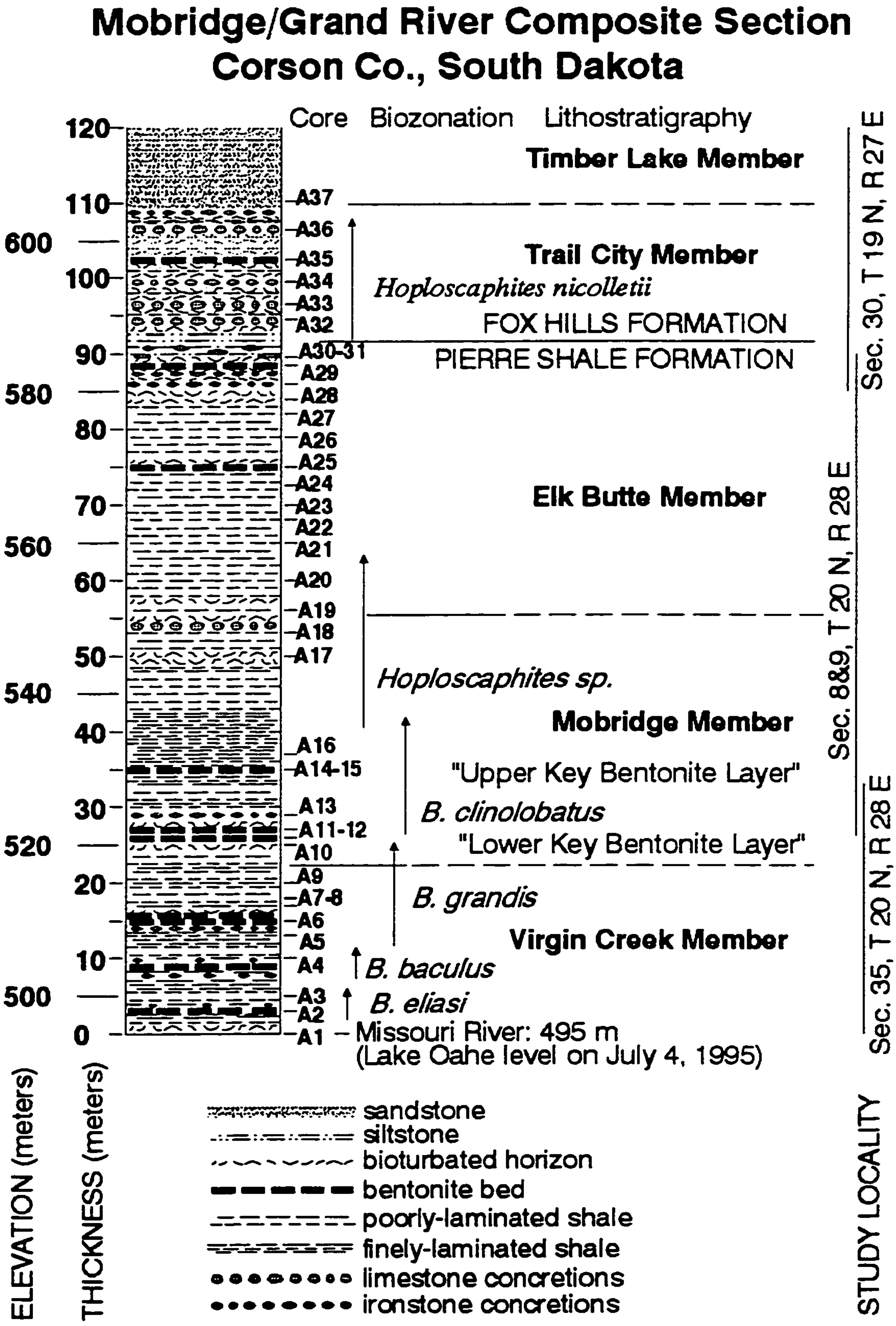


Fig. 86. Mobrdige/Grand River area, South Dakota.

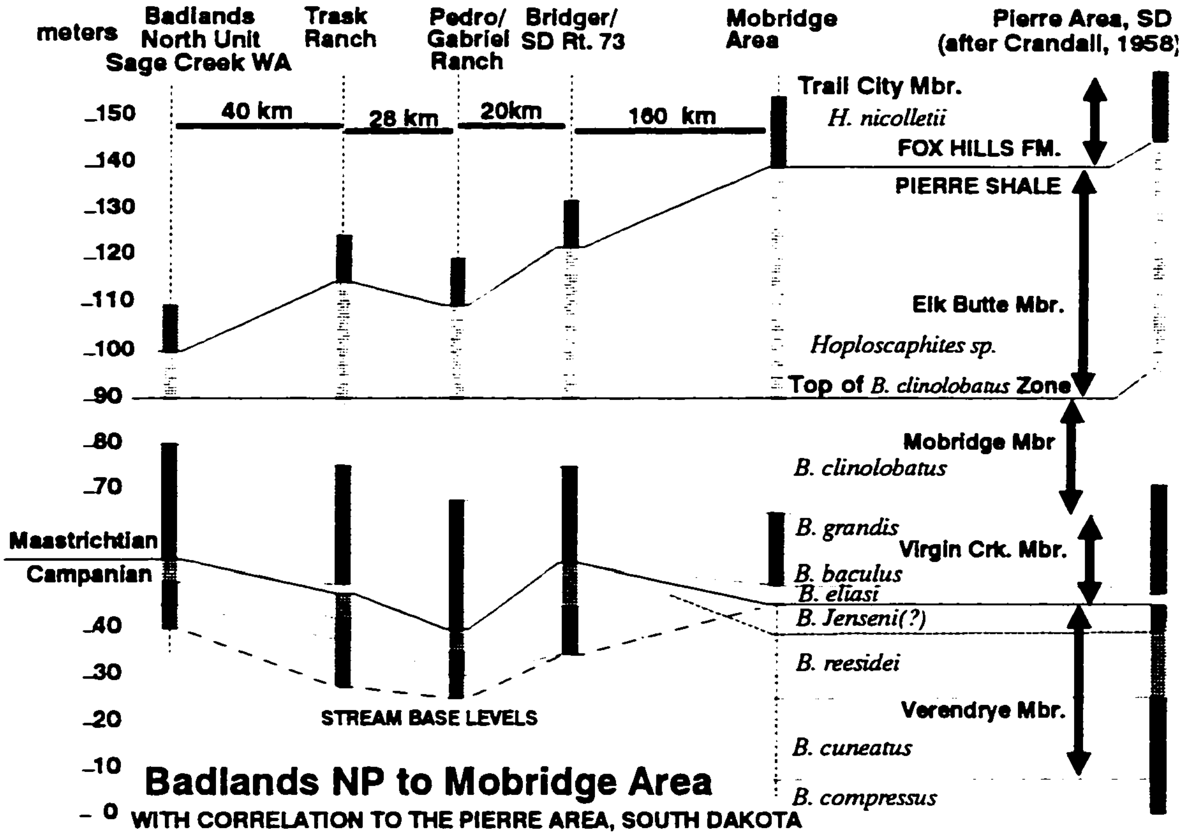


Fig. 87. Correlation diagram of ammonite range zones and stratigraphic units between Badlands National Park and the Missouri River Valley, including sites in the Cheyenne River Valley, and the Mobridge and Pierre, South Dakota areas.

to section from the Badlands area, along the Cheyenne River Valley to the Mobridge type area and includes stratigraphic interpretation of the Pierre Shale in the Pierre, South Dakota area.

Fig. 87 illustrates that the upper Pierre Shale grows progressively *thicker* eastward from the Badlands National Park area to nearly double the Badlands thickness in the Missouri River Valley. However, the thickness of the ammonite range zones remain essentially unchanged or grow progressively *thinner* toward the Missouri Valley. The disparity of these trends is related to the enhanced thickness of the Elk Butte Member in the Missouri Valley region (above the *Baculites clinolobatus* Zone and below the base of the Fox Hills Formation).

### 8.2.1 The Verendrye Member

The base of the Verendrye Member was not observed in any of the Cheyenne River Valley localities. However, we examined the conformable transition between the DeGrey Member to the Verendrye Member in both the Indian Creek area west of Scenic, South Dakota and below the Lake Oahe Dam near Pierre. In both locations the transition from DeGrey to Verendrye is represented by a general change in the character of the sediment and the concretions they contain. In the Scenic area the DeGrey consists of dark-gray to dark-reddish gray silty, bentonitic shale which yields reddish non-calcareous, manganese ironstone concretions containing fragments of inoceramids, baculites (most resembling *Baculites corrugatus*), and body chambers of *Didymoceras cheyennense*. Equivalent strata in the Lake Oahe Dam locality yielded similar manganese ironstone concretions, however, no fossil were observed in the Missouri River Valley.

The Verendrye Member in the Badlands National Park region consists of silty shale which contains an abundant and diverse molluscan fauna and a rich inchnofauna (best preserved in concretions), whereas along the Missouri River Valley the Verendrye is barren of fossils (except for scattered fragments of *Baculites compressus* reported by Crandall, 1958). In the Badlands area the *Baculites reesidei* Zone in the upper Verendrye Member contains an abundance of large septarian limestone concretions with veins filled with yellow calcite. In the Missouri River Valley Crandall (1958) reported that the Verendrye consists of claystone with non-calcareous concretions, some consisting of the body chambers of baculites. The Verendrye Member is estimated about 20 meters thick in the Badlands region, whereas Crandall reported a thickness in the range of 45-50 meters (140-160 feet) in the Pierre area, South Dakota. The differences in the lithology probably indicate that the sediments of the Verendrye Member in the Missouri Valley region was deposited in deeper water. The differences in the thickness of the Verendrye in both areas suggests that in the region around the eastern Black Hills/Badlands National Park region the sediments were either not deposited or were stripped away by submarine erosion and possibly subaerial erosion when sea level fell during or after *Baculites reesidei* time. The top of the Verendrye Member is indicated by a color change, from dark-gray (below) to light-gray (above), and by the presence of a possible weathering surface along the boundary, however this weathering surface was not apparant in outcrops north and east of the Tom Trask Ranch locality.

### 8.2.2 The Virgin Creek Member

The unconformity at the base of the Virgin Creek Member is most apparent in the Badlands region, however eastward in the Cheyenne River valley and in the Pierre area in the Missouri River Valley the unconformity becomes a poorly defined disconformity. Along the Cheyenne River Valley seeps were observed along the boundary in fresh cutbank exposures, particularly in the Wasta and Bridger areas of South Dakota. The Virgin Creek Member generally has an olive-drab to brownish-gray color and yields *Baculites grandis* in increasing abundance in western outcrop areas. The sequence of numerous thin bentonite beds of the lower Virgin Creek Member appears to be continuous throughout the region between Badlands National Park and the Missouri River Valley localities in the Mobridge area. Searight (1937) reported considerable variation in the thickness of the Virgin Creek Member along the Missouri River Valley with a maximum near Mobridge (224 feet or about 70 meters - measured prior to flooding by the reservoir) and a minimum along the Nebraska border in Charles Mix County, SD (55 feet or 17 meters). Crandall (1958) reported that the member ranged in thickness from 120 to 230 feet (about 35 to 60 meters) in the Pierre area of South Dakota. We used the ammonite zones *Baculites eliasi/baculus/grandis* to define the Virgin Creek Member along the Cheyenne River Valley (with *Baculites eliasi* being represented by a single "float" specimen found along Cheyenne River outcrops on the Tom Trask Ranch). In the Badlands National Park area the Virgin Creek Member varies considerably in thickness. It is 14 meters thick in the vicinity of White Butte along the East Fork of Sage Creek. The member increases in thickness on the north side of the Sage Creek Anticline. In the Tom Trask Ranch locality the Virgin Creek Member was measured as approximately 26 meters thick. The measured sections in Pedro and Bridger localities along the Cheyenne River Valley indicate a range of thickness between 20 to 25 meters. The variations of the thickness of the Virgin Creek Member in the Sage Creek Anticline area and in the Pierre area reported by Crandall (1958) are probably related to contemporaneous movement along basement structures, causing enhanced sedimentation in the low areas and reduced sedimentation on the crests of uplifts. Unfortunately, due to lack of accessible outcrops and the flooding by the Oahe Dam reservoir we were unable to resolve a boundary for the base of the Virgin Creek Member in the Mobridge area.

The lower Virgin Creek Member contains an abundance of closely-spaced bentonite layers in both the Badlands National Park area and along the Missouri River Valley. The upper Virgin Creek Member also displays bentonite layers, but not in the abundance of the lower portion of the member in both areas. In general, bentonite beds are more abundant (as least more visible in outcrops) in the Missouri River region. However, fossil are more abundant in the Badlands area. The differences in the fossils, abundance of bentonite layers, and the thickness of the units suggest that water depths were slightly greater in the Missouri Valley region during deposition of the sediments of the Virgin Creek Member. Virgin Creek deposition probably was continuous through *Baculites eliasi* and *Baculites baculus* time in the Missouri Valley region, whereas deposition of the Lower Virgin Creek started in *Baculites baculus* time in the Badlands region, or as the Black Hills rose.

### 8.2.3 The Mobridge Member

Because the Mobridge Member is so difficult to define in lithologic terms, a determination of it thickness via correlation is problematic. Crandall (1958) reported thickness determinations ranging from as little as 20 feet (7 meters) to as much as 190 feet (60 meters) in the Pierre area. The primary criteria we used for defining the Mobridge Member was the occurrence of the ammonite range fossil *Baculites clinolobatus*. In locations where *Baculites clinolobatus* were scarce we used outcrop appearance and the test whether of the shale would fizz when weak acid was applied.

This later method proved inconsistent. In some cases the shale would not fizz even when large limestone concretions bearing *Baculites clinolobatus* were present nearby. Perhaps the most significant lithological character in every location is the occurrence of several laterally continuous beds of large, yellow-weathering limestone concretions which are typically barren of shell material, but display surface impressions of abundant traces created by a diverse benthic fauna.

The Mobridge Member is very thin or unrecognizable in the area around the South Unit of Badlands National Park except for one bed of large, unfossiliferous concretions at the base of the Yellow Mounds Weathering Profile. The Mobridge Member has a fairly uniform 10 meter thickness in the region around the North Unit of Badlands National Park. The Mobridge increases in thickness to 25 meters in the Tom Trask Ranch area (where the strata appears to be dipping gently northward into a structural trough (a basinal outlier along the southern margin of the Williston Basin). East of the Pedro locality fossils in the Mobridge Member become increasingly scarce, the sediment becomes finer-grained which suggests that water depths were somewhat greater in the Mobridge region during *Baculites clinolobatus* time. The member is more recognizable from a distance due to the whitish weathering character of the calcareous shale. The Mobridge Member stands out along the Missouri Valley partly because the overlying Elk Butte is much darker in color, and in the eastern part of the study area the Yellow Mounds Weathering Profile (if present) affects sediments higher in the section.

### 8.2.4 The Elk Butte Member

As mentioned above, the sediments equivalent to the Elk Butte Member vary considerably across the study area, reflecting the general eastward progradation of facies associated with the Sheridan Delta (Gill & Cobban, 1973). The sandy facies of the Interior Zone in the North Unit of Badlands National Park represent pro-delta facies affected by tectonism associated with the Sage Creek anticline/fault system. North of the park along the highest hillsides of the eastern side of the Cheyenne River as little as 10 meters of sandy shale overlies the *Baculites clinolobatus* Zone and underlies the lowest massive sand sheets of the Fox Hills Formation. Unfortunately, north of the national park, the unconformable boundary between the Pierre Shale and the Fox Hills Formation was not resolved due to lack of accessible exposures.

The western-most outcrop where facies most resembling the Elk Butte Member in the type area near Mobridge occurs is in the Bridger, South Dakota area. Here the Elk Butte Member is about 10 meters thick. The Elk Butte Member increases in thickness eastward to its maximum extent in the Mobridge area (about 35 meters). Strata of the Elk Butte Member and the Fox Hills are not preserved or are very poorly exposed for most of the length of the Missouri River Valley south of Mobridge. Where Elk Butte sediments are found, they usually occur in deeply-weathered hilltop areas. Along the central and eastern White River Valley near the town of White River, strata equivalent to the Fox Hills forms a recessed bench along the hilltops. In southern South Dakota along the Missouri River, Searight (1937) measured 60 feet (about 18 meters) of Elk Butte Member below 80 feet (24 meters) of shaley Fox Hills Formation. The Elk Butte Member probably thickens to the east because uplift was occurring in the west in the Black Hills region.

### 8.2.5 The Fox Hills Formation

A synclinal trough on the west side of Bridger, South Dakota (east of the Pedro locality) brings the Fox Hills Formation close to the level of the Cheyenne River. This trough possibly represents an catchment zone in which the sandy facies of the lower Fox Hills Formation were trapped and inhibited from prograding further eastward. A rise in sea level occurred when the prograding facies of the Sheridan Delta had reached the Pedro area and stopped the eastward advancement of the shoreline, shutting off the coarser sand supply to the region east of the Black Hills. This rise in sea level corresponds to the unconformity defining the boundary between the Pierre Shale and Fox Hills Formation exposed in the Badlands National Park and in the Mobridge section. The glauconitic sandstone at the base of the Fox Hills Formation in Badlands National Park is equivalent to the fine-grained silty shale facies of the lower Trail City Member in the Mobridge Region. This lower glauconitic sandstone facies in the Badlands region represents the transgressive systems tract of the Fox Hills Formation. In the Mobridge region the transgressive systems tract is identified by a change in color (from dark gray to buff), a slight increase in the silt content, and erosional truncation of ironstone concretion-bearing gray shale at the top of the Elk Butte Member.

The shale bearing fossiliferous concretions of the Trail City Member (representing by the *Hoploscaphites nicolletii* Zone) is apparently limited to the central region of Corson and Dewey Counties, South Dakota, with no equivalent marine strata in the regions to the west. The lower and middle silty facies and upper sandy facies of the Trail City Member and the overlying massive sandstone facies of the Timber Lake Member represents regression of offshore, nearshore, and littoral facies, with the coal-bearing Iron Lightning Member of the upper Fox Hills representing terrestrial facies. Concretions bearing a rich molluscan fauna of the Trail City Member is the last indication of normal marine conditions in the Western Interior Seaway. The lack of equivalent strata in the Badlands National Park region suggests that regression had already occurred in that region while marine sedimentation was still occurring in the Missouri River Valley region. It is possible that the buff-to-red-colored sediments of the Trail City and Timber Lake Members in the Mobridge region were in part derived from the reworking of older sediments from the Black Hills region. Provenance studies of the sandstone may help to resolve this question.

## 8.3 CORRELATION FROM BADLANDS NP TO WYOMING LOCALITIES

Correlation between the Badlands National Park area and the western flank of the Black Hills reveals an imprint of the cycles in sea-level change and the probable influence of contemporaneous tectonism on sedimentation throughout the region. Fig. 88 is a map of location of measured sections in the eastern Wyoming including Gill & Cobban's (1966) Redbird type reference section for the Pierre Shale on the Old Woman Anticline in Niobrara County. Fig. 89 is a columnar section showing our interpretation of biozonation and lithologic boundaries in the Mush Creek and Osage Oil Fields in Weston County. Fig. 90 show correlation of strata represented by ammonite range zones from Gill & Cobban's Redbird, Wyoming section, the Mush Creek and Osage Oil Field localities, and the South Dakota section represented by the Sage Creek Campground area in Badlands National Park.

### 8.3.1 The Lower Unnamed Shale Member

At Redbird, Gill & Cobban (1966) included the strata below the Kara Bentonitic Member in the Lower Unnamed Shale Member. They mapped the *Didymoceras cheyennense, Baculites compressus*, and *Baculites cuneatus* Zones as thin or missing in the Redbird area. However, they recognized as much as 135 feet (42

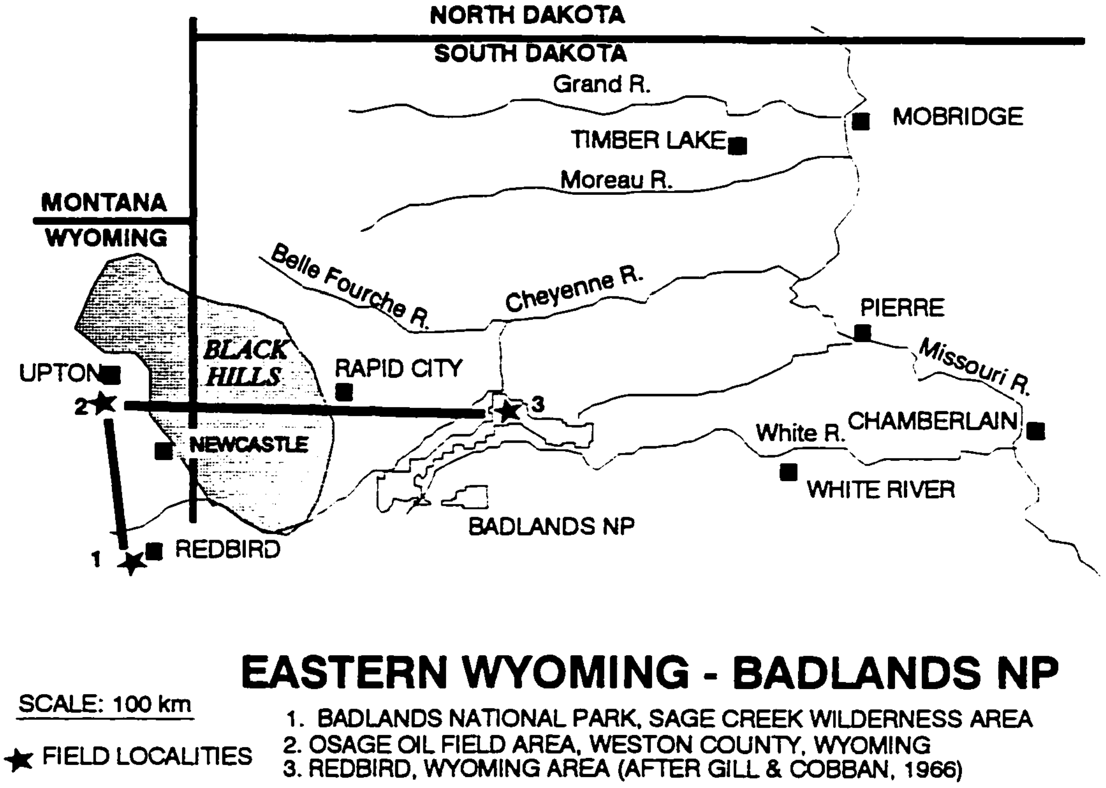


Fig. 88. Location of measured sections used for correlation between Badlands National Park and eastern Wyoming, including the sections for the Osage and Mush Creek Oil Fields in Weston County, and the Redbird, Wyoming type section.

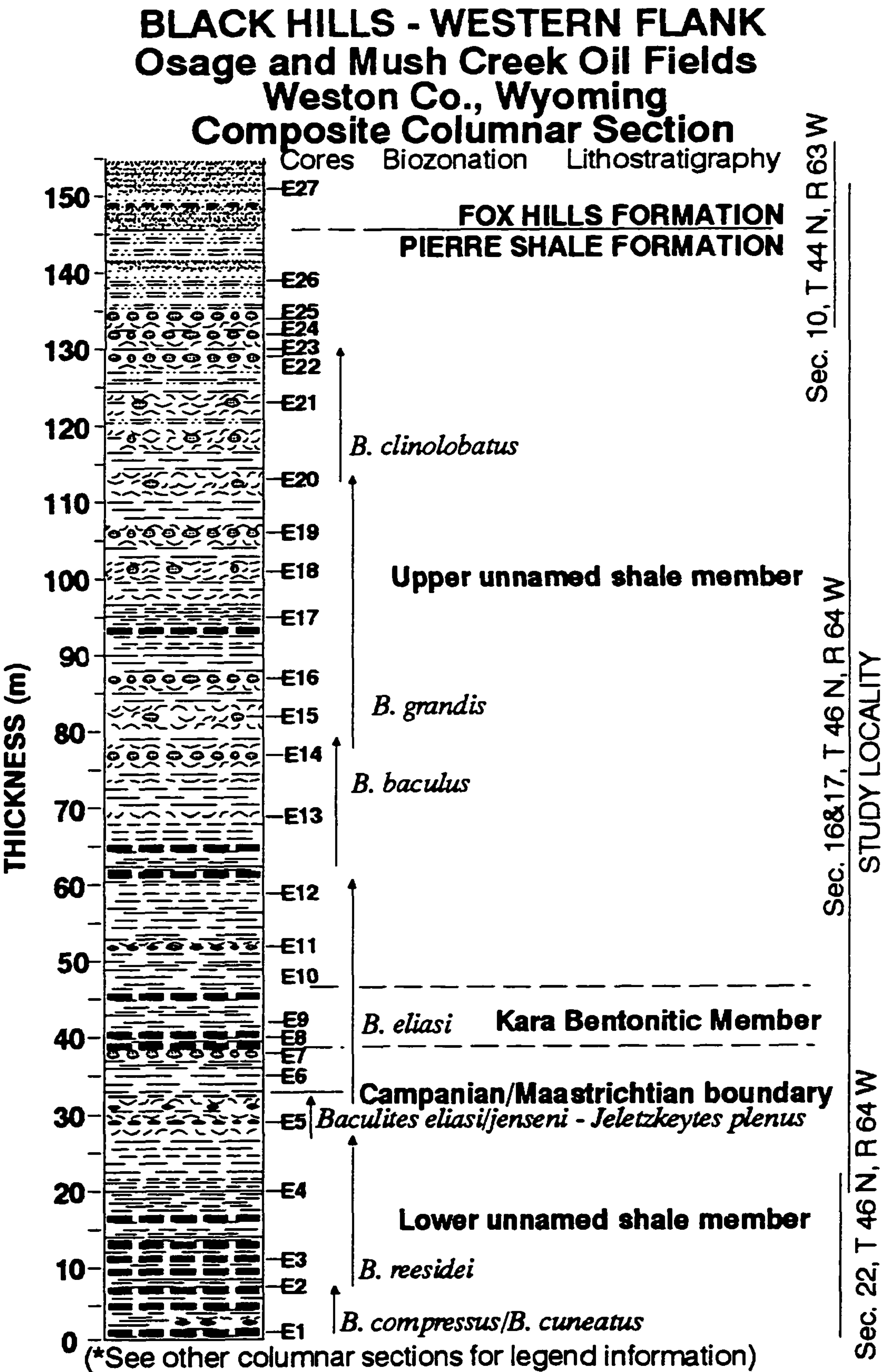


Fig. 89. Mush Creek Oil Field and Osage Oil Fields area, Weston County, Wyoming.

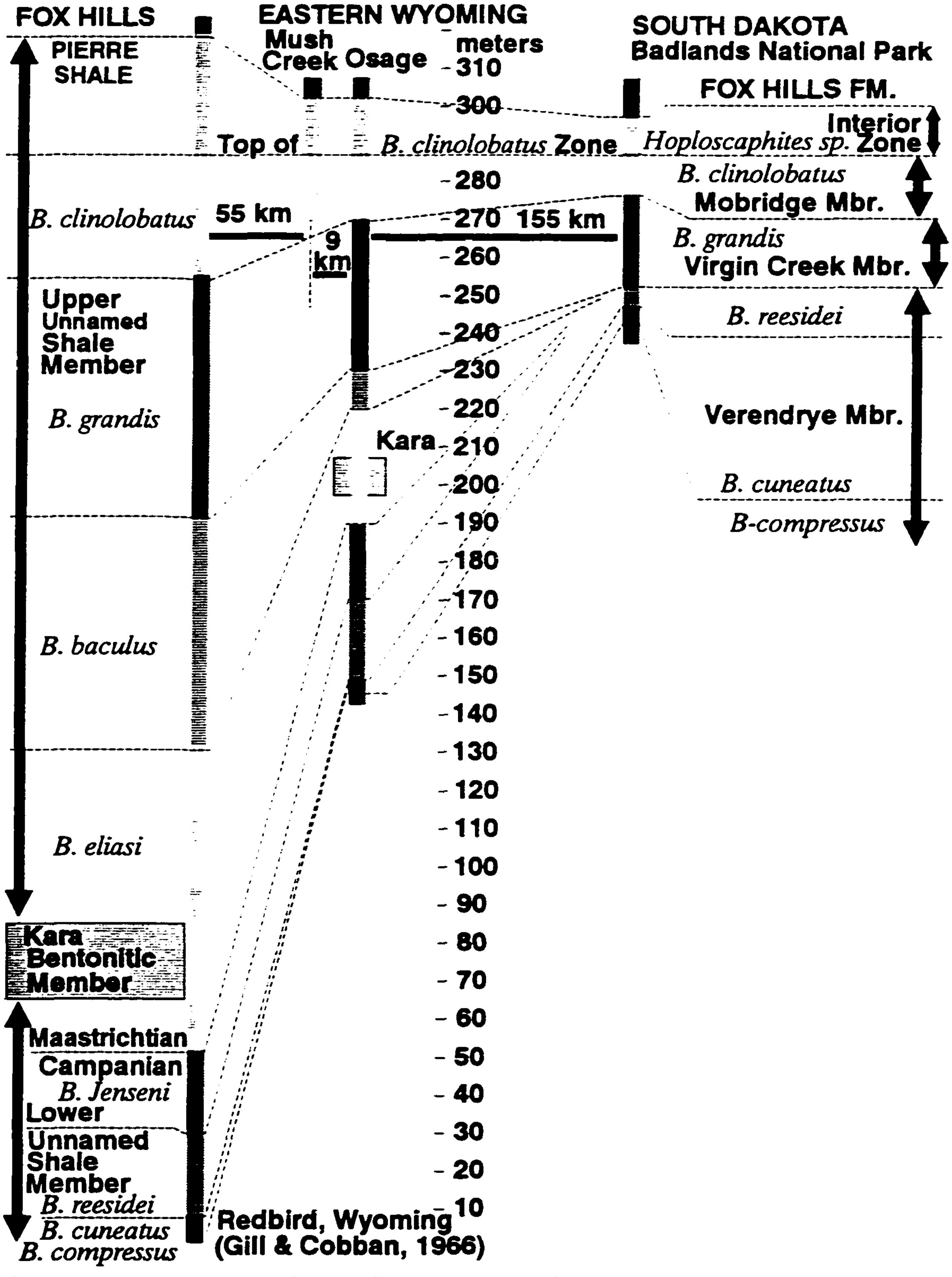


Fig. 90. Correlation diagram showing ammonite range zones and stratigraphic units between between Badlands National Park and eastern Wyoming, including the sections for the Osage and Mush Creek Oil Fields in Weston County, and the Redbird, Wyoming type section.

meters) of *Baculites reesidei* Zone. Although they saw no evidence of an unconformity beneath the *Baculites reesidei* Zone, they suggested that the missing zones were lost to submarine erosion. They suggested that this missing interval corresponds with a regional unconformity associated with the base of the Teapot Sandstone of the Mesa Verde Formation throughout Wyoming. This is a source of conflict in the interpretation of the sequence stratigraphy in the Western Interior region in that Gill & Cobban (1973) showed transgression occurred during the *Baculites compressus* and *Baculites cuneatus* Zones in Montana. Based on their studies in the Montana region Gill & Cobban (1973) and interpreted the *Baculites compressus* and *Baculites cuneatus* Zones as representing a period of high standing seas in the Western Interior Seaway. If this is true, then it would make sense that these fossils would be expected to occur in the Redbird area. The fact that they are missing is possibly an indication that uplift in the Redbird area prevented marine deposition or allowed submarine erosion. The stratigraphy in the South Dakota region adds additional complexity in interpreting the geologic history of the region.

The Verendrye Member in Badlands National Park is approximately 20 meters thick, and contains an abundant fauna in the *Baculites compressus* and *Baculites cuneatus* Zones, whereas the *Baculites reesidei* Zone is generally barren of fossils. The zones of *Baculites jenseni* and *Baculites eliasi* are missing along the unconformity on top of the Verendrye Member. By comparison, we recognized a zone of limestone concretions bearing specimens most resembling *Baculites compressus* in the Osage Oil Field locality. This interval did not yield fossils other than baculites, and these do not occur in abundance. This suggests that water depths were perhaps greater for this interval on the western flank of the Black Hills. This interval is overlain by strata that is barren of fossils, yet contains thin, limonite stained bentonite layers. We assigned this interval to the *Baculites cuneatus* and *Baculites reesidei* zones based on their stratigraphic position and the similarity to Gill & Cobban's (1966) description of this interval in the Redbird area. Like Gill & Cobban (1966) we did not recognize evidence of an unconformity anywhere within this interval. In both the Badlands National Park Region and the Osage Oil Field locality in Wyoming there is an abundance of fossils in the *Baculites compressus* Zone, but a lack of fossils and the occurrence of bentonite beds in the *Baculites reesidei* Zone. This suggests that sea-level was lower during *Baculites compressus* time and that water depths relatively deeper during *Baculites reesidei* time in both the Badlands National Park and eastern Wyoming regions.

The unconformity on top of the *Baculites reesidei* Zone in Badlands National Park suggests that sea-level fell after this time interval. However, the more complete section in the Osage Oil Field area suggests that sedimentation was more continuous. In the Osage Oil Field a zone of fossiliferous phosphatic concretions bearing large arthropods at the transition between the *Baculites jenseni* and *Baculites eliasi* Zones probably represents a period when water depths were shallower in that region. This horizon is about 10 meters below the top of the Upper Unnamed Shale Member. This interval of low-standing seas best explains the occurrence of the unconformity of the eastern flank of the Black Hills in the Badlands National Park region which apparently encompasses both the *Baculites jenseni* and *Baculites reesidei* Zones. The occurrence of a more complete section along the Missouri Valley region implies that the Badlands National Park area was topographically higher than either the Osage Oil Field area or the Missouri River Valley region near Mobridge. This situation allowed submarine and possibly subaerial erosion to occur in the Badlands while sediments were still being deposited in areas to the east and west. Gradual tectonic uplift in the greater Black Hills region would explain this topographic high area.

We also examined the *Baculites compressus* Zone near Casper, Wyoming and observed that it consisted of an approximately 150 meter thick sequence of dark gray shale that lacked evidence of benthic fauna (i.e., no bioturbation features preserved on the surfaces of concretions) which suggests that water depths were much greater in the Powder River Basin in Wyoming than in Badlands National Park. Roehler (1990) studied the equivalent Cretaceous section in central Wyoming and presented an interpretation. His research focused on the Campanian-Maastrichtian stratigraphy on the western margin of the seaway (the Mesaverde Group).

"During this period the normal Mesaverde deposition was interrupted by local and regional uplifts in the Sevier orogenic belt that elevated coastal areas and accelerated the ongoing marine regression to shorelines located mostly east of the study area [in central Wyoming]. A long period of erosion followed during which the uplifted coastal areas were peneplaned, removing rocks in the zones of *Didymoceras nebrascense* upward through *Baculites compressus*. Upon this peneplane were deposited coarse clastics making up the Canyon Creek Member of the Ericson Sandstone and Pine Ridge Sandstone. The Almond and Williams Fork Formations, which generally fall within the zones of *Baculites cuneatus* upward to *Baculites baculus*, represent the final stages of Mesaverde deposition during a major westward transgression of the interior Cretaceous seaway across the study area." (p. 31)

Unresolved questions remain about the story of sea level change recorded in the Late Campanian sediments on the western margin of the Western Interior Seaway. The influence of tectonism, the location of volcanic centers, and the shifting location of depositional centers (deltas) perhaps had a greater role in determining the location of shorelines on the western margin of the seaway than the effects of eustatic change. The structural down-warping of Laramide basins in the Western Interior region probably were also probably significant barriers to the transport of sediments to the eastern margin of the seaway.

### 8.3.2 The Kara Bentonitic Member

We recognized an abundance of *Baculites eliasi* throughout the interval below, including, and above the massive ridge-forming ash beds of the Kara Bentonitic Member. The only fossil fauna observed amongst the bentonite layers were baculites. There is little evidence of benthic fauna in this interval when compared with the more fossiliferous zones higher in the section. The Kara Bentonitic Member probably corresponds to a period when water depths were increasing, with a highstand systems tract corresponding to the lower *Baculites baculus* Zone in the overlying Upper Unnamed Shale Member. Since no massive bentonitic layers or specimens of *Baculites eliasi* were recognized in Badlands National Park, we assume that the interval equivalent to the Kara Bentonitic Member was either not deposited or was lost to submarine erosion in the Badlands National Park region (hence the Campanian - Maastrichtian boundary unconformity). High-standing seas starting during *Baculites baculus* time would explain the occurrence of this ammonite zone in the Badlands National Park region.

### 8.3.3 The Upper Unnamed Shale Member

The interval encompassing the upper *Baculites baculus, Baculites grandis*, and lower *Baculites clinolobatus* Zones on the western flank of the Black Hills display some of the most fossiliferous units in the region. Fossils were collected both in concretions and loose in the shale from all three units. By comparison, these zones generally lack abundant fossils in the Badlands National Park region with the exception of the upper *Baculites clinolobatus* Zone which contains fossiliferous beds, such as in the exposures along the South Fork of Sage Creek.

In the Osage Oil Field area bentonite beds were observed in the poorly exposed interval near the base of the *Baculites baculus* Zone above the Kara Bentonitic Member. Within the middle of the *Baculites grandis* Zone there is a dark bentonitic shale horizon approximately two meters thick that is essentially barren of fossils. This bed may correlate to the bentonite beds in the lower Virgin Creek Member. This interval stands out in contrast to the fossiliferous concretion-bearing horizons above and below within the *Baculites grandis* Zone in the Upper Unnamed Shale Member. The calcareous content of portions of the *Baculites baculus*, *Baculites grandis*, and particularly the lower *Baculites clinolobatus* Zones in the Upper Unnamed Shale Member is perhaps as great or greater than the Mobridge Member along the Missouri River Valley.

The upper *Baculites clinolobatus* Zone in the Mush Creek and Osage Oil Fields contains at least three laterally continuous beds of massive limestone concretions encased in silty to sandy gray shale approximately 2-3 meters apart. These concretions, up to two meters in diameter and up to a meter thick, display an abundance of bioturbation features on their bottom surfaces (see Fig. 33, p. 109). The upper *Baculites clinolobatus* Zone in the Badlands National Park region also displays the same type of continuous beds of massive limestone concretions in a silty to sandy gray shale about 2 meters apart. (The uppermost concretion beds are heavily affected by Yellow Mounds-style weathering.)

In both Weston County localities and in the Badlands National Park region, the interval above the limestone concretion beds becomes highly variable with thin to thick-bedded sand sheets, shale beds, and large limonite-stained, sandy and calcareous concretions occurring in both areas. Gill & Cobban (1966) reported a thickness 175 feet (54 meters) for the *Baculites clinolobatus* Zone. However, they included the upper gray, sandy, glauconitic shale interval within the range zone of *Baculites clinolobatus*, yet they did not report the occurrence of the index fossil within the uppermost 77 feet (24 meters). Therefore, based on their descriptions of the lower 98 feet (about 30 meters) is equivalent to the Mobridge Member. The upper 77 feet (24 meters) fossil-barren interval is equivalent to the Interior Zone in Badlands National Park, and is equivalent the Elk Butte Member in other localities to the east in central South Dakota.

In the Osage Oil Field the measured thicknesses for strata equivalent to the Mobridge Member to be approximately 20 meters thick (compared to 30 meters in the Redbird Wyoming section and about 10 meters in the Sage Creek area of Badlands National Park). In the Osage Oil Field and the Mush Creek Oil Field localities the unfossiliferous unit above the massive limestone concretion beds at the top of the *Baculites clinolobatus* Zone and below the massive glauconitic sandstone unit at the base of the Fox Hills Formation is about 15 meters thick (compared to 24 meters in the Redbird, Wyoming section). This interval is equivalent to the 5-25 meter thick interval of the Interior Zone in the Sage Creek area in Badlands National Park).

### 8.3.4 The Fox Hills Formation

Gill & Cobban (1966) reported a thickness of 249.5 feet (76 meters) for the Fox Hills Formation in the Redbird, Wyoming type section. They reported a 1.2 feet thick bentonite bed as a marker horizon for the top of the Pierre Shale and the base of the Fox Hills Formation. We did not observe the bentonite at our localities, however, we did find a massive glauconitic sandstone in the Mush Creek Oil Field locality which we interpreted as equivalent to Gill & Cobban's basal unit of the Fox Hills. They reported that the lowest sandstone unit, about 4 meters thick, consisted of greater than 50 percent glauconite.

Gill & Cobban (1966) reported that the middle of the Fox Hills Formation at Redbird, Wyoming is dominated by glauconitic and calcareous siltstone, and that the upper portion of the formation is dominated by quartz sandstone. Although no fossils were observed to validate correlation, this sequence matches the general profile of the Fox Hills Sandstone in the Cheyenne River Valley.

The lower massive glauconitic sandstone unit in the Mush Creek Oil Field locality in eastern Wyoming is nearly identical in appearance and composition to the "Lower Unit" (a massive glauconitic sandstone) in the Badlands National Park, Dillon Pass/Conata Basin locality (see Fig. 59, p. 174). Correlation to the "Upper Unit" in the Badlands National Park area is unclear. The significance of the unconformity between the lower and upper units is unresolved due to lack of identifiable fossils or other means of correlation (partly due to the heavy imprint of Yellow Mounds-style weathering). Contemporaneous uplift along the Sage Creek Anticline or in the greater Badlands region may explain the thin or missing Fox Hills Formation.

This is in contrast to thicknesses reported by Landman & Waage (1993) for the Fox Hills Formation in the Corson, Dewey and Ziebach counties region of South Dakota. In this region they measured the thickness of the marine mudrocks and sandstone of the lower Fox Hills Formation (Trail City and Timber Lake Members) to be more than 160 feet (about 49 meters) thick. Above this they found an addition 90 feet - 27 meters of marginal to non-marine sediments of the overlying Iron Lightning Member which is included in the Fox Hills Formation.

In the vicinity of Wall, South Dakota and northward into central Pennington County the middle of the Fox Hills Formation consists of thick, even-bedded sheet sands interbedded with silty to sandy shale. The sand beds are typically densely cemented whereas the shale is poorly consolidated and weathers more quickly. The upper Fox Hills Formation consists of limonite-stained fine to medium-grained, thick-bedded sandstone which coarsen-upward to medium-grained, massive cross-bedded sandstones more typical of shallow nearshore to littoral environments.

The Fox Hills Sandstone is not recognized throughout the region south and west of the North Unit of Badlands National Park (on the east flank of the Black Hills), although there is an abundance of limonite-cemented sandstone concretions within the interval affected by Yellow Mounds-style weathering in the region west of Cuny Table (on the south side of the South Unit of Badlands National Park). Our casual examination of the uppermost Pierre Shale in the Chadron, Nebraska area suggests that the Yellow Mounds Weathering Profile rests on top of the *Baculites grandis* Zone, with no Fox Hills Sandstone preserved in that region.

# CHAPTER 9

## DISCUSSION TOPICS ON SEDIMENTARY GEOLOGY

This chapter addresses selected topics relating to the paleoenvironmental conditions affecting sedimentation patterns and processes in the Western Interior Seaway, and addresses geochemical aspects of the diagenetic history of the upper Pierre Shale/lower Fox Hills Formation study interval. Topics of discussion are limited to the presentation and interpretation to data derived from the analyses of core samples described in the Methodology Section (Chapter 4, p. 36), and sedimentary features observed in the field, including bentonite beds, bedding structures, bioturbation, concretions, and weathering features. The examination of core sample data and these sedimentary features yield information about the composition and origin of the strata, and evidence of early and late diagenetic changes.

### 9.1 OVERVIEW OF GEOCHEMICAL AND SEDIMENTOLOGICAL STUDIES

In 1956 the U.S. Geological Survey began an intensive investigation into the geologic setting and the geochemistry of the Pierre Shale with a presidentially mandated mission to gain understanding about the generation of ore deposits from extensive shale units. This resulted in a series of professional papers describing whole rock, trace element, and mineralogical composition of the Pierre Shale (Barnett, 1961; Rader & Grimaldi, 1961; Tourtelot, 1962; Schultz, 1964; Schultz, 1965). These reports were conducted in conjunction with studies of the stratigraphy and biostratigraphy of the Pierre Shale (Gill & Cobban, 1965; Gill & Cobban, 1966; Sohl, 1967; Mello, 1971; and, Gill & Cobban, 1973). Seventeen shale samples had been selected from throughout the Western Interior region and subdivided amongst the geochemists for their investigation (an expensive and time consuming process at that time!). The conclusion of this initial investigation was that the "samples were too few for any final interpretation to be reached" (Tourtelot, 1962). However, the geochemical and mineralogical investigations generated data that supplemented interpretations by the stratigraphers.

Tourtelot (1962) summarized basic understanding of geochemical processes affecting sediments in the Western Interior Seaway from source areas, surface weathering and transport processes, and early and late diagenetic processes. This overview is a revision of Tourtelot's discussion, integrating information from selected, more recent references.

Most of the land beyond the western shoreline consisted of preexisting sedimentary rock, with active volcanic centers in numerous places (McGookey et al., 1972). In the Late Cretaceous, massive volcanic centers associated with the Idaho

Batholith (Idaho and western Montana), and the Boulder Batholith in the Elkhorn Mountains and Deer Creek volcanic areas of Montana were active during deposition of the Pierre Shale (Tilling & Gottfried, 1969; Gill & Cobban, 1973; and Alt & Hyndman, 1989). These volcanic centers produced volcanic rock mostly of dioritic and quartz monzonite compositions. During the Late Cretaceous these volcanic areas probably behaved similarly to island arc-style volcanic regions that exist today - having episodes of massive eruptions with extensive ash-falls punctuating long quiescent periods of terrestrial weathering. Weathering ultimately converts the calc-alkaline volcanic sediments to smectite (montmorillonite) clays. The shear volume of volcano-clastic sediment during the Late Cretaceous and their geochemical instability in the surface environment probably account for the majority of the fine-grained sediment fraction in the Pierre Shale (Tourtelot, 1962).

Eustatic changes in sea level and episodes of tectonism controlled the extent of the coastal plain along the western margin of the seaway. Sediments deposited during transgressive cycles (such as the Claggett and Bearpaw Shales) inter-tongue with coastal and alluvial plain sediments deposited during regression (such as the Eagle and Judith River Formations)(Gill & Cobban, 1973; Jerzykiewicz & Sweet, 1988). The influence of eustatic cycles on climate, and on the weathering and transport of sediments to the seaway, can be qualitatively inferred (Tourtelot, 1962). According to Tourtelot, weathered material would have passed through the coastal plain adjacent to the Western Interior Seaway with some of the material trapped at least temporarily in coastal swamps, lakes, and lagoons. There the sediment would have been exposed to relatively more concentrated and reactive reducing solutions than in more terrestrial, oxidizing environments of erosion and transport encountered early in transport history. With additional leaching in coastal plain environments the clay-rich sediments would become increasingly deficient in alkali and alkaline-earth elements. Assuming that the original sediment had a relatively homogeneous composition it follows that conditions relating to the geographic extent of the coastal plain and the climate of the seaway might be reflected in the composition of the shale.

However, additional geochemical processes in the marine environment probably dominate the processes affecting shale diagenesis, masking or altering any effects on the sediment which occurred in the terrestrial environment. According to Tourtelot (1962), upon entering the marine environment clay fractions undergo a series of reactions that replenish alkali and alkaline-earth elements, bringing the sediment towards chemical stability with seawater. The incorporation of intraformational sediments, such as calcium carbonate and organic matter, also affected the geochemistry of the sediment. Both calcium carbonate and organic matter would have been contributed by plankton, by fecal material, and to a lesser degree, by the remains of shelled organisms and other animals and plants. It follows that during periods when sediment supply to the basin was reduced, these intraformational fractions would be better represented in the section. This hypothesis is supported by regional mapping which shows that calcareous facies (including marl and chalk) are best represented on the eastern side of the Western Interior Seaway (away from the orogenic source areas to the west)(McGookie et al., 1972).

Upon burial on the seabed the decay of organic matter, assisted by microbial respiration, subjects the sediment to intense chemical activity (Tourtelot, 1962). According to Tourtelot, early diagenesis begins at the sediment/water interface and proceeds downward until compaction (via dewatering) reduces sediment volume by about 30-40 percent. Bacterial reduction of sulfate (from seawater) and devolitilization of organic matter (methanogenesis) increases the amount of acidity in the sediment and results in the dissolution of calcite and the mobilization of soluble ions and compounds which, via dewatering from sediment compaction, are cycled back into the seaway. Depending on variable pH and eH potentials these mobile ions in saturated or supersaturated solution contribute to the growth of concretions or may react with other minerals or organic residues in the sediment (Berner, 1968; Hudson & Friedman, 1976; Curtis & Coleman, 1986; Raiswell, 1988, and Coleman, 1993).

Rates of sedimentation, marine circulation patterns, basin anoxia, and organic productivity would have been influenced by factors such as climate and eustatic change (Gill & Cobban, 1973; Wright, 1987; Jewell, 1993). Shultz (1965) suggested that compositional variation between marls and shales are a function of eustacy, where shallowing conditions increased the circulation of oxygenated bottom waters. Elevated oxygen levels at the sea bottom allowed bottom dwelling organisms to churn the sediment and remove organic matter that would have otherwise been incorporated into the sediment. Schultz argued that a lack of organic carbon resulted in an increase in pH in the sediment, creating an environment more favorable for the preservation of calcite shell material. According to Shultz, during periods when deeper water persisted, increased organic content of the shale resulted in the dissolution and recycling of calcite. This argument has significance for the origin of concretions and shell taphonomy. However, factors other than greater water depths have been suggested for higher organic contents in shales, including density stratification of the seawater column, marine upwelling, or flood events. Each of these phenomena are known to limit oxygen availability at the sea bottom in modern depositional environments (Waage, 1964; Wright, 1987; Parrish & Gautier, 1988; Carpenter et al., 1988; and Jewell, 1993). Savrda & Bottjer (1989) demonstrated that ancient bottom oxygenation condition can be interpreted by examination of the abundance and diversity of trace fossil assemblages preserved in sediments of the Western Interior Seaway. Kauffman (1977) suggested that varying degrees of abundance and diversity of fossil assemblages, where preserved, can provide perhaps the best indication of both water depths and oxygenation conditions on or within the sea bottom.

Diagenesis is the sum of physical-, inorganic-chemical-, and biochemical changes in a sedimentary deposit after its initial accumulation (Friedman et al., 1992). Sediments continuously undergo diagenetic reactions with this interstitial pore water throughout their existence. During periods when the seaway withdrew from portions of the Western Interior, marine sediments in this region were subjected to influx of meteoric waters, which can be expected to have caused varying degrees of diagenetic alteration depending on exposure. Studies of modern coastal environments show that leaching of soluble minerals, particularly calcium carbonate, occurs in the vadose zone, and the precipitation of calcite cement occurs in the fresh-water phreatic zones, and perhaps most intensely in the marine phreatic zone where mixing of meteoric and marine water occurs (Friedman et al., 1992). Ludvigson et al., (1994) suggested that concretion formation in the Western Interior region (Greenhorn Cycle; Cenomanian and Turonian) is related to meteoric diagenesis, and marine diagenesis to a lesser degree, within upward shallowing sequences.

Meteoric leaching and eluviation processes resulted in the formation of soil profiles imprinted on ancient land surfaces. Perhaps the best indication of this is the the Yellow Mounds Weathering Profile seen throughout the Badlands National Park region (Retallack, 1983; Retallack, 1985)(see Fig. 51, p. 156). Other weathering profiles were observed beneath unconformities including the Campanian/Maastrichtian boundary unconformity (see Fig. 45, p. 138), and along the Pierre Shale/Fox Hills boundary in Badlands National Park (see Fig. 55, p. 163). These ancient soil profiles are marked by limonite and hematite stains, crusts, and fracture-fillings (probably from the oxidation of pyrite and the break-down of glauconite in the marine shales). Calcareous fossil material are generally absent from these horizons. Late stage cone-in-cone overgrowths and septarian fracture-filling in concretions, like the surface rinds on massive limestone concretions in the upper *Baculites clinolobatus* Zone, probably represent intervals where calcium carbonate from the overlying sediment accumulated by meteoric processes (see Fig. 65, p. 192). Where concretions in the *Baculites clinolobatus* Zone have not been affected by diagenetic processes associated meteoric weathering the concretions still preserve marine bioturbation features and calcareous fossils (see Fig. 33, p. 109).

Evaporative conditions (associated with dry climate conditions as exists in the region today) affect the modern surface weathering profile by promoting the accumulation of salts (i.e., selenite and barite) in fractures and along surfaces of bedding features, and the development of caliche.

## 9.2 CORE SAMPLE ANALYSES

Cores samples were collected using a hand-operated piston driver to produce uniform samples for sedimentological and geochemical analyses (see methodology in Chapter 4). One hundred and eleven cores collected during the summer of 1995 from five field study areas were used for analyses (Fig. 91). Data derived from the analysis of these cores are compiled in the Appendices A-E.

The stratigraphic position and precise geographic location where each core was taken is indicated on the right side of measured sections (in Chapter 6) and columnar sections (in Chapter 8) for the: 1) Mobridge/Grand River area localities (p. 91 and p. 261), 2) Weston County, Wyoming localities (p. 103 and p. 273), 3) Badlands National Park, South Unit, Cedar Creek locality (p. 119 and p. 231), 4) Badlands National Park, North Unit, Sage Creek Campground localities (p. 132 and p. 234), and 5) the Tom Trask Ranch localities (p. 188 and p. 257). All but the Cedar Creek locality represent composite sections, meaning that two or more localities in close proximity were used to define a more complete or continuous stratigraphic exposure of the upper Pierre Shale/Fox Hills transition interval.

It is important to emphasize that core analyses were conducted in order to supplement field observations. (It is my opinion that, without field observations, data from core samples in themselves are of limited value.) The analyses of cores provided little information for the purposes of correlation. However, information derived from core sample analyses provided some useful information about sedimentological conditions in the seaway through time, and information relating to diagenetic characteristics of concretions and the shale that surrounds them (discussed below).

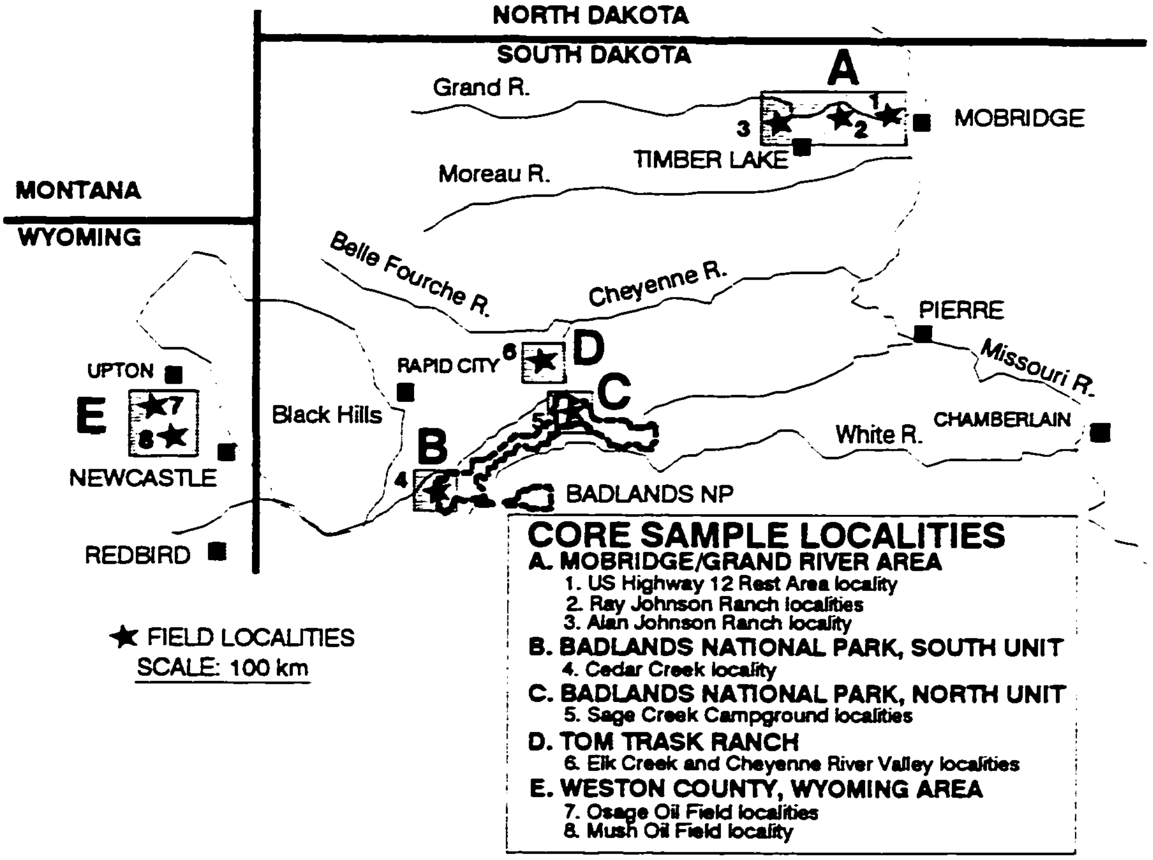


Fig. 91. Map of localities where core samples were collected.

Appendix A is a table of precise locality information about each core in relation to creek or lake level at the base of an outcrop, and includes notes about each core and a preliminary interpretation of its stratigraphic position. The sample spacing between cores averaged approximately 3 meters, but varied considerably depending on the condition of outcrop exposures. Cores were collected only if fresh shale was not encountered when digging exploratory holes in preparation for collecting a core sample. This explains the uneven gaps in sample spacing.

The coring device produces cores approximately .5 kilogram in weight encapsulated in clear buterate plastic tubes six-inches long and two-inches in diameter. Appendix B is a summary of descriptive physical characteristics of each core prior to their extraction from their core cylinders for destructive analyses. This information was consulted in the construction of the measured sections for the localities shown in Fig. 91. For instance, the calcareous content, gypsiferous content, bioturbation characteristics, and sediment lamination characteristics from this table were used for adding detail to each of the five composite measured sections (mentioned above). These were the first five measured section constructed after the summer of 1995. All of the additional measured sections presented in Chapter 6 were compiled during the summers of 1996 and 1997 using these first five sections as reference.

### 9.2.1 Sieve Fraction Analyses

Sieve fractions were derived from 0.250 kilograms of oven dried sediment from each core. The disaggregated sediment was washed through a tower of four standard sieves: 1000$\mu$m, 500$\mu$m, 250$\mu$m, and 63$\mu$m mesh (sieve numbers 18, 35, 60, and 230, respectively). The first four columns in Appendix C is a tabulation of data of each sieve fraction. This data was then manipulated to determine percentages of the whole sample that consisted of the "coarse sand fractions" (sieves 18 & 35) and "fine sand fractions" (sieves 60 & 230). A third percentage represents the fine sediment (silt and clay) that were washed through the sieves into the drain. The percentages of the three fractions are summarized in a graphic format for the five composite sections (discussed below).

The 250$\mu$m (fine sand) fraction from each core were examined under a microscope. Mineral content of each 250$\mu$m sand sample was determined by examining and counting three hundred sand grains from each sample and dividing by three to express a percentage. The content of the sand is summarized in Appendix D. This data was perhaps most significant in demonstrating that in nearly every sample the sand fraction consists dominantly of *intraformational clasts*. *Intraformational clasts* are sediments that form by processes *in location* (within a sedimentary basin), as apposed to *extraformational clasts*, such as quartz sand or mica flakes in bentonite, that are transported into a depositional setting from sources outside of a basin

(Tucker, 1995). Sand fraction contents included:

**Cemented mud grains** - These pelloidal grains are typically angular to sub-rounded grains of mud cemented by phosphatic material, organic material, calcite, siderite, hematite, or silica. These grains of mud survived the disaggregation process and washing. They possibly represent pellets or coprolites, or grains derived from cementation along small fractures or bedding lamination. They are *intraformational* in origin, and generally have no significance for sedimentological analyses because of their ambiguous origin and character.

**Calcite grains** - These grains appeared bright white, pale yellow, to brown. These possibly represent shell material from disaggregated excrement. They tend to be quite angular is shape, displaying the typical cleavage of calcite. Some grains are rounded. They may also represent small fracture filling cement in the shale. The rod-shaped crystals of the inner nacreous shell layer of inoceramids are fairly easy to recognize. Calcite grains are *intraformational* in origin.

**Microfossils** - Nearly all microfossil noted were calcareous foraminifera in varying stages of dissolution. Unidentified rods (possibly urchin spine material) and cone-shape microfossils were also observed. No attempt was made to identify species of foraminifera (see Mello, 1969). Microfossils are *intraformational* in origin.

**Organic residues** - Organic material occurs as gelatinous resins or brownish black-colored tissue remnants, and may also be phosphatic in content. Other than fossil wood, organic residues are *intraformational* in origin.

**Glauconite** - Glauconite occurs as rounded, green grains replacing pelloids (possibly representing excrement from invertebrates). The abundance of glauconite approaches "greensand" concentrations in some beds in the lower Fox Hills Formation. Glauconite grains are *intraformational* in origin.

**Selenite or gypsum grains** - Fibrous selenite crystals occur as overgrowths on calcite grains. The occurrence of selenite demonstrates that drying, evaporative conditions possibly prevailed during deposition, but may also represent a late diagenetic phase. Selenite or gypsum grains are *intraformational* in origin.

**Limonite and hematite grains** - Rust-colored and orange masses of iron probably represent the precipitation of iron oxides along small fractures or mineral replacement of other grains (particularly glauconite) or fossils. The limonite and hematite grains in the Pierre Shale are most likely *intraformational* in origin. In the Fox Hills Formation they may represent *extraformational clasts* where they occur in association with quartz sand, particularly if magnetite grains are present.

**Quartz sand** - The occurrence of rounded grains of quartz sand and cemented silt demonstrate higher energy current transport or reworking. Quartz sand can occur in deep water deposits created by turbidity currents, and nearshore sand deposits where storm and wave energy was strong enough to transport sand. They are scarce in the Pierre Shale. Quartz sand is *extraformational* in origin.

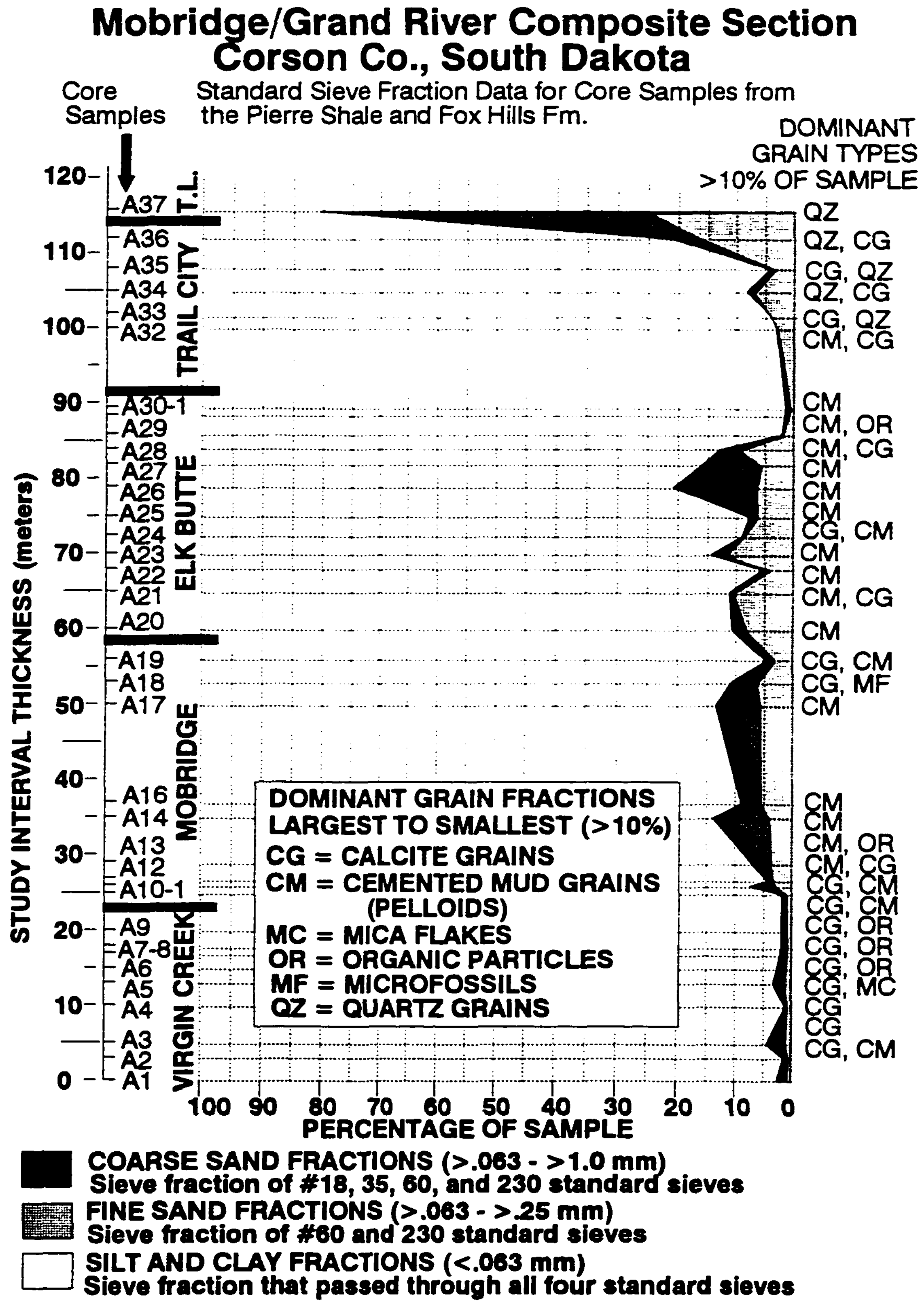
**Mica flakes** - Thin sand-sized sheets of mica appear most abundant in bentonite layers encountered in the coring process. They were also noted in association with quartz sand deposits in the Fox Hills Formation. Mica flakes are *extraformational* in origin.

**Chert or opal grains** (*Extraformational)* - Chert turned out to be insignificant, along with grains of feldspar or other extraformational clasts other than quartz and mica.

Although stratigraphic boundaries were chosen in the field based of visual lithological characteristics, the sedimentological data from cores yielded some useful information for sequence stratigraphic interpretation. Figs. 92-96 are graphic tabulations that show percentages of clastic fractions (coarse sand, fine sand, and silt & clay) and information about the dominant and secondary contents of the fine sand fraction. Interpretations of sieve fraction data for each section are presented below.

### Mobridge/Grand River Area Localities

The stratigraphic position of core samples on Fig. 92 correspond to the same locations indicated on the composite measured section for the Mobridge/Grand River



**Complete sieve fraction data is presented in Appendix C.**

Fig. 92. Sieve fraction analyses of core samples from localities in the Mobridge/Grand River area, South Dakota.

area localities (see Fig. 86, p. 261). Sieve fraction data is possibly useful for helping to help define the boundary between the Virgin Creek and Mobridge Members. An increase in the sand fraction was noted between cores B9 and B10 in the vicinity of a "color change" observed in the field. The dominant grain types, cemented mud grains and calcite grains, fluctuate in abundance upward through the Mobridge Member into the Elk Butte Member. The boundary between the Mobridge and the Elk Butte Member is placed between cores A19 and A20 but not for any reason based on sedimentological or geochemical data derived from the cores. The boundary location was chosen in the field because the sediment changes in appearance from a light gray color is a darker-colored shale just above a bed of large limestone concretions that forma a ledge-forming break in slope (at core A18).

The increase in the sand content from the Virgin Creek Member into the Mobridge suggests two possibilities. Sedimentation rates could have been faster during deposition of the Virgin Creek facies, whereas a rise in sea level or blockage or diversion of sediment supply to the Missouri Valley region reduced the influx of fine-grained sediment to the region. This slow down in clastic sedimentation allowed calcareous material to accumulate in higher concentration. Perhaps the clearer water conditions also promoted greater biogenic activity. The increase in the calcareous sand fraction content in the Mobridge and Elk Butte Members is probably directly related to biogenic activity, both in the substrate (as suggested by the abundance of cemented mud grains - possible pellets) and in the water column (as suggested by the calcite grains which probably represent excreted shell remains).

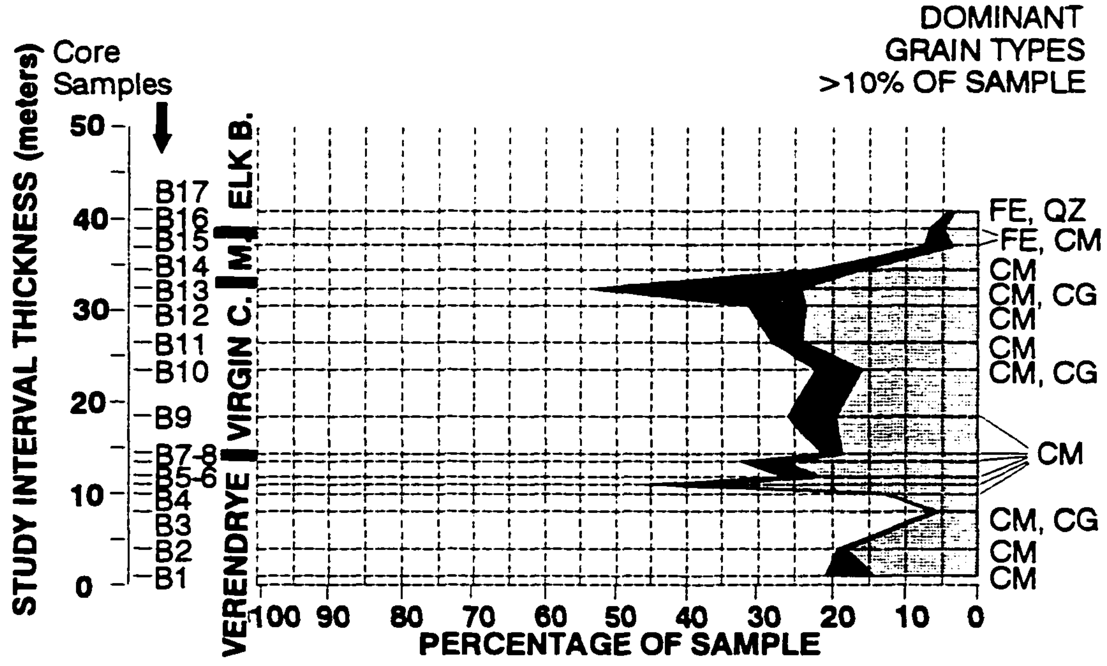
The boundary between the Pierre Shale and the base of the Timber Lake Member of the Fox Hills Formation is also based on a visible change in lithology. The sediment among concretions bearing *Hoploscaphites nicolleti* in the lower Trail City Member were very fine-grained compared with samples in the upper Elk Butte Member. This supports an interpretation that a transgression occurred at the close of Elk Butte time, followed by regression represented by the coarser-grained sediment of the upper Trail City and Timber Lake Members. The difference between the Fox Hills in the Mobridge area compared other locations is that it apparently lacks glauconite in the lower portion of the formation. The more massive sandstone in the Timber Lake Member consists of quartz sand cemented with iron minerals (possibly derived from the dissolution of glauconite). The core samples in the lower Trail City Member did not contain an abundance of calcite grains even though the unit yields an abundance of fossiliferous concretions. Dissolution of the calcareous sand fraction of the sediment probably contributed to the growth of fossiliferous limestone concretions in the lower Fox Hills.

### Badlands National Park, South Unit, Cedar Creek

The sieve fraction diagram shown in Fig. 93 corresponds to the measured

## BADLANDS NATIONAL PARK
## Stronghold Unit - Cedar Creek Area
## Columnar Section
## SE, Sec.11, T 5 S, R 10 E

Standard Sieve Fraction Data for Core Samples from the Pierre Shale and Fox Hills Fm.



**DOMINANT GRAIN FRACTIONS LARGEST TO SMALLEST (>10%)**

CG = CALCITE GRAINS
CM = CEMENTED MUD GRAINS (PELLOIDS)
FE = IRON MINERAL GRAINS
QZ = QUARTZ GRAINS

■ **COARSE SAND FRACTIONS (>.063 - >1.0 mm)**
**Sieve fraction of #18, 35, 60, and 230 standard sieves**

▨ **FINE SAND FRACTIONS (>.063 - >.25 mm)**
**Sieve fraction of #60 and 230 standard sieves**

☐ **SILT AND CLAY FRACTIONS (<.063 mm)**
**Sieve fraction that passed through all four standard sieves**

**Complete sieve fraction data is presented in Appendix C.**

Fig. 93. Sieve fraction analyses of core samples from the Cedar Creek locality, Badlands National Park, South Unit.

section for the Cedar Creek area (see Fig. 71, p. 231.). Sieve fraction analysis shows that the Pierre shale in the Cedar Creek area has a much higher sand fraction content, more than double, than equivalent strata in localities both the Mobridge region or on the western flank of the Black Hills. The higher sand fraction content can be interpreted as a result of winnowing of the fine-grained sediment fraction by higher current energy in shallower water environments (due to uplift in the Badlands National Park region). The majority of the sand fraction consists of cemented mud grains (probably fecal pellets). A core from the top of the section yielded a small amount of quartz sand, suggesting that the shale at the top of the section is possibly equivalent to the Fox Hills Formation.

### Badlands National Park, North Unit, Sage Creek Campground

The sieve fraction diagram shown in Fig. 94 corresponds to the measured section for the Sage Creek Campground area (see Fig. 74, p. 234.). The sieve fraction data for the Sage Creek Area also shows a higher sand fraction content of the shale than the localities in the Mobridge area and western flank of the Black Hills. The dominant sand-size particles are cemented mud grains, probably fecal pellets. Samples representing the Mobridge Member show a slightly lower sand fraction content. The dominant grain-type from Mobridge samples consisted of calcite grains, probably excreted shell material. A sample from the lower Fox Hills Formation

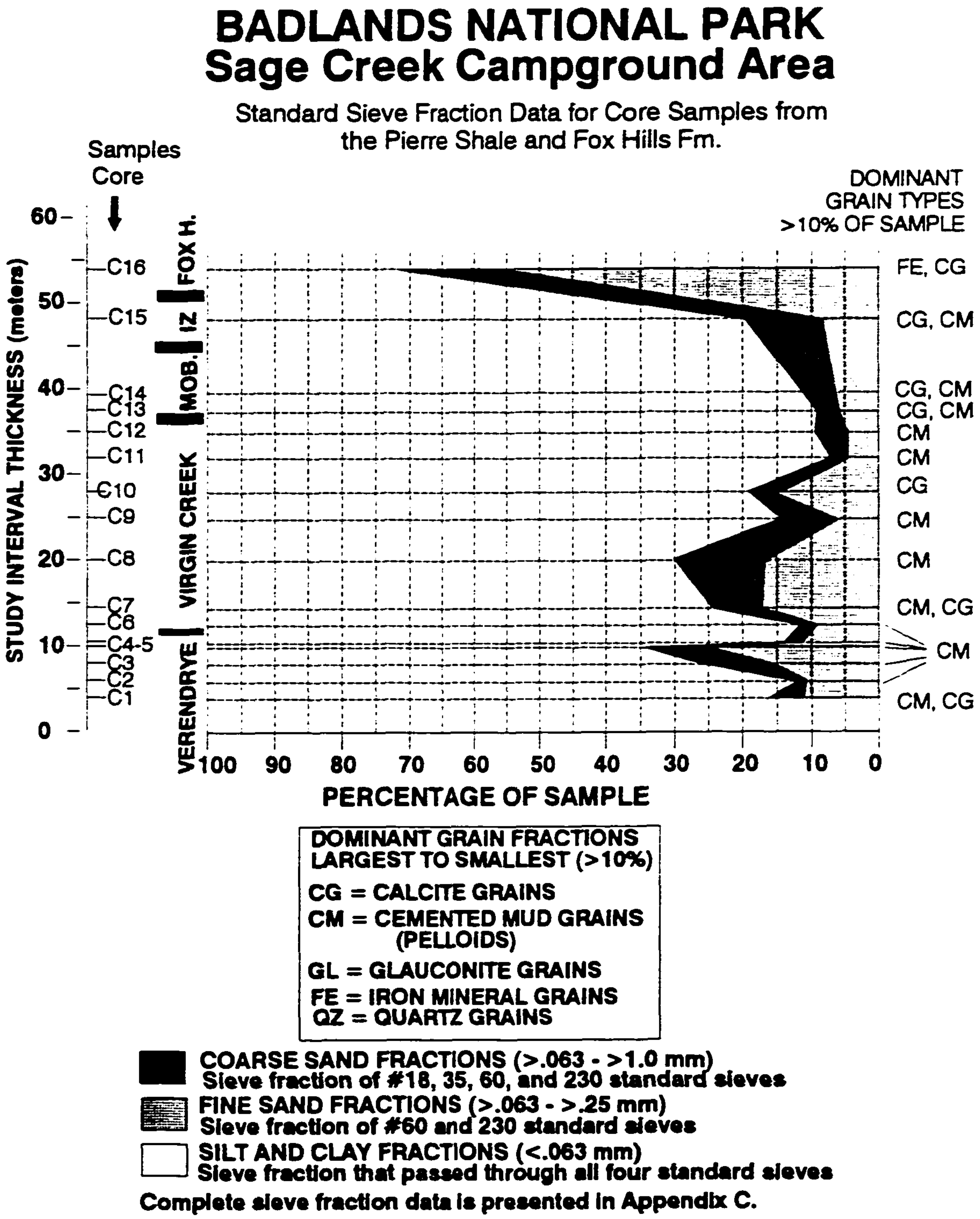


Fig. 94. Sieve fraction analyses of cores samples from the Sage Creek Campground area, Badlands National Park, North Unit.

yielded no quartz grains, but yielded an abundance of glauconite and iron grains (probably glauconite grains altered by Yellow Mounds-style weathering).

### The Tom Trask Ranch

The sieve fraction diagram shown in Fig. 95 corresponds to the measured section for the Tom Trask Ranch area (see Fig. 82, p. 257.). Sieve fraction data from the Tom Trask Ranch localities show an intermediate abundance between the Badlands National Park localities and the Mobridge/Grand River section. Samples from the Mobridge Member yielded a larger fraction of calcareous grains than in the Badlands National Park area. The increased thickness of the members of the upper Pierre Shale and the reduced sand fraction content suggest that more fine-grained sediment was being deposited, possibly because water depths were slightly greater than in the Badlands area.

### Weston County, Wyoming Localities

The sieve fraction diagram shown in Fig. 96 corresponds to the composite measured section for the two localities (see Fig. 89, p. 273.). Sieve fraction studies of the Osage Oil Field showed that the sediment is generally much finer-grained on the western flank of the Black Hills than equivalent strata to the east. The lower sand fraction (consisting of intraformational clasts) suggests that the sedimentation rate of

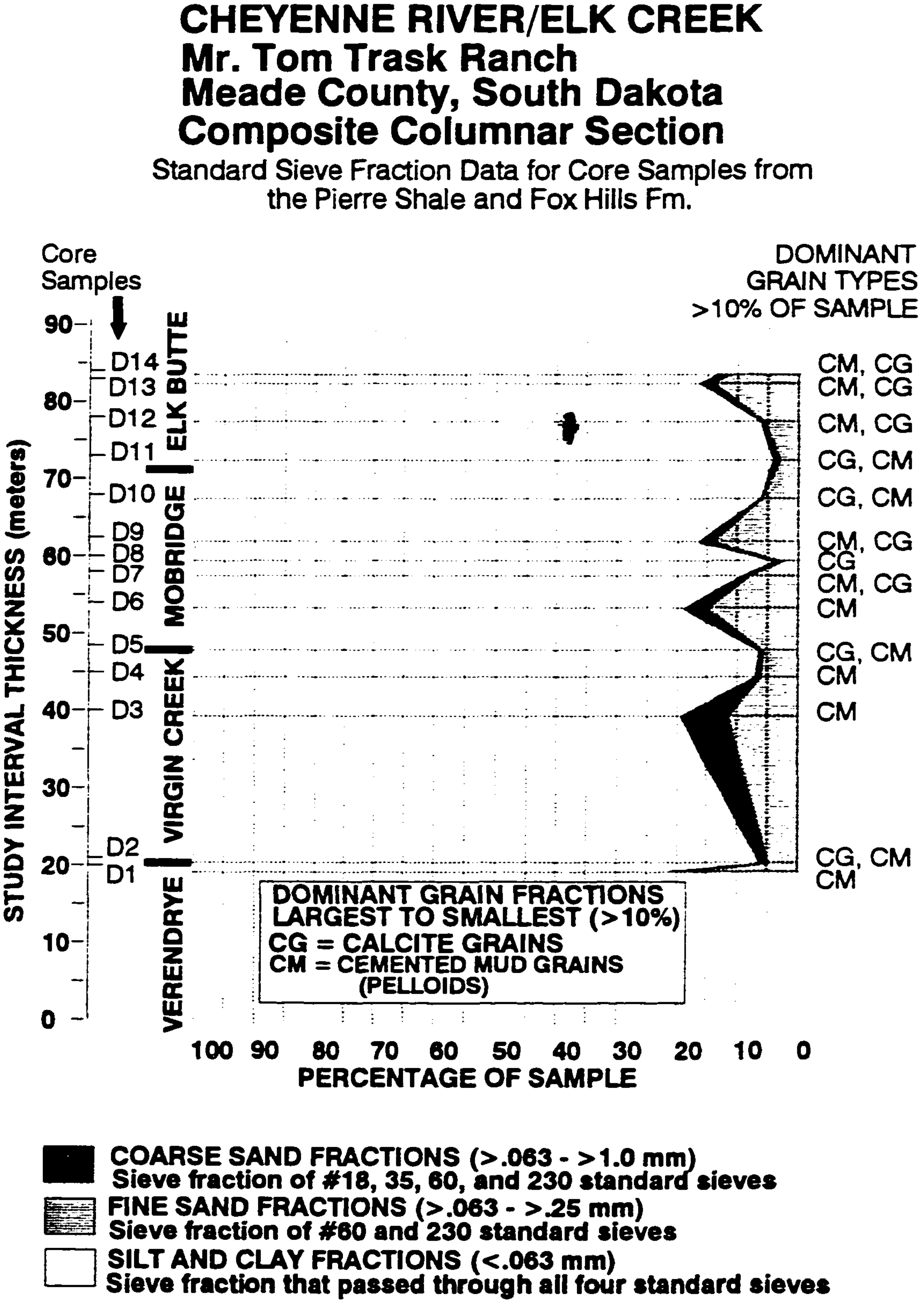


Fig. 95. Sieve fraction analyses of core samples from the Tom Trask Ranch localities, Meade County, South Dakota.

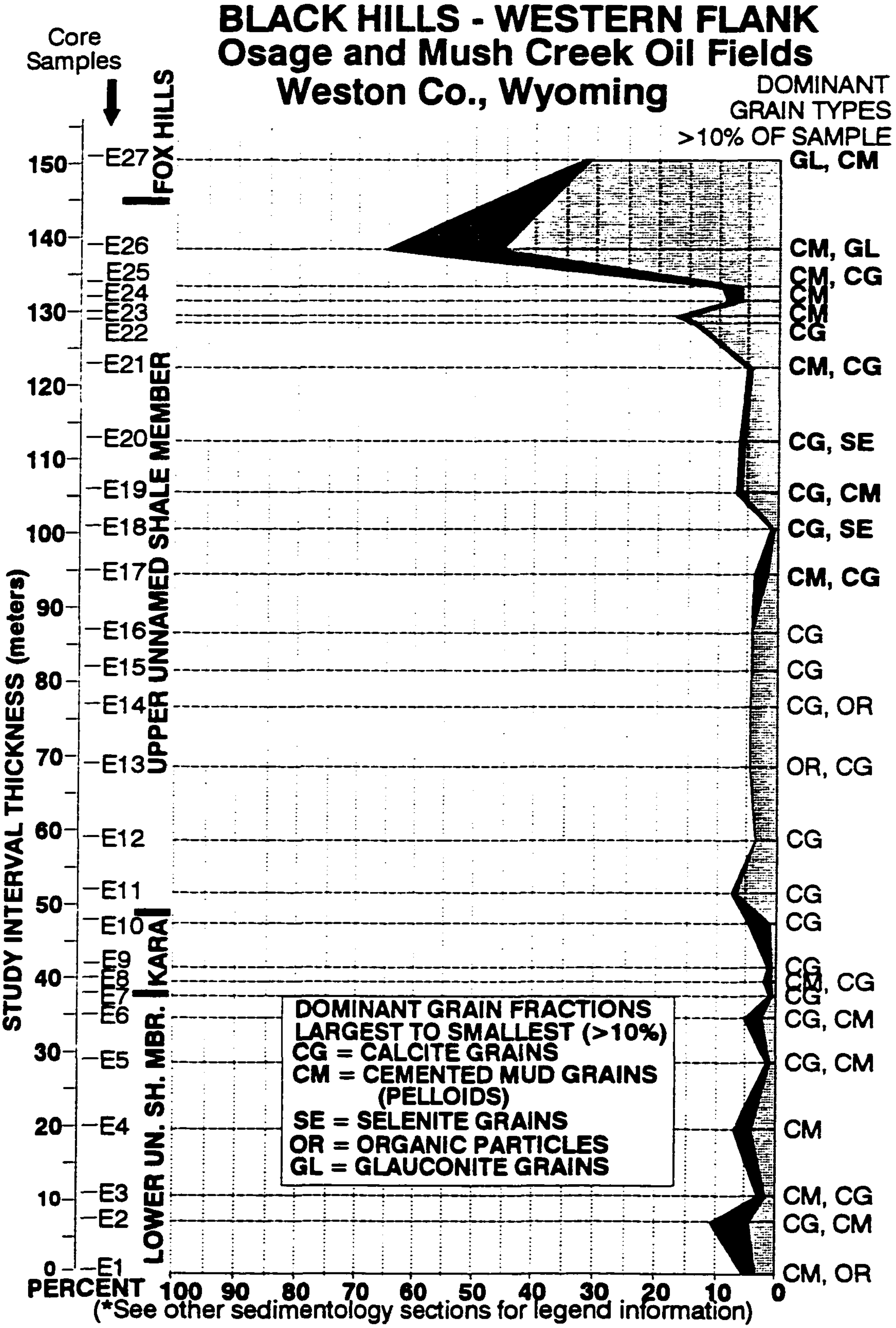


Fig. 96. Sieve fraction analyses of core samples from the Osage Oil Field and Mush Creek Oil Field localities, Weston County, Wyoming.

fine-grained materials was more rapid, therefore diluting the coarser sand fraction. The low intraformational sand-fraction content within the Upper Unnamed Shale Member, particularly in the intervals which contain an abundance of large, fossiliferous limestone concretions, suggests that shell fragments in the shale were dissolved, with the calcite redistributed to form limestone concretions.

Samples from a sandy unit at the top of the Pierre Shale and from the massive sandstone unit at the base of the Fox Hills formation yielded no quartz grains, but demonstrated that the sandstone consisted of a high glauconite content. The high glauconite content suggests that sediment supply was reduced, allowing organic activity to contribute the majority of the sediment in the form of fecal material. This is consistent with the interpretation that the basal Fox Hills represents a transgressive systems tract. The quartz-rich upper portion of the formation represents the final regression sequence associated with the Sheridan Delta suggested by Gill & Cobban (1973).

### 9.2.2 Geochemical Analyses

While conducting field investigations we observed that variations in the color of the shale in some zones alternated from dark to light zones. In a series of concretion beds in the upper *Baculites clinolobatus* Zone the beds of concretions tended to occur in intervals that were lighter in color than the intervening shale. This observation was part of the motivating factor for conducting geochemical tests. The objective of geochemical analyses was to gain quantitative measures of a suite of standard whole rock element (reported as oxides) to resolve several questions. First, were the physical color variations we observed between concretion horizons and the intervening shale reflective of chemical variations between units? Second, does the chemical composition of the sediment differ between stratigraphic members and between regional localities? Third, if there were recognizable differences in geochemical composition, are there plausible explanations for these differences? Finally, how does the composition of the samples from this study area compare with previously reported data for the Pierre Shale (Tourtelot, 1962), and with other shale data (Pettijohn, 1975)?

Because sediments undergo so many changes during transport and diagenesis interpretation of geochemical data in shales is problematic. Geochemical analyses of shales are useful for mineral exploration, however, as Tourtelot (1962) suggested, without incorporating the data in the context of sedimentological observations they have limited utility. On the advice of Jim Hoffman (personal communication, 1995), a clay mineralogist with many years of experience in mineralogical applications of clays to basin analysis, I chose not to pursue conducting detailed X-ray diffraction analyses to identify the clay minerals in the samples. His contention is that post-depositional diagenetic processes completely alter the clay minerals shortly after burial, making interpretations about pre-depositional conditions (such as climatic conditions) impossible.

Tourtelot (1962) described the effects of surface weathering on the composition of shales. Samples from a single horizon in the Claggett Shale were sampled through a modern weathering profile that extended from fresh, black shale in the subsurface through to the surface zone where the shale had been altered to a brown soil-like weathering product. Samples from the brown, degraded shale on the surface were enriched in Si, Al, and Fe, but depleted in Mg, Ca, S, and $CO_2$. These results demonstrates the necessity to reject samples that display evidence of surface weathering.

Geochemical analyses of core samples from the study area were conducted in the fall of 1995. A twenty five gram sample of sediment was selected from each dried core specimen, examined, disaggregated, and ground with a mortar and pestle, and passed through a 125$\mu$m sieve (standard no. 120). This grain size was essential to conduct geochemical analyses with the X-ray diffraction method. Pieces of shale were selected that did not display visible alteration. Core samples were rejected if they displayed degradation by surface weathering, contained roots, if they contained visible bentonite beds, or if they were originally collected fairly close to other cores. Within each dried core sample pieces of shale were selected that did not display cemented fractures, iron-stains, selenite, barite, or calcite veins, or contained visible fragments of fossil material. Pieces were selected that generally had a "typical appearance" for that particular sample, having consistent color, bedding, and fracture pattern. It is important to emphasize that the geochemical data represents "whole sediment" in that most of the sand fraction, with the possible exclusion of quartz grains, were disaggregated by grinding. The goal was to obtain a fairly even representation of fresh shale samples from throughout each section, and to examine selected horizons where concretion beds occur. Of the 111 cores collected in 1995, only 81 samples were selected for testing.

XRAL offered a suite of whole rock analyses by X-ray diffraction method, with results represented in standard oxides of Si, Al, Fe, Mg, Ca, Na, K, P, Ti, Mn, and LOI with reliability guaranteed in the parts per 10,000 range. An add-on suite of trace elements included Rb, Sr, Y, Zr, Nb, and Ba. Carbon and sulfur are lost in the LOI (loss on ignition) process, and can be evaluated by this means. The water content was eliminated by thoroughly drying each sample in a laboratory oven at 185 degrees C for four days prior to analysis by XRAL.

Full tabulation of geochemical data is presented in Appendix E. Table III is a summary of the average composition and standard deviation of whole rock oxides and selected trace elements for the 81 core samples tested compared with published data by Pettijohn (1975) and Tourtelot (1962). For the various elemental concentrations that the data sets have in common, the average from the 81 samples from the study

## TABLE III

## Composition of Pierre Shale vs. Average Shale

| Analyses | AVERAGE SHALE Pettijohn (1975) | PIERRE SHALE Tourtelot (1962)* % (St. Dev.) 11-17 samples | PIERRE SHALE Stoffer** % (St. Dev.) 81 samples |
|---|---|---|---|
| $SiO_2$ | 58.10 | 59.68 (3.49) | 59.4 (4.6) |
| $Al_2O_3$ | 15.40 | 15.4 (1.52) | 14.6 (1.44) |
| Fe oxides | 4.02 as $Fe_2O_3$<br>2.45 as FeO<br>Total as $Fe_2O_3$: 6.74 | 4.56 (1.00) as $Fe_2O_3$<br>0.96 (0.64) as FeO | 5.92 (2.16) as $Fe_2O_3$ |
| MgO | 2.44 | 2.11 (0.47) | 2.05 (0.46) |
| CaO | 3.11 | 1.52 (1.12) | 2.93 (2.78) |
| $Na_2O$ | 1.30 | 1.09 (0.42) | 1.13 (0.38) |
| $K_2O$ | 3.24 | 2.49 (0.26) | 2.81 (0.57) |
| $CO_2$ | 2.63 | 0.87 (1.35) |  |
| C | .80 |  |  |
| $H_2O$ | 5.00 | 3.73 (1.09) as $H_2O^+$<br>4.77 (4.77) as $H_2O^-$ |  |
| LOI | 7.13 |  | 8.83 (2.22) |
| $P_2O_5$ |  | 0.15 (0.04) | 0.16 (0.1) |
| S |  | 0.21 (0.17) |  |
| TiO |  | 0.60 (0.05) | 0.61 (0.1) |
| MnO |  | 0.19 (0.39) | 0.04 (.05) |
| Rb |  |  | 106 (18.4) ppm |
| Sr |  | "depleted" | 277 (180) ppm |
| Y |  | "depleted" | 29.3 (6.3) ppm |
| Zr |  |  | 165 (30) ppm |
| Nb |  | "depleted" | 12.3 (2.3) ppm |
| Ba |  | 0.08 % | 1124 (1941) ppm |
| F |  | 0.07 % |  |
| B |  | "enriched" |  |

*Tourtelot's data represents scattered samples from throughout the entire Pierre Shale and equivalent strata in Wyoming, Montana, and around Pierre SD (lower Pierre Shale).

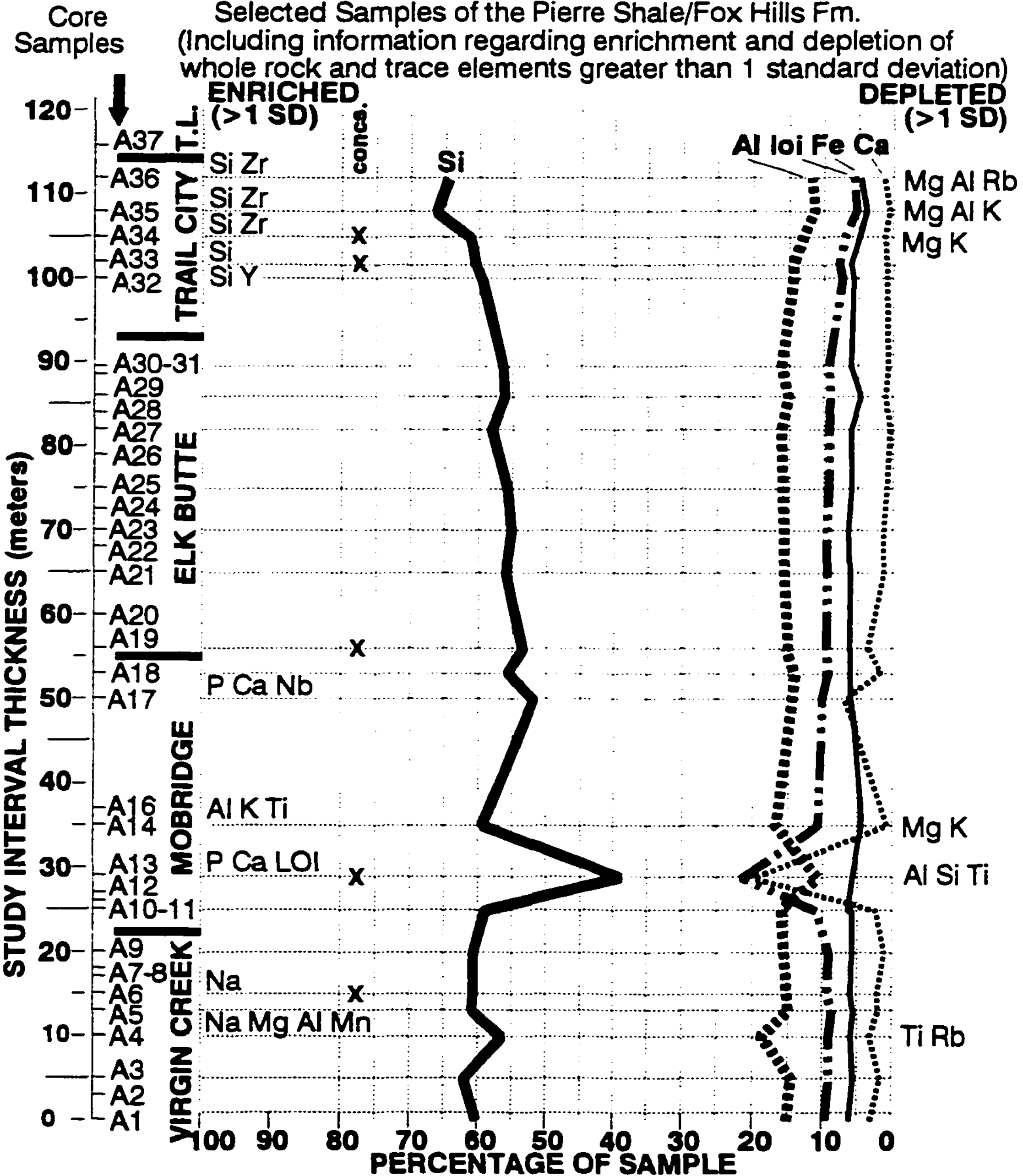
**81 sample represent sub .125 mm sieve fraction for all samples from Mobridge, SD, Badlands and Cheyenne River, SD localities, and Weston County, WY from the *Baculites compressus* Zone at the base to the first occurrence sands of Fox Hills Formation at the top.

area falls within one standard deviation of both Pettijohn's data and Tourtelot's data.

Figs. 97-101 are graphic tabulations that show percentages of selected whole rock oxides ($SiO_2$, $Al_2O_3$, CaO, and $Fe_2O_3$) and loss on ignition (LOI) for each of the field localities where core samples were collected. These five whole rock parameters were chosen for graphic presentation because they demonstrated the greatest variability in percentage of whole rock composition between samples. On the right side of each graph "depleted" elements are listed if their content in the sample fell beyond one standard deviation below the average of all 81 samples. On the left side of each graph "enriched" elements are listed if their content in the sample fell beyond one standard deviation above the average of all 81 samples. Spikes on the chart are related to composition variations between horizons where samples were collected. The graphs demonstrate that the overall composition of the Pierre Shale is fairly uniform throughout each of the sections. Evaluation of these figures show that geochemical criteria from the sample set are essentially useless for purposes of correlation. The most obvious composition variations reflect that in samples where $SiO_2$ is depleted the CaO content is enriched. In addition, in most samples where the $SiO_2$ content is depleted the $Al_2O_3$ content is also depleted. In most samples where CaO is enriched loss on ignition (LOI) also tends to be higher. This is probably because LOI partly represents $CO_2$ derived from calcite. One other observation from these graphs is that the greatest variation in sample composition occurred within

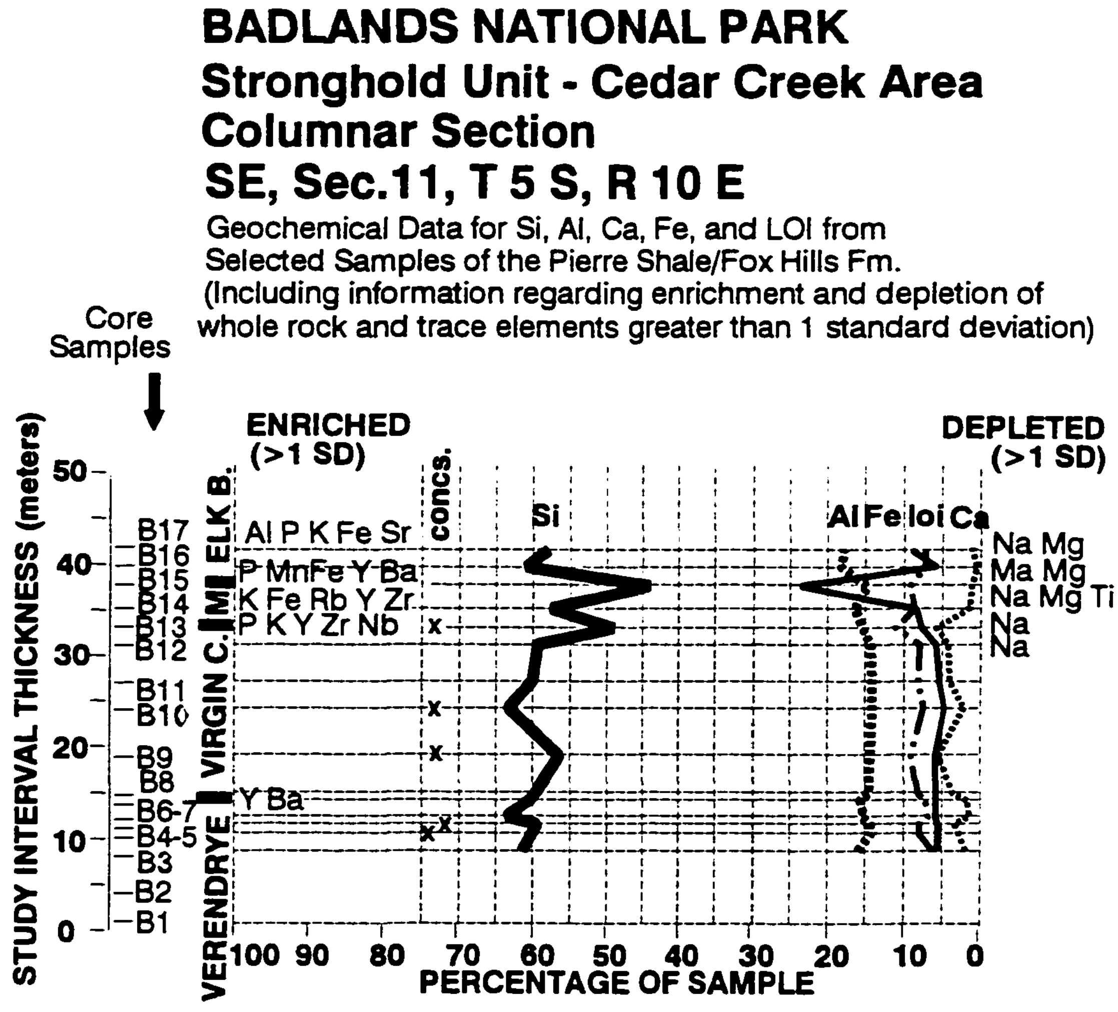
**Mobridge/Grand River Composite Section**
**Corson Co., South Dakota**

Geochemical Data for Si, Al, Ca, Fe, and LOI from Selected Samples of the Pierre Shale/Fox Hills Fm. (Including information regarding enrichment and depletion of whole rock and trace elements greater than 1 standard deviation)



**Data is shown as percent of each dried sediment sample. The geochemical data for Silicon ($SiO_2$), Aluminum ($Al_2O_3$), Calcium (CaO), Iron ($Fe_2O_3$), and volitiles compounds represented as Loss On Ignition (LOI) are presented. Horizontal lines represent data for individual core samples. Core spacing corresponds to core sample spacing displayed on columnar sections in the Field Investigations section of this report. Complete geochemical analyses data tables are presented in Appendix E. An "X" indicates a concretion bed.**

Fig. 97. Geochemical analyses of core samples from localities in the Mobridge/Grand River area, South Dakota.

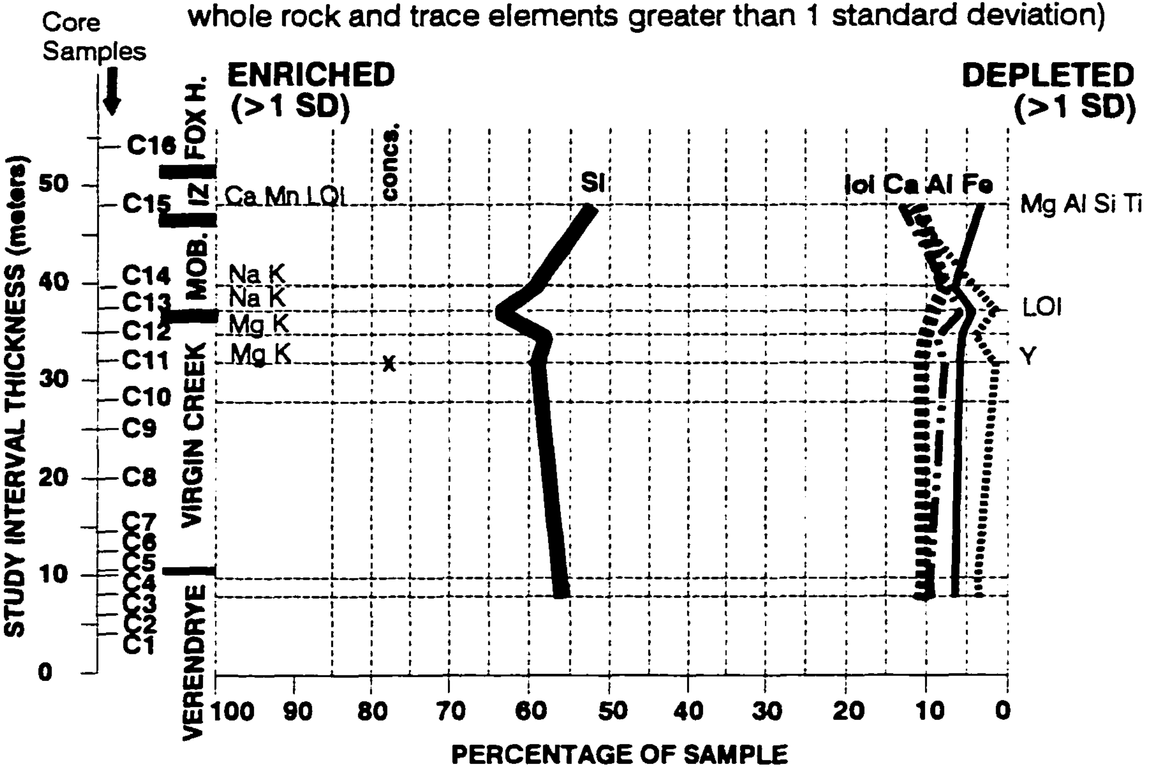


## BADLANDS NATIONAL PARK
## Stronghold Unit - Cedar Creek Area
## Columnar Section
## SE, Sec.11, T 5 S, R 10 E

Geochemical Data for Si, Al, Ca, Fe, and LOI from Selected Samples of the Pierre Shale/Fox Hills Fm. (Including information regarding enrichment and depletion of whole rock and trace elements greater than 1 standard deviation)

**Data is shown as percent of each dried sediment sample. The geochemical data for Silicon ($SiO_2$), Aluminum ($Al_2O_3$), Calcium (CaO), Iron ($Fe_2O_3$), and volitiles compounds represented as Loss On Ignition (LOI) are presented. Horizontal lines represent data for individual core samples. Core spacing corresponds to core sample spacing displayed on columnar sections in the Field Investigations section of this report. Complete geochemical analyses data tables are presented in Appendix E. An "X" indicates a concretion bed.**

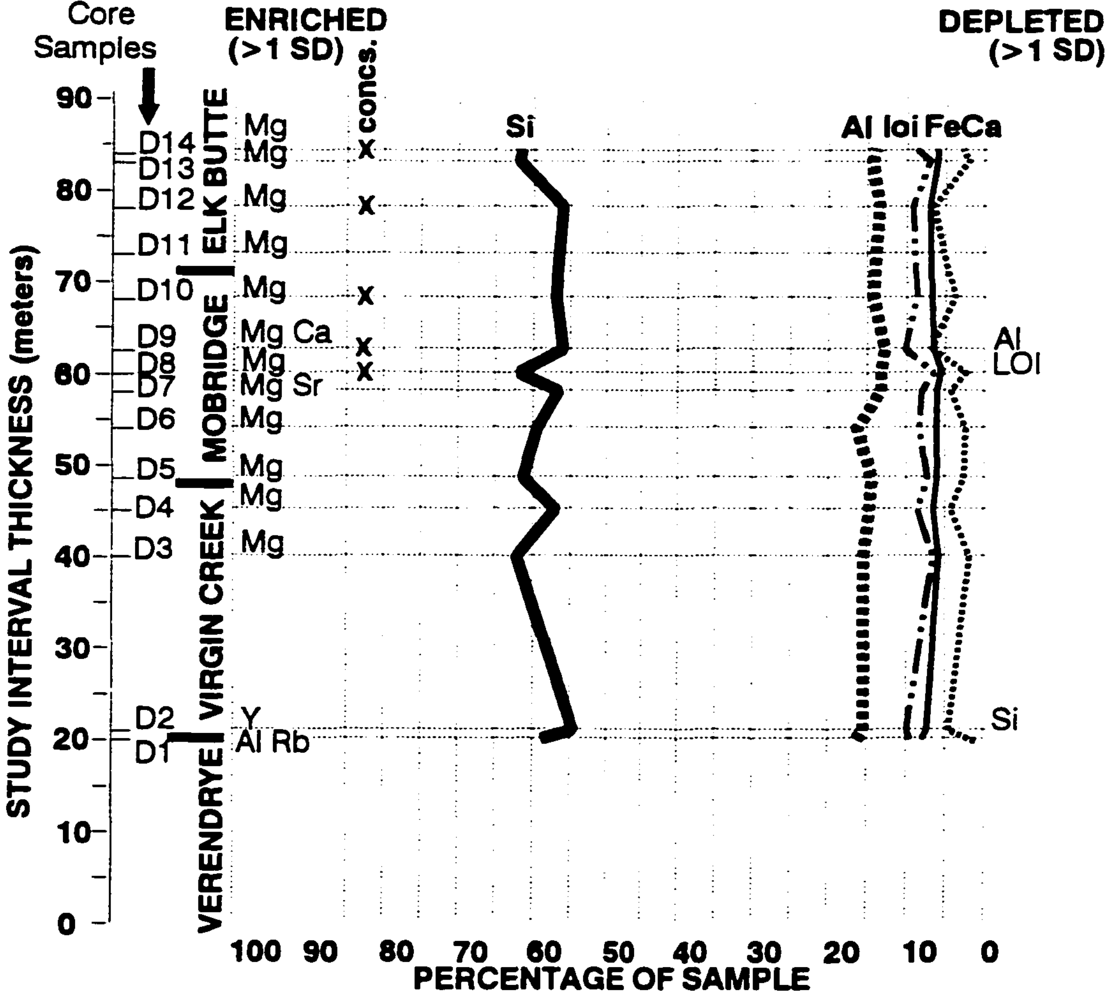
Fig. 98. Geochemical analyses of core samples from the Cedar Creek locality, Badlands National Park, South Unit.



**BADLANDS NATIONAL PARK**
**Sage Creek Campground Area**
Geochemical Data for Si, Al, Ca, Fe, and LOI from
Selected Samples of the Pierre Shale/Fox Hills Fm.
(Including information regarding enrichment and depletion of
whole rock and trace elements greater than 1 standard deviation)

**Data is shown as percent of each dried sediment sample. The geochemical data for Silicon ($SiO_2$), Aluminum ($Al_2O_3$), Calcium (CaO), Iron ($Fe_2O_3$), and volitiles compounds represented as Loss On Ignition (LOI) are presented. Horizontal lines represent data for individual core samples. Core spacing corresponds to core sample spacing displayed on columnar sections in the Field Investigations section of this report. Complete geochemical analyses data tables are presented in Appendix E. An "X" indicates a concretion bed.**

Fig. 99. Geochemical analyses of core samples from the Sage Creek Campground area, Badlands National Park, North Unit.



CHEYENNE RIVER/ELK CREEK
Mr. Tom Trask Ranch
Meade County, South Dakota
Composite Columnar Section

Geochemical Data for Si, Al, Ca, Fe, and LOI from Selected Samples of the Pierre Shale/Fox Hills Fm. (Including information regarding enrichment and depletion of whole rock and trace elements greater than 1 standard deviation)

**Data is shown as percent of each dried sediment sample. The geochemical data for Silicon ($SiO_2$), Aluminum ($Al_2O_3$), Calcium (CaO), Iron ($Fe_2O_3$), and volitiles compounds represented as Loss On Ignition (LOI) are presented. Horizontal lines represent data for individual core samples. Core spacing corresponds to core sample spacing displayed on columnar sections in the Field Investigations section of this report. Complete geochemical analyses data tables are presented in Appendix E. An "X" indicates a concretion bed.**

Fig. 100. Geochemical analyses of core samples from the Tom Trask Ranch localities, Meade County, South Dakota.

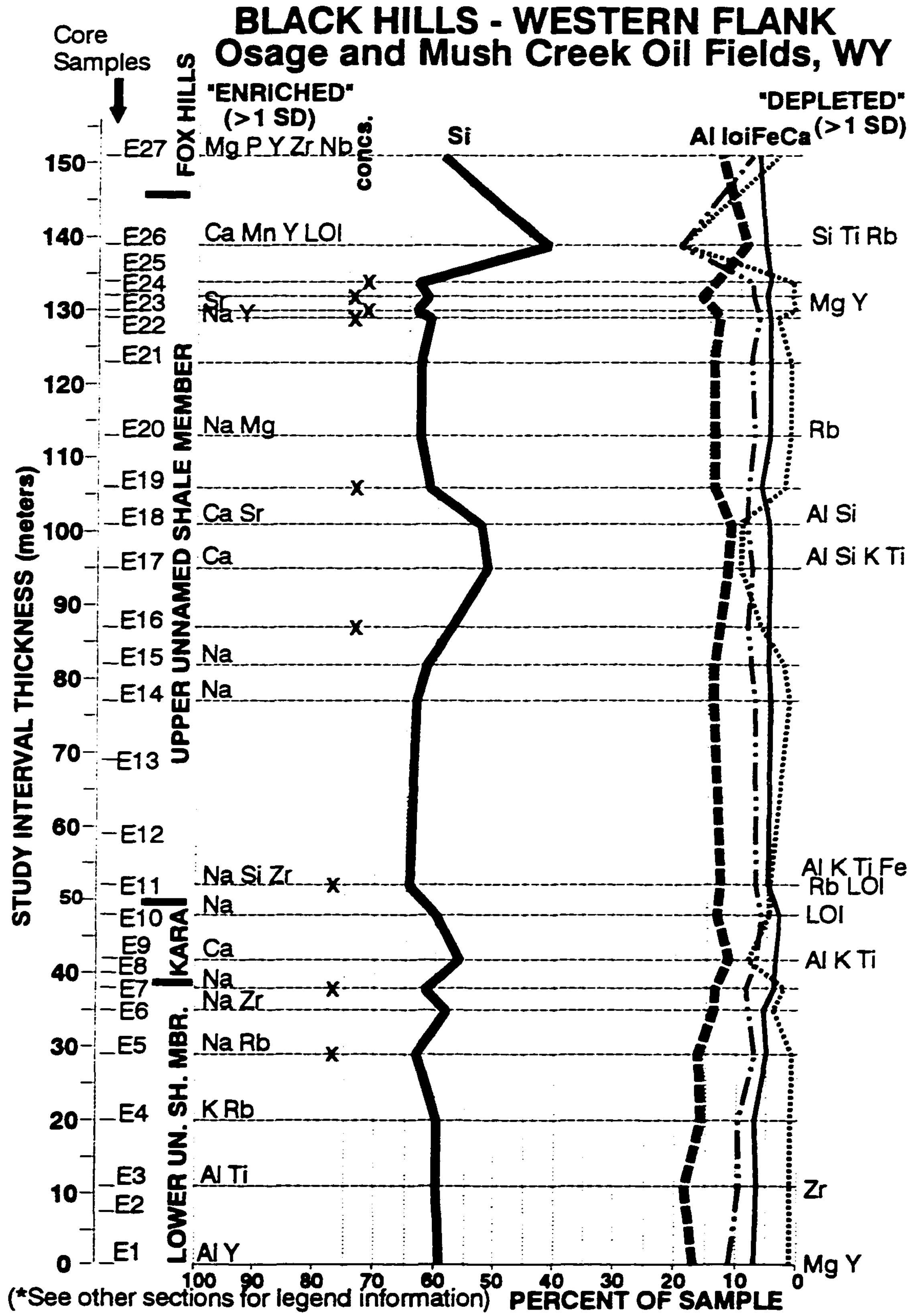


Fig. 101. Geochemical analyses of core samples from the Osage Oil Field and Mush Creek Oil Field localities, Weston County, Wyoming.

samples in the *Baculites grandis* and *Baculites clinolobatus* Zones. Whether these composition variations were related to the occurrence of concretion beds is unclear. Based on these observations statistical analyses were conducted on subsets of the data.

Table IV is a comparison of data from all samples with: 1) subsets of the data for samples that were collected from within or near concretion beds (shown as an "X" on the geochemical section figures), 2) samples that displayed enrichment of CaO (greater than 4% of the sample), and 3) samples that were depleted in CaO (less than 2% of the sample. For samples derived from concretion zones there is a slight correlation towards enrichment of alkaline metals (Na, K) and alkaline earth metals (Mg, Ca). Data for barium is probably related to barite fracture filling that was not detected when samples were prepared. The reasons for barium enrichment is unclear.

For comparison with concretion zones, subsets were generated for samples that were enriched (>4%) and depleted (<2%) in CaO content. Samples that showed enrichment in CaO only showed a slight enrichment for $P_2O_5$, MnO, and Sr. They showed a significant depletion in $SiO_2$ and $Al_2O_3$ (beyond one SD), and slight (statistically insignificant) depletion for all other elements. Conversely, samples that showed depleted values for CaO showed only very slight (statistically insignificant) variation from the mean and SD from all samples, with only slightly higher values for $Al_2O_3$ and $Fe_2O_3$.

Based on the data on Table IV, the slight enrichment of alkaline metals (Na,

# TABLE IV

**Composition of Pierre Shale compared with data from concretion bed samples, Ca enriched samples, and Ca depleted samples**

| | All Samples[1] | Concret. Zones[2] | Ca >4 % enriched[3] | Ca <2 % depleted[4] |
|---|---|---|---|---|
| samples | 81 | 25 | 17 | 19 |
| $Na_2O$ % | 1.15 (.38) | 1.24 (.36) | 1.07 (.34) | 1.07 (.30) |
| MgO % | 2.04 (.47) | 2.14 (.47) | 2.03 (.48) | 1.81 (.43) |
| $Al_2O_3$ % | 14.4 (1.5) | 14.1 (1.0) | 12.8 (1.7) | 15.2 (1.30) |
| $SiO_2$ % | 59.3 (5.0) | 59.4 (5.8) | 53.0 (6.9) | 61.4 (4.3) |
| $P_2O_5$ % | .17 (.09) | .20 (.15) | .22 (.19) | .16 (.05) |
| $K_2O$ % | 2.80 (.57) | 2.83 (.53) | 2.74 (.59) | 2.85 (.57) |
| CaO % | 3.13 (3.29) | 3.58 (3.59) | 7.99 (4.82) | 1.31 (.37) |
| $TiO_2$ % | .61 (.07) | .59 (.06) | .54 (.07) | .64 (.06) |
| $Cr_2O_3$ % | .01 | 0.01 | 0.01 | .00 |
| MnO % | .04 (.05) | .04 (.06) | .06 (.06) | .02 (.02) |
| $Fe_2O_3$ % | 5.93 (2.12) | 5.48 (0.70) | 5.35 (1.00) | 6.46 (3.20) |
| Rb ppm | 105 (19) | 103 (16) | 98 (20) | 109 (20) |
| Sr ppm | 278 (178) | 274 (88) | 319 (98) | 289 (258) |
| Y ppm | 30 (7) | 31 (6) | 33 (7) | 28 (7) |
| Zr ppm | 166 (31) | 165 (24) | 155 (23) | 174 (42) |
| Nb ppm | 12 (2) | 12 (3) | 12 (4) | 12 (2) |
| Ba ppm | 1120(1930) | 810 (198) | 842 (245) | 1560(3045) |
| LOI % | 8.42 (2.21) | 8.34 (2.71) | 10.1 (4.00) | 7.94 (1.33) |

[1] Average composition and standard deviation (SD) of 81 samples analyzed (data from

[2] Average (SD) of 22 samples collected from shale within or near concretion beds (selection based on data in Appendix A).

[3] Average (SD) of 17 samples that displayed greater than 4 % CaO of total composition (samples selected from data in Appendix E).

[4] Average (SD) of 19 samples that displayed less than 2 % CaO of total composition. (samples selected from data in Appendix E)

K) and alkaline earth metals (Mg, Ca) in concretion zones suggests that the sediment in these zones were probably subjected to longer periods of exposure to seawater during periods when sedimentation rates were slower. The mixing of more oxygenated seawater with reduced but saturated pore waters would cause an increase in both eH and pH potential, encouraging precipitation of calcium carbonate enriched in other alkaline and alkaline earth metals below the sediment/water interface (and therefore forming concretions). It is interesting to note that CaO is slightly, but not significantly, enriched in concretion zones. This is perhaps because $CaCO_3$ precipitation was concentrated on the surfaces of growing concretions during early diagenesis (Berner, 1968; Raiswell, 1988; Coleman, 1993).

Table V compares data from three locations in the study area (eastern Wyoming, Badlands National Park - South Unit, and the Mobridge sections) with the complete data set of all samples. Sample averages from all three locations fell within the range of standard deviation values of the complete data set for all elements tested. Slight (yet statistically insignificant) variations occur between the three study areas. The slight enrichment of $Al_2O_3$ and $Fe_2O_3$ and the slight depletion of $Na_2O$, MgO, CaO, $SiO_2$, and LOI in the Badlands National Park, South Unit is consistent with interpretation of meteoric weathering processes (laterite soil development in warm humid climates), both in the vicinity of the Campanian/Maastrichtian boundary unconformity interval and within the Yellow Mounds Weathering Profile. The reason

# TABLE V

**Composition of Pierre Shale compared with data from localities in eastern Wyoming, Badlands NP South Unit, and near Mobridge, SD**

| | All Samples[1] | Wyoming section[5] | Badlands NP South[6] | Mobridge section[7] |
|---|---|---|---|---|
| samples | 81 | 22 | 14 | 23 |
| $Na_2O$ % | 1.15 (.38) | 1.41 (.42) | 0.95 (.30) | 1.09 (.31) |
| MgO % | 2.04 (.47) | 1.99 (.34) | 1.70 (.39) | 1.91 (.34) |
| $Al_2O_3$ % | 14.4 (1.5) | 13.8 (1.90) | 15.0 (1.3) | 14.8 (1.5) |
| $SiO_2$ % | 59.3 (5.0) | 59.2 (4.8) | 58.5 (5.3) | 60.4 (6.2) |
| $P_2O_5$ % | .17 (.09) | .16 (.04) | .20 (.21) | .15 (.06) |
| $K_2O$ % | 2.80 (.57) | 2.66 (.44) | 3.10 (.67) | 2.47 (.52) |
| CaO % | 3.13 (3.29) | 3.91 (4.10) | 2.52 (1.46) | 2.59 (3.65) |
| $TiO_2$ % | .61 (.07) | .59 (.08) | .59 (.07) | .63 (.06) |
| $Cr_2O_3$ % | .01 | .01 | .01 | .01 |
| MnO % | .04 (.05) | .03 (.04) | .03 (.03) | .04 (.07) |
| $Fe_2O_3$ % | 5.93 (2.12) | 5.50 (1.00) | 7.29 (4.60) | 5.70 (.67) |
| Rb ppm | 105 (19) | 99 (27) | 116 (21) | 96 (16) |
| Sr ppm | 278 (178) | 301 (110) | 386 (353) | 220 (52) |
| Y ppm | 30 (7) | 29 (7) | 33 (9) | 29 (5) |
| Zr ppm | 166 (31) | 160 (21) | 178 (48) | 163 (37) |
| Nb ppm | 12 (2) | 11 (2) | 12 (3) | 13 (2) |
| Ba ppm | 1120(1930) | 810 (151) | 2424(4461) | 833 (142) |
| LOI % | 8.42 (2.21) | 8.19 (2.57) | 7.89 (.98) | 9.17 (2.70) |

[1] Average composition and standard deviation (SD) of 81 samples analyzed (data from Appendix E).

[5] Average (SD) of 22 samples collected from Osage and Mush Creek Oil Field Localities in Weston County, Wyoming.

[6] Average (SD) of 14 samples collected from the South Unit of Badlands National Park, South Dakota.

[7] Average (SD) of 23 samples collected from the Mobridge/Grand River localities, SD.

for a slightly higher sodium content in the Wyoming samples is unclear.

Table VI compares samples from select stratigraphic intervals across the study area with the complete data set. Each of the subsets of data for the members were chosen using ammonite range zones that correspond to the members of the Pierre Shale: Mobridge Member (*Baculites clinolobatus*), Virgin Creek Member (*Baculites baculus/grandis*), and Verendrye Member (*Baculites compressus/cuneatus/reesidei*). Once again, the data demonstrates that each of the members of the Pierre examined varies only slightly from the composition of the whole data set. One surprising variation is that the sample set chosen for the Virgin Creek Member showed a slightly higher CaO content than the Mobridge Member, demonstrating that the "acid fizz test" (Mello, 1969) is not a reasonable method for determining whether the sediment of the *Baculites clinolobatus* Zone is part of the Mobridge Member. In addition, $SiO_2$ and $Fe_2O_3$ are slightly depleted in the Virgin Creek Member. The lower $SiO_2$ content is possibly at the expense of the higher $CaCO_3$ content. The reason for the lower $Fe_2O_3$ content in the Virgin Creek Member is unclear. It could be related a general rise in sea-level during *Baculites baculus/grandis* time which reduced the influx of terrestrial- derived sediments to the study area region. This might also explain the slightly higher CaO content in the Virgin Creek Member.

# TABLE VI

## Composition of Pierre Shale compared with data from all samples collected from the Mobridge Member (*Baculites clinolobatus* Zone) and from the Verendrye Member in the Badlands NP region

| | All Samples[1] | Mobridge Member[8] | Virgin Crk Member[9] | Verendrye Member[10] |
|---|---|---|---|---|
| samples | 81 | 19 | 18 | 11 |
| $Na_20$ % | 1.15 (.38) | 1.22 (.29) | 1.26 (.38) | 1.32 (.39) |
| MgO % | 2.04 (.47) | 2.25 (.53) | 2.19 (.36) | 2.05 (.35) |
| $Al_2O_3$ % | 14.4 (1.5) | 14.5 (.85) | 14.3 (1.5) | 15.2 (.98) |
| $SiO_2$ % | 59.3 (5.0) | 59.0 (4.6) | 58.2 (4.0) | 59.9 (2.1) |
| $P_2O_5$ % | .17 (.09) | .18 (.06) | .19 (.18) | .14 (.02) |
| $K_2O$ % | 2.80 (.57) | 3.11 (.46) | 2.70 (.70) | 3.02 (.21) |
| CaO % | 3.13 (3.29) | 2.67 (1.5) | 3.69 (2.25) | 1.95 (1.07) |
| $TiO_2$ % | .61 (.07) | .61 (.06) | .59 (.06) | .62 (.06) |
| $Cr_2O_3$ % | .01 | .01 | .01 | .01 |
| MnO % | .04 (.05) | .04 (.03) | .04 (.03) | .03 (.03) |
| $Fe_2O_3$ % | 5.93 (2.12) | 6.47 (4.0) | 5.53 (.59) | 5.92 (.60) |
| Rb ppm | 105 (19) | 105 (11) | 101 (18) | 117 (10) |
| Sr ppm | 278 (178) | 287 (121) | 293 (83) | 243 (83) |
| Y ppm | 30 (7) | 28 (7) | 30 (6) | 30 (5) |
| Zr ppm | 166 (31) | 162 (14) | 161 (15) | 163 (18) |
| Nb ppm | 12 (2) | 12 (2) | 12 (1) | 12 (1) |
| Ba ppm | 1120(1930) | 1767(3642) | 869 (223) | 1337(1967) |
| LOI % | 8.42 (2.21) | 7.95 (1.40) | 7.91 (.59) | 7.96 (1.11) |

[1] Average composition and standard deviation (SD) of 81 samples (Appendix E).

[8] Average (SD) of 19 samples collected from the Mobridge Member represented by the *Baculites clinolobatus* Zone from all five sample localities.

[9] Average (SD) of 18 samples collected from the Virgin Creek Member represented by the *Baculites baculus/grandis* Zones from all five sample localities.

[10] Average (SD) of 11 samples collected from the Verendrye Member in South Dakota from equivalent strata in the Osage Oil Field, Wyoming locality.

## 9.3 SEDIMENTARY PROCESSES AND PATTERNS

This section is an examination and interpretation of small and large scale bedding features. Discussion begins with estimations of sedimentation rates through time across the study area. Discussion follows about the identification and interpretation of sedimentary processes and patterns related to selected bedding features observed in the field, including bentonite beds, bioturbation and ichnofacies, storm deposits, concretions, clinoform-style mudbank features, and paleosols. Each of these factors add evidence to support the interpretation of sequence stratigraphy and the geologic history or the study interval (discussed in Chapter 10).

### 9.3.1 Sedimentation Rates

Gill & Cobban (1973) presented estimates of sedimentation rates based on the thicknesses of ammonite range zones across the Western Interior Basin. Their estimates demonstrate that along the western margin of the seaway sediments accumulated at a rate of about one meter per thousand years whereas in the eastern margin region (in central South Dakota) sedimentation rates accumulated at a rate of about 10 cm to 20 cm per thousand years (Fig. 102). By comparison, sands and silts deposited on modern continental shelf environments commonly accumulate at rates of +10 cm per thousand years (Gross, 1972). Estimates by Winn, Bishop & Gardner (1987) suggest that maximum water depth of the seaway during *Baculites clinolobatus*

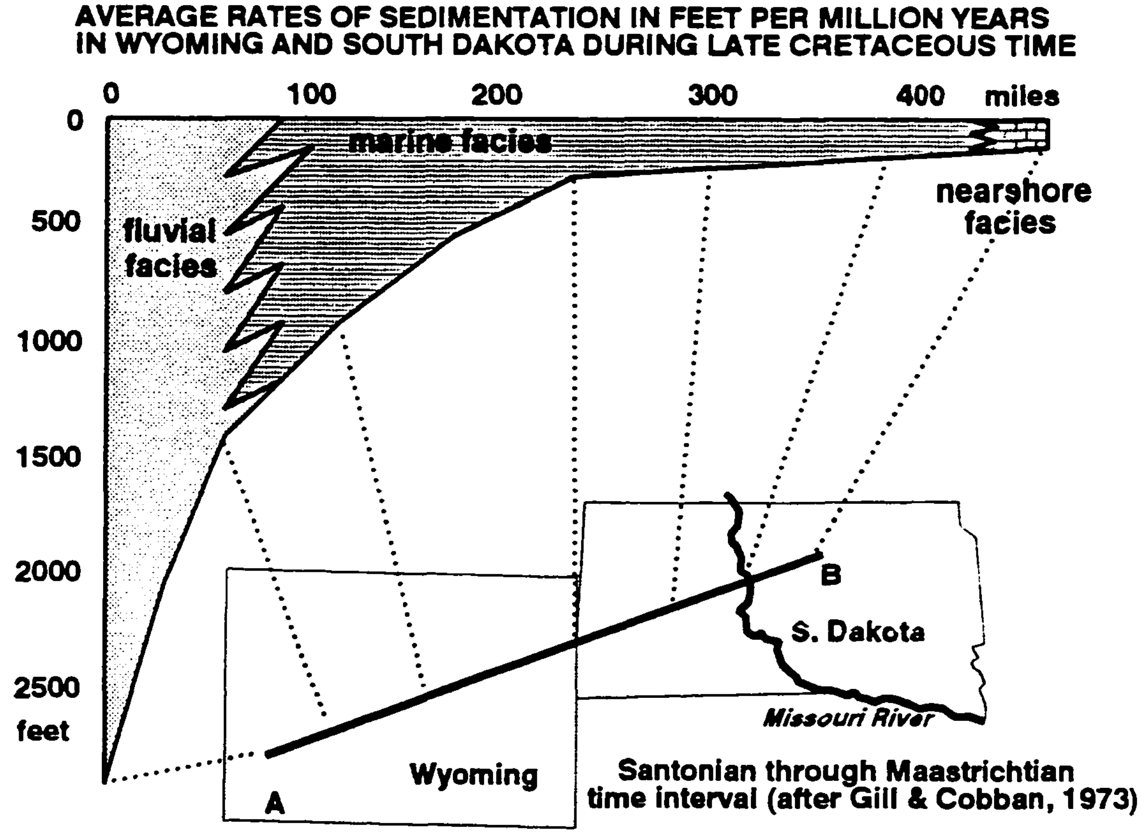


Fig. 102. Estimates of sedimentation rates across the Western Interior Basin (after Gill & Cobban, 1973).

time was in the range of 200 meters in the central basin area of central Wyoming. This demonstrates that sedimentation processes affecting the central basin area of the Western Interior Seaway are analogous to processes occurring on modern continental shelf environments.

Table VII is an estimate for sedimentation rates in the study area using Gill & Cobban's (1973) method of measuring the thicknesses of ammonite range zones. The estimates for each zone varies considerably, with the highest rates of accumulation occurring during *Baculites grandis* time in eastern Wyoming (70 cm/1000 years) and in Badlands National Park (50 cm/1000 years). Sedimentation rates are slow in the Mobridge/Grand River area until deposition of the Elk Butte Member, when sedimentation rates were about 75 cm/1000 years. Slowest periods of sedimentation occurred during *Baculites compressus/cuneatus* time in Wyoming and South Dakota, and *Baculites jenseni/eliasi* time when non-deposition or erosion were occurring in South Dakota.

Table VII shows that the overall sedimentation rate in the Badlands National Park area was nearly half the rate of sedimentation in both eastern Wyoming and in the Mobridge/Grand River area. The slower sedimentation rate in the Badlands region is a result of the period of non-deposition or erosion along the Campanian-Maastrichtian boundary unconformity, and probably to an overall slower rate in the region probably due to shallower water depths. The higher sand fraction in the

# TABLE VII

## Comparison of sedimentation rates during the accumulation of ammonite range zones in eastern Wyoming, Badlands NP - North Unit, and the Mobridge area, South Dakota

| AMMONITE ZONE[1] | $^{87}$Sr/$^{86}$Sr AGE (duration) in Ma[2] | Wyoming section Thickness m (accum. rate) (cm/Ka) | Badlands NP section Thickness m (accum. rate) (cm/Ka) | Mobridge section Thickness m (accum. rate) (cm/Ka) |
|---|---|---|---|---|
| *Hoploscaphites nicolleti* | 68.8<br>(.5) | | | 20 m<br>40 cm/Ka |
| *Hoploscaphites birkelundi* | 69.3<br>(.6) | 20 m<br>33 cm/Ka | 5 m<br>10 cm/Ka | 45 m<br>75 cm/Ka |
| *Baculites clinolobatus* | 69.7<br>(.5) | 18 m<br>36 cm/Ka | 10 m<br>20 cm/Ka | 20 m<br>40 cm/Ka |
| *Baculites grandis* | 70.2<br>(.5) | 35 m<br>70 cm/Ka | 25 m<br>50 cm/Ka | 12 m<br>24 cm/Ka |
| *Baculites baculus* | 70.7<br>(.5) | 22 m<br>44 cm/Ka | 5 m<br>10 cm/Ka | 8 m<br>16 cm/Ka |
| *Baculites eliasi* | 71.2<br>(.5) | 20 m<br>40 cm/Ka | 0 | 8 m<br>16 cm/Ka |
| *Baculites jenseni* | 71.7<br>(.5) | 10 m<br>20 cm/Ka | 0 | |
| *Baculites reesidei* | 72.2<br>(.4) | 20 m<br>50 cm/Ka | 5 m<br>13 cm/Ka | |
| *Baculites cuneatus* | 72.6<br>(.5) | 5 m<br>10 cm/Ka | 5<br>10 cm/Ka | |
| *Baculites compressus* | 73.1<br>(.8) | 5 m<br>6 cm/Ka | 5 m<br>6 cm/Ka | |
| TOTAL FOR SECTION | 4.7 Ma | 154 m<br>37 cm/Ka | 60 m<br>14 cm/Ka | 110 m<br>35 cm/Ka |

[1] Ammonite Zones after Cobban (1993). The Elk Butte Member and the Interior Zone are included in the *Hoploscaphites birkelundi* Zone.

[2] Interpolated $^{87}$Sr/$^{86}$Sr dates after McArthur et al., (1994). Time ranges are the difference between the age of the zone subtracted from the age of the previous (older) zone.

sediment in the Badlands region suggests that currents in shallower water conditions helped to winnow the finer sediment fractions away from the area. During the interval between *Baculites eliasi* to *Baculites clinolobatus* time sedimentation rates were high along the western flank of the Black Hills and relatively low in the Mobridge/Grand River area. The rapid pace of sedimentation during *Hoploscaphites birkelundi* time in the Mobridge/Grand River area is an indication of the rapid eastward regression at the close of Pierre Shale deposition. The slowdown in deposition during *Hoploscaphites nicolleti* time supports the hypothesis that a transgression occurred in the region at that time.

### 9.3.2 Bedding Features

Weathering and mass wasting destroy most bedding features on outcrops in the field area. Only the freshest exposures in cutbanks and recent excavations reveal bedding structures in the unconsolidated mudrocks. Only the more resistant materials, such as concretions and cemented sandstones, preserve a variety of sedimentary structures and bioturbation features. This section discusses selected bedding features that range in scale from a single bed to a sequence of units, and provides interpretations of their origin and their significance in the geologic history of the seaway. Topics addressed include bentonite beds, bioturbation features, storm deposits, concretion beds, mudbank structures, and weathering profiles. Some or all of these features are found in every outcrop examined.

### 9.3.2.1 Bentonite beds

In addition to their value for absolute dating and correlation, the occurrence of bentonite beds in the Pierre Shale provides a variety of useful paleoenvironmental information. Bentonite beds represent ash fall events from volcanic source areas on the western margin of the seaway (Gill & Cobban, 1973). For instance, the Ardmore Bentonite in the lower Pierre Shale has been correlated from central Montana into easternmost South Dakota (Dyman et al., 1994). The existence of bentonite beds in the Pierre Shale demonstrate that the prevailing wind in the Western Interior region during the Late Cretaceous was directed from west to east as is the case with wind patterns in mid-latitude regions of the world today. Gill & Cobban (1966) hypothesized that the occurrence of bentonite beds in shallow marine environments of the Pierre Shale throughout the Western Interior region is an indication that the Late Cretaceous climate in the region generally did not produce weather extremes typical of the modern world.

Bentonite beds also provide information about water depths and bioturbation activity. Gill & Cobban (1966) suggested that water depths in eastern Wyoming were less than 200 feet for all members of the Pierre Shale above the base of the Lower Unnamed Shale Member in the Redbird, Wyoming area. They suggested that wave base in the Western Interior Seaway was generally in the range of 35 to 90 feet in the Western Interior Seaway, with the shallower range of wave base occurring closer to shore. They interpreted that the occurrence of bentonite beds is an indication of greater water depths.

It is apparent that bentonite beds are abundant in certain horizons, whereas equivalent strata elsewhere may lack bentonite beds. If water turbulence is a function of depth, then where other current-related bedding structures are absent bentonite beds are a good indicator of water depth. Using Gill & Cobban's range for wave base, bentonite beds are an indication of water depths in the range of at least more than 35 feet and more likely, greater than 90 feet.

Bentonite beds were observed throughout the Pierre Shale, with certain intervals displaying a greater abundance of bentonite beds (with better preservation) than others. The most significant bentonite unit, the Kara Bentonitic Member, is apparent on the western flank of the Black Hills but is missing or not recognized on the eastern flank of the Black Hills. Although the ash falls that produced the Kara Bentonitic Member may not have affected the eastern flank of the Black Hills, the extensive occurrence of other bentonite zones suggests otherwise (such as the Adrmore Bentonite which is recognized throughout Wyoming and South Dakota). This observation suggests that an unconformity in the region on the eastern flank of the Black Hills with non-deposition and erosion enduring throughout *Baculites* *jenseni/eliasi* time.

In the Badlands National Park area bentonite beds were observed in the *Baculites reesidei* Zone, and in the *Baculites baculus/grandis/clinolobatus* Zones. Bentonite beds are not apparent in the Interior Zone or in the Fox Hills Formation. Thin, well preserved, closely spaced bentonite beds in the *Baculites baculus* Zone (lower Virgin Creek Member) suggest that sea level was high and sedimentation rates were slow across the South Dakota region at that time. The lack of bentonite beds in the Interior Zone, but the occurrence of bentonite beds in equivalent strata on the Elk Butte Member is another indication of greater water depths in the Missouri River Valley region compared with shallower depths in the Badlands region.

#### 9.3.2.2 Bioturbation Features

Gill & Cobban (1966) noted that bedding structures are scarce or absent above the base of the Lower Unnamed Shale Member in the Redbird, Wyoming section. They attributed the lack of bedding structures to the activity of sediment feeding organisms. As demonstrated by the sieve fraction analyses, the content of the clay, silt, and sand fractions of the poorly consolitated sediment vary considerably throughout the study interval, and that the sand fraction in all Pierre Shale samples are intraformational in origin. Cemented mud grains (pelloids and pellets), glauconite, calcite grains derived from shell material were probably generated mostly by sediment feeding organism.

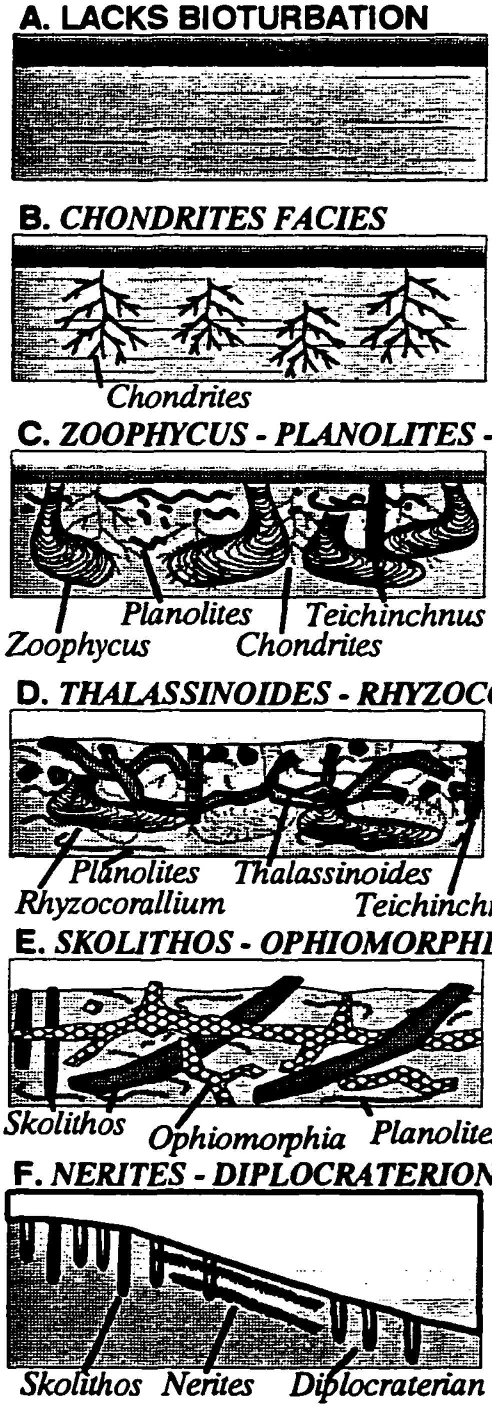
Appendix B includes general descriptions of lamination characteristics and bioturbation features in the core samples collected throughout the study area. Study of the core samples yielded some general observations about bedding structures and bioturbation in the shale. In sediments where lamination is not obvious there is usually a high degree of bioturbation. In samples where bioturbation had not destroyed all the lamination, the finest-grained, organic-rich sediments typically displayed paper-thin laminated bedding. Silty to sandy sediment typically preserve evidence of current-formed structures such as ripple bedding and cross-bedding where these structures have not been destroyed by bioturbation.

Savrda & Bottjer (1989) suggested that the range in size and complexity of bioturbation networks are directly related to availability of oxygen in the substrate and the rate of sediment accumulation. They demonstrate that in substrates where oxygen concentrations were high, burrows tend to be larger, there is a greater variety of trace patterns, and bioturbation tends to be more thorough. In sediments of the Western Interior Seaway they demonstrated that trace fossil patterns frequently changed from one series of beds to the next. They interpreted these changes as a reflection of changing oxygen levels and sedimentation rates in the seaway. They suggested that, in general, where sedimentation rates were higher, oxygen levels were probably lower due to higher concentrations of organic matter in the water column available for oxidation. Low oxygen levels in the lower water column was possibly a reflection of stratification due to evaporative concentration of seawater and stagnation of denser water in the deeper water setting (similar to the modern Black Sea)(Kauffman, 1984; Kauffman & Sageman, 1990; Wright, 1987). However, the abundance of bioturbation features throughout the upper Pierre Shale in the study area suggests that stagnation was the exception rather than the rule.

Fig. 103 illustrates bioturbation features that represent generalized ichnofacies that I observed in the Pierre Shale and Fox Hills Formation throughout the study area. Bioturbation ranges from little or none in some horizons, to pervasive in others to the point that the sediment is nearly homogeneous in appearance with individual traces being difficult or impossible to discern. In general, ichnofacies are difficult to see in the shale, but are very apparent on the weathered surfaces of many concretions. Each of the different ichnofacies are gradational with other ichnofacies. References used for identifying inchnofossils used in this investigation include Maples & West (1992), Hasiotis, Brown, & Abston (1994), and Savrda & Bottger (1989). Examples of the various ichnofacies are presented below.

Examples where the sediment lacks biotubation (Fig. 103-A) include portions of the Elk Butte Member in the Mobridge/Grand River area where the shale is very black, possibly deposited in highly restricted, anoxic conditions when the size of the seaway was greatly reduced. Another example of sediments that lack bioturbation,

## ICHNOFACIES OF THE PIERRE SHALE AND FOX HILLS FORMATION



**A. LACKS BIOTURBATION**

finely laminated or lacks bedding structures
fine-grained shale or silty shale, bentonites
fossils are scarce
intermediate to deep water depths, anoxic benthic waters, high sedimentation rate

**B. *CHONDRITES FACIES***

finely laminated or lacks bedding structures
claystone, siltstone, bentonite beds
scarce baculites
intermediate to deep water, hypoxic benthic waters, medium to high sedimentation rate

**C. *ZOOPHYCUS - PLANOLITES - CHONDRITES FACIES***

thinly-laminated or destroyed bedding
claystone or siltstone, concretions common, discontinuous bentonite beds
inoceramids and baculites common
intermediate water depts, slighty hypoxic conditions, medium sedimentation rate

**D. *THALASSINOIDES - RHYZOCORALLIUM FACIES***

thick lamination or destroyed bedding
silty shale to sandstone, concretions bentonite beds discontinuous or missing
ammonites, shallow marine fauna
shallow to intermediate depths, normal marine water, medium sedimentation rate

**E. *SKOLITHOS - OPHIOMORPHIA FACIES***

thickly laminated or destroyed bedding
silty shale to sandstone, concretions bentonite beds are destroyed
bivalves, arthropods, mollusk fragments
shallow to nearshore depths, normal marine waters, low to medim sedimentation rate

**F. *NERITES - DIPLOCRATERION - SKOLITHOS FACIES***

ripple bedding, drag marks, flute casts
sandstone, sandy shale, glauconitic sandstone, Bouma sequence beds, concretions
fossil wood, reworked fossil debris
prodelta and offshore mudbank, shallow to intermediate depths, medium to high sedimentation rates

Fig. 103. Bioturbation features representing ichnofacies in sediments of the Pierre Shale and Fox Hills Formation observed in outcrops throughout the study area.

but from a different cause, are the sediments within portions of the Interior Zone and the Fox Hills in Badlands National Park where dissolution by Yellow Mounds-style weathering as essentially destroyed all evidence of bioturbation and bedding structures.

*Chondrites* are thin traces that have a up-side-down tree-like structure. *Chondrites* can occur with other traces, however, the ***Chondrites*** facies represents rocks that display only *Chondrites*. *Chondrites* facies (Fig. 103-B) are most obvious in bentonite horizons and in concretions that occur where bentonite beds are present. The lower Virgin Creek Member in the Badlands National Park region displays *Chondrites* facies. On White Butte the lower portion of the Virgin Creek Member still maintains original bedding structures which have not been completely destroyed by *Chondrites*-type bioturbation. Savrda & Bottger (1989) suggested that sediments that bear only *Chondrites* indicates low oxygenation conditions in the benthic environment.

*Zoophycus* - *Planolites* - *Chondrites* facies (Fig. 103-C) occurs in many horizons in the Verendrye, Virgin Creek and Mobridge Member Members in the Badlands National Park Region and in the Cheyenne River Valley. It is perhaps the most typical ichnofacies of the upper Pierre Shale. Savrda & Bottjer (1989) suggested that the co-occurrence of three types of ichnofossils indicates slightly hypoxic conditions in the benthic environment. Where thicker bentonite beds occur within these facies they are typically highly disrupted and are locally completely destroyed. *Planolites* are sinuous traces typically no thicker than a pencil, and generally follow bedding surfaces which indicates that they represent organisms that probably lived near the sediment-water interface. In some places *Planolites* traces are pervasive throughout the sediment. *Zoophycus* are deep-penetrating traces that display progressive feeding tracks that radiate away from a central feeding tube. The furrowed appearance of *Zoophycus* was generated when a worm-like organism would scoop out sediment adjacent to its previous pass through the sediment. An additional trace, *Teichinchnus*, is a U-shaped feeding trace that displays a progressive feeding method similar to *Zoophycus*, but is much smaller and occurs in a vertical plane only. *Teichinchnus* occurs with these traces in some horizons.

*Thalassinoides - Rhyzocorallium* facies also include traces of *Zoophycus*, *Planolites*, *Zoophycus*, and abundant *Teichinchnus* but they are typical destroyed by the overprint of the larger *Thalassinoides* and *Rhyzocorallium* traces (Fig. 103-D). This facies is most evident on concretions in the *Baculites grandis* and *Baculites clinolobatus* zones in the Osage Oil Field area, Wyoming, and in the *Baculites compressus/cuneatus* Zones in Badlands National Park region. The facies also occurs in the fossil-rich concretions in the Fox Hills in the Grand River Valley area, South Dakota. The large bioturbation networks in the Cedar Creek area (Fig. 37, p. 121) is an example of this facies. According to Savrda & Bottjer (1989) the occurrence of

*Thalassinoides* suggests high oxygen levels in normal marine waters. These facies probably represent water depths close to wave base where wave agitation was able to recirculate a constant supply of oxygen to the seabed. Where this ichnofacies occurs there is typically the highest concentration and diversity of shell materials and other fossils. *Thalassinoides* is recognizable as a series of round tube-like traces with passage connections. Massive networks of *Thalassinoides* often have the appearance of a hopelessly tangled garden hose or *very large* spaghetti. *Rhyzocorallium* is similar to *Zoophycus*, but is made by a much larger organism, and its progressive feeding traces show that it utilized the entire infaunal zone.

*Skolithos* - *Ophiomorphia* ichnofacies (Fig. 103-E) occurs in the glauconitic marl and sandy portions of the Fox Hills Formation in the Cheyenne River Valley in the Powerlines Locality. It also was recognized in concretions in the uppermost *Baculites clinolobatus* Zone in the Osage Oil Field area, Wyoming. In the Osage Oil Field area these traces occurred as an overprint on *Thalassinoides*, *Planolites*, and possibly other traces. The occurrence of this facies within sandy beds suggests that the facies represents shallow to nearshore facies. *Skolithos* is a vertical trace created by bivalves. *Skolithos* sometimes is a thick round trace that forms an inclined but relatively straight passage without connections. *Ophiomorphia* shows straight to sinuous passages with numerous intersections. The surfaces of *Ophiomorphia* have a corn cob-like appearance due to balls of fecal material packed along the sides or filling the passageways.

Sandstone beds in the Interior Zone and the lower Fox Hills Sandstone in Badlands National Park preserved *Nerites - Diplocraterion - Skolithos* facies (Fig. 103-F). These traces occur where sediments were deposited on gently inclined bedding surfaces in a pro-delta or offshore mudbank environment in shallow to intermediate depths. An example of a sand sheet displaying this facies is shown in Fig. 26, p. 72). *Nerites* are crawling traces the have imprints of leg-like appendages on either side of a straight sediment feeding trace. *Diplocraterion* are U-shape resting traces that are expressed as two closely spaced holes on a bedding surface. *Skolithos* in this facies are generally not as large, and are typically more vertical, than are the *Skolithos/Ohiomorphia* facies.

#### 9.3.2.3 Storm Deposits

Sediments derived from rivers along the western Cordilleran Ranges accumulated as vast sediment wedges along the western margin of the seaway. These clastic wedges advanced eastward during periods of regression (McGookey et al., 1972; Gill & Cobban, 1973; Roehler, 1993). Whereas regional structural patterns were significant in controlling the location of sediment sources (rivers) and basin geometry (shorelines and subsiding basins), the critical factor controlling sedimentation in the central and eastern basin areas appears to have been basin circulation patterns and eustatic changes in sea level (Gill & Cobban, 1973; Wright, 1987; Dyman et al., 1994). Perhaps a very significant force in controlling sedimentation in the central and eastern portions of the seaway region was the occurrence of storms (summer hurricanes and winter cyclonic storms).

The effects of storms on modern nearshore environments are well known, particularly in the Gulf of Mexico region where offshore drilling platforms must be designed to withstand hurricane force winds and currents. Less is known about the effects of storms on intermediate depths to the deepest portions of the seaway. Turbidites are known from the central Wyoming region where water depths were probably in the range of 200 meters (Winn, Bishop & Gardner, 1987). Storm deposits are recognized as graded beds ranging in thickness from several centimeters to several meters, and are most obvious in shelf and nearshore environments. The graded pattern of the sediment is essentially the same as turbidity flow deposits, except that the sediment preserve characteristics of shallow water settings, particularly the occurrence of omission surfaces and shallow water benthic fauna and ichnofacies consistent with higher oxygenating conditions. Morton (1988) described the influences of Gulf Coast hurricanes on sediment redistribution patterns on the sea bed in relation to drilling structures, and documented both sediment erosion and accumulation in the range of several meters in a single storm event. Studies of modern depositional processes on the sand-starved, mud dominated outer Texas shelf are probably a reasonable corollary of sedimentation processes associated with the deposition of Late Cretaceous sediments in the Western Interior Seaway.

The relationship of storm-wave energy to storm-driven currents is complex. Wave base (the depth to which wave energy extends in a downward direction) in normal seas is approximately equivalent to one-half the wavelength (the distance between two wave crests)(Victor Goldsmith, personal commumication, 1995). During storms wave speeds and wavelength increase. This causes wave base to increase to depths of about 90 meters or more below the sea surface during great storms. The significance of wave energy as a mover of sediment diminishes with increasing depth until at wave base, waves are completely insignificant in relation to storm-generated bottom currents. Storm-generated bottom currents can attain speeds capable of moving boulders in shallow to moderate depths on the continental shelf, and are a significant triggering force behind gravity displaced slumps and turbidity flows (Morton, 1988; Friedman et al., 1992). According to Victor Goldsmith (personal communication, 1995) the circulation pattern of storm generated currents are not necessarily equivalent to the direction in which surface waves or wind propagate. Such circulation patterns are also controlled, in part, by the geometry of shorelines, water depth, submarine structures, and density stratification in the water column. The importance of both wave and current energy depends more on storm duration than it does on storm intensity. Storm currents are responsible for most sediment transport in modern shelf environments (Morton, 1988) In the study area storm currents are probably very significant to the origin of graded silty and sandy deposits.

Bathymetric studies on the Gulf shelf after Hurricane Camille suggest that topographic changes on the sea floor induced by storm generated sediment transport ranged from +2 m to -10 m; graded beds produced by the storm range in thickness from several decimeters to several meters (Morton, 1988). The greatest of these changes were associated with slope failure and mass movement of heavily water-saturated sediments lying at depths below normal wave-base. These observations suggest that waves and currents associated with tropical and extra-tropical storms are capable of eroding vast quantities of nearshore sediment and redistributing it over extensive areas of the shelf. In greater water depths the influence of density currents triggered by storm activity can redistribute fine-grained sediment for great distances across the basin.

Morton (1988) suggested that an individual graded bed is not necessarily the result of a single storm, but rather may represent sediments being transmitted offshore by a series of moderately intense events, and later selectively sorted during a single extreme storm lasting several days. On the Texas shelf water-saturated sediments associated with the post-Pleistocene (Flandrian) transgression range in thickness from +40 m near deltas along the coast to a thin veneer (~2 m) elsewhere. In the vicinity of deltas along the Gulf Coast shelf mud grades upward into storm deposits interlayered with mud. In the sediment-deprived regions the thin veneer of sediments is continuously being reworked. These modern sediments overlie stiff relict sediments that display evidence of dewatering and compaction (Morton, 1988).

Currents and biological mixing modify the post-storm stratification and sediment textures (Morton, 1988). In sand-starved regions, such as the central basin and eastern margin region of the Western Interior Seaway, storm-deposits would consist of graded sandy silt and silty mud (due to the general lack of sand). In sandier environments hummocky cross-stratification and ripple bedding are evident (as in the top Interior Zone in the North Unit of Badlands National Park, and lower undifferentiated marine Fox Hills in the Cheyenne River valley). Poorly consolidated siltstone and mudstone deposits generally do not reveal stratification characteristics in outcrop, particularly where they have been heavily reworked by bioturbation.

Fig. 52 (p. 158) is a photograph of beds that probably represent storm-generated deposits in the base of the Fox Hills Formation in the Roberts Prairie Dog locality. These beds have many similarities of a Bouma sequence, having a basal graded sand unit, overlain by contorted beds of silty sediment, which is overlain by a thin clay-rich unit beneath the next overlying sand sheet. However, the proximity of this unit to the crest of the Sage Creek Anticline suggests that instead of having been deposited on fans in deeper water environments, these graded-beds probably represent storm-generated sediment accumulation on a prograding mudbank. The bottom sides of the sand sheets display scour and fill traces, drag marks, dewatering structures, and soft-sediment deformation features (see Fig. 26B, p. 72).

The sieve fraction analyses of the shale demonstrate that sand-sized extraformational sediments are depleted in the central basin area of the Western Interior Seaway. The lack of quartz sand perhaps explains why storm deposits are difficult to interpret within the Pierre Shale. However, beds rich in intraformational clasts display evidence of storm-induced bedding structure in some horizons. For example, the occurrence of shell hash beds, particularly where baculite shells are stacked with parallel orientation suggest storm activity. Storm-generated currents possibly are responsible for the concentration of phosphatic pebbles, mud clasts, reworked shell and bone material, and concretions in some horizons, particularly in the vicinity of the Campanian/Maastrichtian boundary unconformity in the Badlands National Park region. Reworked concretions can be distinguished from concretion formed in situ by the presence of breakage, imbrication, borings, organic overgrowths, and association with lag deposits (Ricken & Eder, 1991). In the Cedar Creek locality in the South Unit of Badlands National Park concretions up to one meter or more in diameter appear to have been reworked and deposited in the interval immediately above the unconformity (see Fig. 38, p. 122). The Campanian/Maastrichtian boundary unconformity in the Badlands National Park region is defined in different locations by such features as a scoured, irregular surface on the top of the Verendrye Member, and beds of concentrated intraclasts and phosphatic pebbles in many localities in this interval along the Cheyenne River Valley. Storm-generated currents perhaps best explain the occurrence of all these sedimentary features. In addition, the occurrence of storm-generated graded-bedding perhaps best explains the origin and occurrence of concretion horizons in many units in the Pierre Shale and Fox Hills Formation (discussed below).

### 9.3.2.4 Concretions

Concretions have been studied in Cretaceous rocks on every continent around the world. Studies of concretions and their fauna in the Western Interior region have been conducted in the Greenhorn Formation (Ludvigson et al., 1994), the Gammon Shale (Gautier, 1982), the Sharon Springs Member of the Pierre Shale (Hudson & Friedman, 1976), the *Baculites grandis* Zone of the Montana Bearpaw Shale (Reiskind, 1975), and the Fox Hills Formation (Waage, 1964, 1968; Carpenter et al., 1988). Concretion horizons are important stratigraphic markers because they can be traced significant distances, they stand out in field exposures, and they frequently contain fossils in abundance and with exceptional quality in preservation. Concretions preserve important aspects of the diagenetic history of their host sediments, and preserve sedimentary features that would otherwise by destroyed or altered by compaction and dissolution processes.

Fig. 104 illustrates the common forms of concretions found in the Pierre Shale. Concretions occur in all members of the Pierre Shale. Many concretions in the dark gray shales of the DeGrey Member and the Elk Butte Member in South Dakota, and in the Lower Unnamed Shale Member in the eastern Wyoming do not fizz when treated with acid, suggesting that their composition consists dominantly of non-calcareous minerals, perhaps apatite and siderite. Concretions in the upper Verendrye, Virgin Creek, and Mobridge Members of the Pierre Shale and the Trail City Member in the Fox Hills Formation in South Dakota, and in the Upper Unnamed Shale Member in eastern Wyoming are calcareous. Within the Interior Zone and Fox Hills Formation of Badlands National Park limonite and silica have replaced calcite in part, or completely, in many concretions by processes associated with Yellow Mounds-style weathering.

The lateral extent of specific concretion horizons is unknown, although my field work suggests that some concretion-bearing beds extend for many kilometers. Unfortunately, it would essentially be impossible to follow individual concretion horizons for long distances in the field because of the lack of continuous outcrops and the many difficulties in gaining access to land in the region. However, characteristics of certain concretion beds are unique; their positions relative to certain ammonite zones suggest that individual beds or horizons may be traced for great distances across the region. At least one zone of several concretion-bearing horizons in the

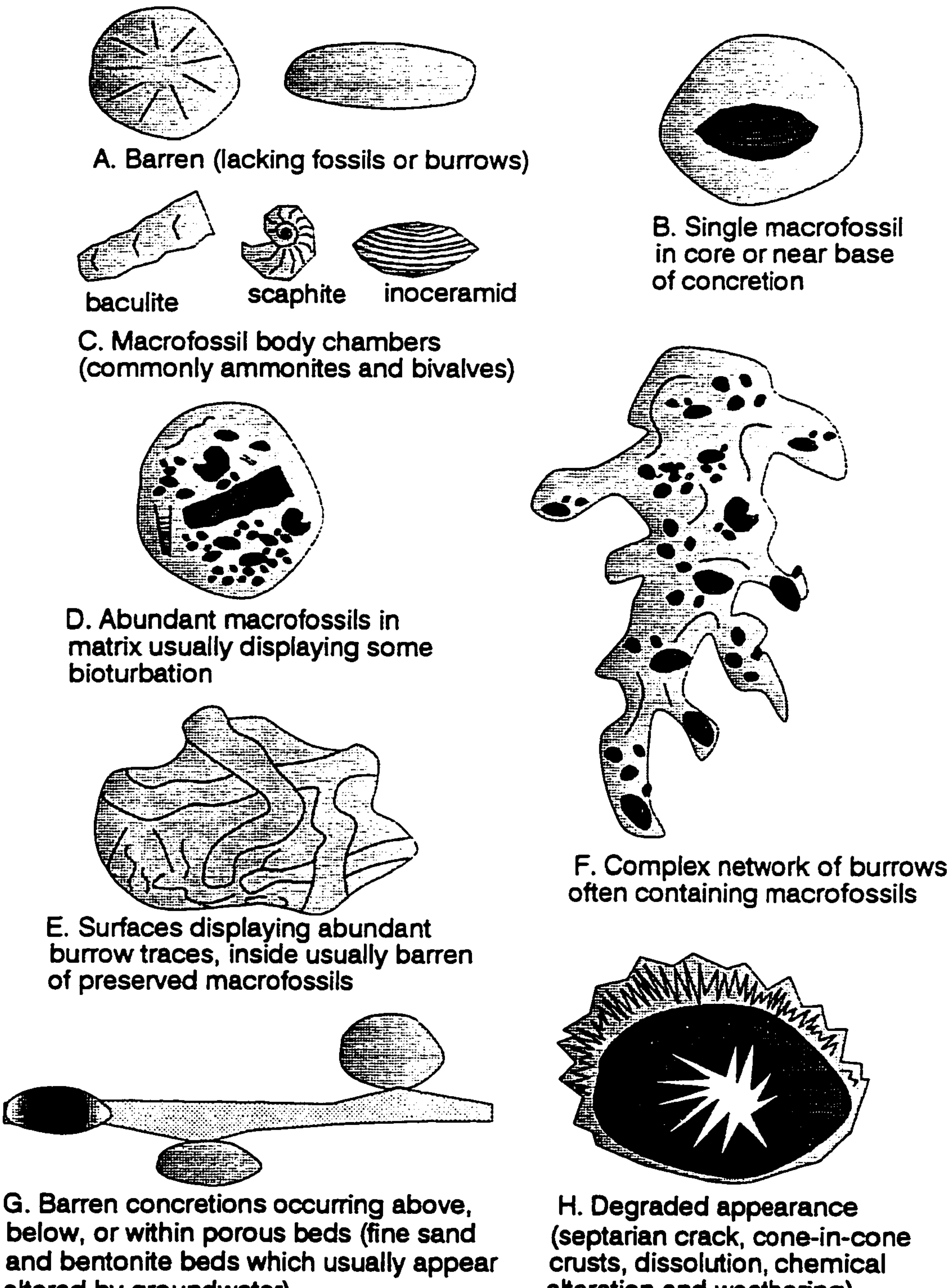


Fig. 104. Characteristic shapes, forms, and occurrences of common concretions in the Pierre Shale.

upper *Baculites clinolobatus* Zone appears traceable across most of study area.

An explanation of the complex geochemistry of concretions is beyond the scope of this research, however, some basic information about their origin and growth is as follows. Geochemical studies of concretion growth have revealed that concretions grow around nucleation sites by processes involving diffusion and mass transfer of carbonate or other compounds from the surrounding host sediment (such as from shell fragments, bone, microfossils, and other organic remains and minerals in the sediment) (Berner, 1968; Coleman, 1993). This helps to explain why shell material is abundant within concretions yet is heavily degraded or absent outside of concretions in some horizons. The sites where concretion nucleation begins, concretion growth rate, and the size to which concretions grow, are dependent on a variety of factors, including: 1) the abundance of carbonate mineral material (or other concretion forming compounds: Fe, P, Ca, etc.); 2) the porosity and permeability of the sediment; 3) age and burial history of the host sediment; and 4) the chemical thermodynamics (potential energy) of the nucleation site and the surrounding sediment. This last factor is perhaps the most difficult (or impossible) to evaluate because, 1) reagents (i.e., organic tissue, shell debris) are consumed in the concretion formation process; 2) fluids diffusing into, and dewatering out of, the sediment, through time, means that sediments on the bottom of the seaway were partially an open system, particularly where bioturbation allowed marine and pore waters to mix;

and 3) organic/sediment reactions which involve biological activity are complex, particularly microbial respiration (sulphate reduction and methanogenesis)(Berner, 1968; Berner & Westrich, 1975; Raiswell, 1988).

The common mineral content of concretions in the Pierre Shale varies from member to member, and range in composition between being purely calcite to featuring other minerals in varying concentrations including siderite, dolomite, limonite, hematite, goethite, apatite, barite, pyrite, marcasite, silica, and possibly others. The occurrence of these minerals is a function of redox potential and pH, and the concentration ions in solution. This, in turn, is probably a function of the character of the sediment and the depositional environment in which it accumulated, and the character of the fluids that migrate through the sediment through time (Hudson & Friedman, 1976; Gautier, 1982; Curtis & Coleman, 1986; Raiswell, 1988; Coleman, 1993).

The similarity of concretion horizons within specific zones in the Pierre Shale across the field area suggests that basin-wide processes are partially responsible for their occurrence. An interpretation introduced here, is that certain zones of concretions are a result of long quiescent periods when low sedimentation rates and well-oxygenated condition persist at the sea bottom allowing benthic communities to flourish. The concretions at the top of the *Baculites clinolobatus* Zone in the Badlands National Park area and in the Pedro area are examples. These periods are punctuated by catastrophic storm events where benthic communities are smothered by an influx of fine-grained sediment from floods or sediments eroded from the shallower margins of the seaway. Several lines of evidence support this interpretation, including characteristics of bedding structures and bioturbation features, $^{13}C/^{12}C$ and $^{18}O/^{16}O$ data, and comparisons with modern sedimentary processes (each topic is discussed below).

Multiple beds of limestone concretions were observed in the upper *Baculites clinolobatus* Zone in all study localities in South Dakota and Wyoming. Whether these beds are laterally continuous is unclear, however, their widespread distribution in association with the last occurrence of *Baculites clinolobutus* suggests that the concretion beds do correlate across the study area, although the number of concretion beds vary for one locality to the next (for example: three beds in the Osage Oil Field, three beds in the Sage Creek area, five beds in the Pedro area, one bed in the Mobridge area, etc.).

Two localities in the upper *Baculites clinolobatus* Zone, one near Pedro, South Dakota, and the other in the Osage Oil Field serve to illuminate essential characteristics of these concretion horizons (discussed below). Equivalent concretion beds were noted throughout North Unit of Badlands National Park in the transition between the Mobridge Member and the overlying Interior Zone.

### Locality #1: Osage Oil Field, Wyoming, *Baculites clinolobatus Zone*

Fig. 105 is a cross section through near-surface strata in the Osage Oil Field, Weston County, Wyoming. The poorly exposed strata of the upper Pierre Shale dip gently westward off the western flank of the Black Hills uplift downward into the eastern Powder River Basin. The cross-section demonstrates that concretions occur in multiple discrete horizons. Concretions in the Osage locality contain abundant, well-preserved invertebrate fauna (mostly ammonites, scaphopods, and bivalves) and display intense bioturbation (dominantly *Thalassinoides-Rhyzocorallium* facies). Deep surface weathering and early diagenetic processes have both significantly altered shell material and burrow traces inside and outside of concretions. A well exposed, ledge-forming bedding surface covered with large limestone concretions displaying abundant bioturbation (but generally lacking fossils) occurs near the top of the *Baculites clinolobatus* Zone (Figs. 105-106).

Fig. 106 is a map of the top of the bedding surface upper *Baculites clinolobatus* Zone in the Osage Oil Field, and shows the size, abundance, and spacing of these concretions within this horizon. The general distribution pattern of the concretions on the bedding surfaces is analogous to the random spacing of trees in a forest (~.5 - 4.0 m). According to Raiswell (1978) the size and spacing of concretion is random, and size is limited by the availability of nutrients in the host sediment and the flow of pore fluids through the sediment. The random distribution

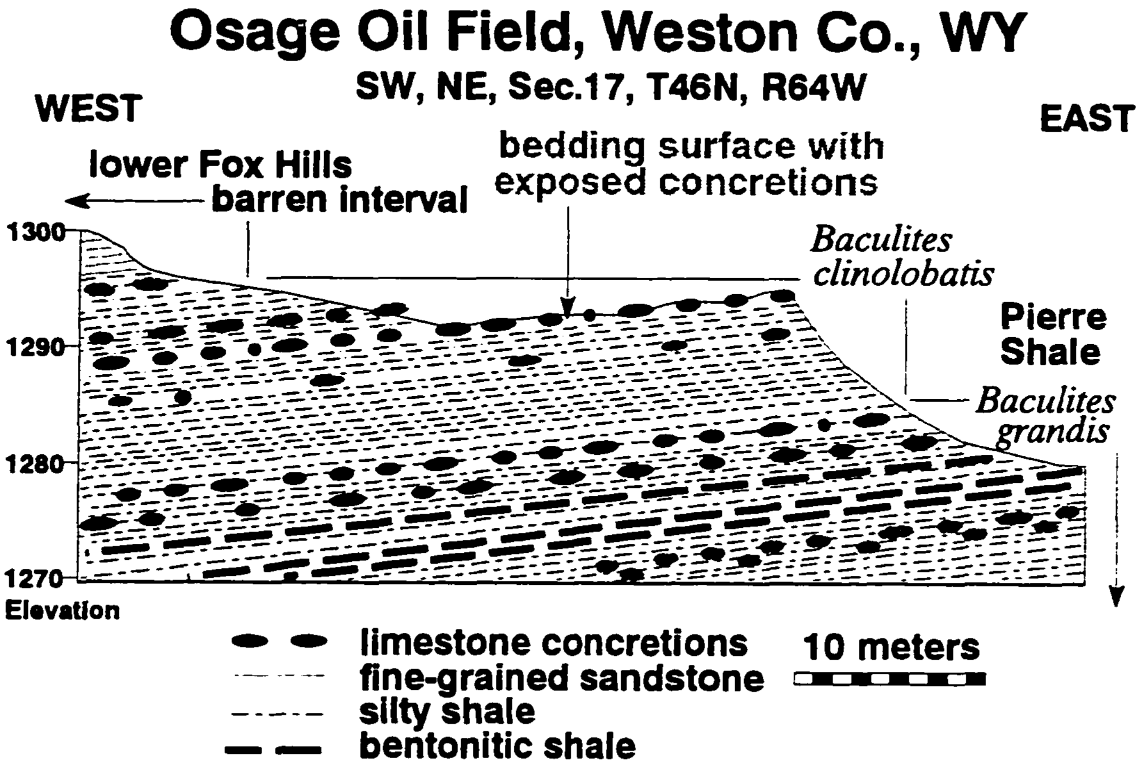


Fig. 105. Cross-section of the upper portion of the Upper Unnamed Shale Member in the Osage Oil Field showing the occurrence of concretion beds (NW, Sec. 17, T 46 N, R 64 W).

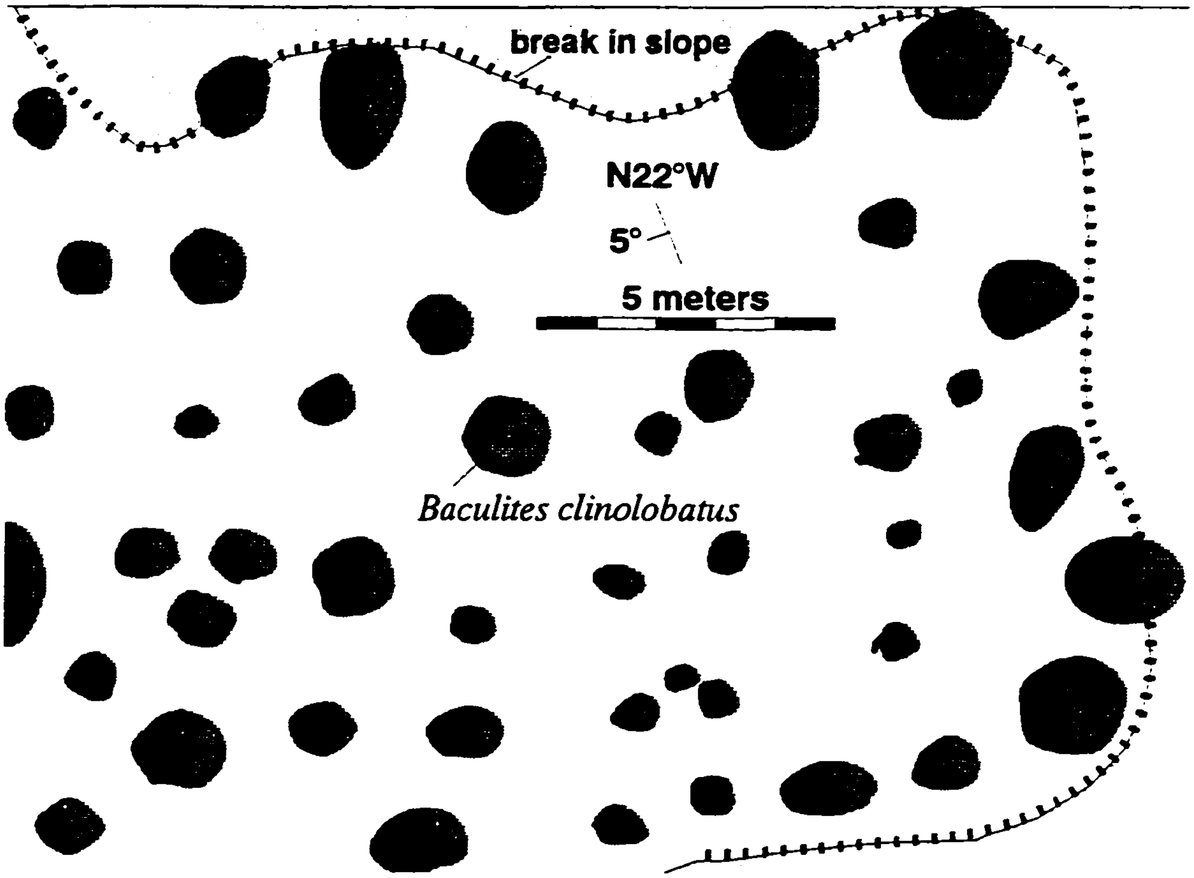


Fig. 106. Map view of a concretion bed along a bedding surface near the top of the *Baculites clinolobatus* Zone in the Upper Unnamed Shale Member of the Pierre Shale in the Osage Oil Field, Weston County, Wyoming (NW, Sec. 17, T 46 N, R 64 W).

of concretions is perhaps a function of inheterogeneity of the host sediment. Geraghty & White (1994) suggested that bioturbation features, such as fish nests filled with shell material, serve as nucleation sites for some concretions. Our observations show that bioturbation features and shell material are common nucleation sites for the growth of concretions in the Pierre Shale and Fox Hills Formation. The spacing of concretions may, in part, reflect the agonistic spacing behavior of burrowing crustaceans which colonize the sediment during an extended period between storms (Dingle, 1983). This is particularly apparent where concretions perfectly preserve the shape of concretion networks (see Fig. 37, p. 121). From my own experiences watching crabs on beaches, these organisms prefer to compete for, occupy, and modify an existing burrow than go through the trouble of digging a new hole. In this manner, certain burrows remain stationary for long periods, occupied by successive generations and possibly multiple species. These stationary burrows on the sea bed would serve a as passage for marine waters into the substrate, and pore waters out of the substrate. The mixing zones around burrows would be the logical places where calcite cements would start to precipitate, forming the nucleation sites of concretions. However, the general pattern of concretion distribution and the preservation of bioturbation features within them, however, is not proof that burrows are necessary for concretions to form. Many burrows occur in the sediment that are not encased in concretion material. The distribution of concretion is possibly more of a reflection of spatially-controlled chemical reaction kinetics within a confining sedimentary unit, and compounded by a long and complex diagenetic history.

### Locality #2: Pedro, South Dakota, *Baculites clinolobatus Zone*

The same multiple limestone concretion horizons seen in the upper *Baculites clinolobatus* Zone at the Osage Oil Field occur in outcrops all along the Cheyenne River valley from the Badlands National Park area northward and eastward to the vicinity of Pedro, South Dakota. Based on the stratigraphic position near the top of the *Baculites clinolobatus* Zone, and the similarity of the lithology of both localities, these exposures probably represent the same biostratigraphic interval. In the Pedro area the stratigraphic interval at the top of the *Baculites clinolobatus* Zone is represented by alternating horizons of fossiliferous concretion-bearing units and gray shale. Within and above the *Baculites clinolobatus* Zone are thin sheet sand beds, which appear to be traceable for many miles throughout the region and probably represent either storm-graded deposits and/or turbidity current-transported sand.

A trench dug into unweathered shale through a concretion horizon in the upper *Baculites clinolobatus* Zone reveals details of lithology and bioturbation patterns (Fig. 107). In comparison to the shale above and below, concretions formed within a horizon that contained an abundance of trace fossils, an elevated carbonate content, finer-grained sediment, and a lighter color. In addition to *Chondrites* and *Planolites*, the concretion zone displays more *Thalassinoides* and *Cruziana* ichnofauna. This

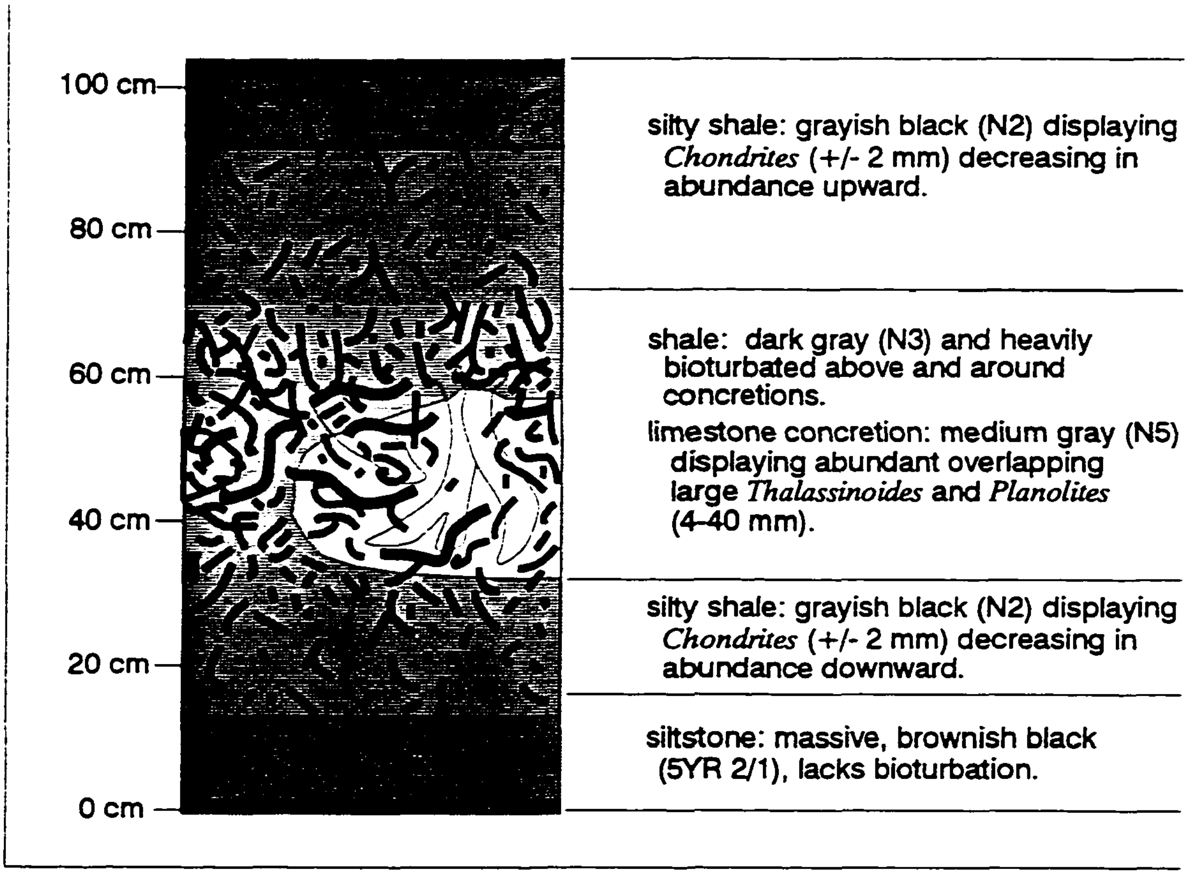


Fig. 107. Interpretation of bioturbation characteristics in one meter thick section through a concretion bed in the upper *Baculites clinolobatus* Zone in the Mobridge Member on the land of the Gabriel Ranch near Pedro, South Dakota (Sw, NE, Sec. 26, T 5 N, R. 16 E. Color information is based on the *Geological Society of America Rock Color Chart*.

pattern of sedimentological, geochemical, and paleontological characteristics tends to be a common theme among concretion-bearing horizons, although significant variability exists. Calcareous fossils of ammonites, bivalves, and other invertebrates are abundant in some horizons, but not in others. This may be a taphonomic artifact related to sediment composition and accumulation rates, and may be a factor of the distribution and abundance of species in the seaway through time. Aragonite and calcite shell material can remain unaltered indefinitely in the presence of pore-water supersaturated with respect to calcium and bicarbonate ions without precipitating or dissolving shell material, particularly in sediments saturated with seawater (G. M. Friedman, personal communication, 1994). In early diagenesis calcium carbonate dissolution and precipitation reactions can be driven by processes of bacterial-induced sulphate reduction and methanogenesis (Berner, 1968; Berner & Westrich, 1975; Hudson & Friedman, 1976). In late stage diagenesis calcium carbonate dissolution and precipitation reactions can be driven by the introduction of meteoric water (Hudson & Friedman, 1976; Ludvigson et al., 1994). Unless shells become isolated from the surface environment, they will not survive surface dissolution process and bioerosion long enough to be preserved as fossils (hence the need for rapid burial in calcium carbonate-enriched sediments).

The one meter-thick section, illustrated in Fig. 107, shows what might be interpreted as an "oxygenation event" (after Bottjer and Savrda, 1989). The cause of this oxygenation event might be better interpreted as the consequence of normal marine oxygenated substrate conditions between storms. The section shows an increasing burrow diameter, with maximum burrow diameter attained in the concretion zone. The top of the concretion zone probably represents an omission surface where the accumulation of fine-grained extraformational clastic debris was greatly reduced for a long period of time. This hiatus in clastic sedimentation allowed intense bioturbation to completely churn the interval just below the sediment/interface while increasing the calcareous content by churning shell debris and remains of microfossils into the sediment.

Above the concretion zone burrow diameters become smaller and the sediment appeared siltier. The influx of silty sediment probably represents a graded storm deposit. Concretions began to form within the zone of bioturbation because of the higher carbonate content and probably a higher organic content. Berner & Westrich (1985) demonstrated that burrowing organisms can actually increase the organic content of some marine sediments by packing organic detritus and fecal material into burrows. However, penetrating burrows allow the passage of oxygenated marine water into the substrate. Fluid migration into the substrate can be provided by organisms, bottom currents, wave energy, and tidal pumping. Roehler (1993) suggests that the margins of the seaway were subject to about 10 feet of tidal fluctuation. In addition, the passage of storm fronts are also known to cause fluctuations in water tables. Studies of south Florida aquifer system have demonstrated the significance of tidal pumping on contaminated groundwater transport and mixing (Friedman et al., 1992). Fluid migration out of the substrate is also provided by sediment compaction dewatering and regional hydrostatic pressures provided by both structural compression and distant terrestrial freshwater loading (Ludvigson et al., 1994). The combination of available oxygen, sulfates in seawater, and organic matter trapped by storm events and by bioturbation in the host sediment provides ample energy for microbial activity (sulphate reduction and methanogenesis) and diagenesis.

Unusual rock formations in the Western Interior region called "Tepee Buttes" are essentially bus-sized concretions. They are localized zones of carbonate-cemented shale that resist weathering in relation to the surrounding shale, hense they stand out like tepees on the prairie. They typically contain fossils and display complex septarian fracture filled with sparry calcite. The occurrence of Tepee Buttes in the Pierre Shale in Colorado have been interpreted as having formed around submarine springs associated with fault zones (Kauffman & Howe, 1991). Tepee Butte-like structures also occur in the *Baculites grandis* in Weston County. Several occur along WY Route 116 road west of Upton, Wyoming approximate one half mile beyond the bridge over Beaver Creek. If tepee buttes are result of springs on the sea floor, then the occurrence of tepee buttes on the western flank of the Black Hills is another indication that uplift in that region was occurring during Maastrichtian time. Hydrostatic head from exposed lowlands are known to provide freshwater springs offshore in many places (such as around Florida, along the coastal plain, and islands in the Pacific).

## A Model For the Formation of Concretion-Bearing Horizons

Single or multiple laterally continuous beds of concretions, as illustrated in Fig. 105, can be interpreted as a bed set or a succession of bed sets (a parasequence). Each cycle is defined as a bed set consisting of a fining-upward, silty shale overlain by a bed containing fossiliferous concretions with an overlying omission surface. The silty shale horizons correspond to periods of enhanced turbidity and rapid sedimentation (consistent with graded storm deposits and Bouma sequence-style sedimentation with an overprint of varying degrees of bioturbation). In the Western Interior Basin the sedimentation processes would be more consistent with shallow continental shelf ramp processes rather than deeper slope and basin environments since great basin depths probably did not occur in the seaway, particularly in the eastern margin region of South Dakota. The more calcareous, fossiliferous, bioturbated, concretion-bearing horizons correspond with periods of reduced clastic sedimentation within the Seaway. Carbonate sedimentation dominated periods of reduced turbidity when benthic organisms flourished. However, the organic-rich character of clay-dominated sediments in the Pierre Shale suggest that turbid conditions probably prevailed throughout the seaway, as in to the modern northern Gulf of Mexico in the Mississippi Delta region.

The fossiliferous concretion horizons in the Badlands National Park region and in the Osage Oil Field region reveal a similar story. Each concretion horizon corresponds with a punctuated colonization of the substrate between periods of famine or sediment-induced suffocation. Waage (1968) observed that tightly-packed, uniformly-sized clusters of bivalves and pelecypods preserved in concretions suggested that "broods" of offspring were wiped out by the same rapid-kill event. Bioturbation patterns of *Thalassinoides*, *Rhizocorallium*, *Planolites*, and *Chondrites* burrows preserved in concretions mimic crustacean/worm ecological associations observed in both ancient and modern environments (Bishop, 1987; Rebach & Duncan, 1983; Stoffer and Chamberlain, 1995a,b). Our study of back-reef muddy bottoms of coral-lined lagoons in the U.S. Virgin Islands revealed information about burrowing behavior of crustaceans and worms (Stoffer & Chamberlain, 1995a,b). Between storms, benthic organisms churn the substrate creating abundant mounds, pits, and tunnels, aerating the substrate. Crustaceans, worms, and burrowing fish dig out the substrate and pile the sediment around their burrows, creating as much as a meter of relief. In places where the substrate in the Western Interior Seaway was heavily bioturbated the seabed probably had a similar appearance. In areas where wave energy affects the sea bottom the sediment surface is generally smooth. During storms when wave base increase in depth, a rugged surface of a highly bioturbated seabed is probaby subjected to intense churning and submarine erosion. The descriptions of changes in the relief of the seabed after the passage of Hurricane Camille by Morton (1988) demonstrate that storms are capable of moving vast quantities of sediment capable of smothering benthic communities.

Once an environment favorable for the development of concretions forms diagenetic reactions causing the precipitation of calcareous material begins. Berner (1968) demonstrated this by sealing dead clams in jars fill with sediment. He observed that decaying flesh of the organisms caused the release of ammonia which caused calcite to precipitate in a spherical halo around the organism. Hudson & Friedman (1976) suggested that many concretions, including those bearing fragile fossils, form quickly in the upper few meters of the sediment, and continue to grow during compaction. They suggest that septarian cracks form during the dewatering of concretions, and the minerals that accumulate in the cracks of concretions may represent several stages of diagenetic alteration through the late chronological evolution of concretions. Isotopic data from shells and concretions also support a theory of early diagenesis via bacterially-induced sulphate reduction and methanogenesis in the formation of calcareous concretions (Hudson & Friedman, 1976; Richen & Eder, 1991).

We tested shell material and concretion matrix material from four ammonite zones in the Osage Oil Field, Weston County, Wyoming for compositional values of stable isotopes of carbon and oxygen ($\delta^{13}C$ and $\delta^{18}O$). The results of analyses are shown in Table VIII. Fig. 108 shows isotopic values from shells and concretion material that we tested from the Osage Oil Field compared with data by Hudson & Friedman (1976) and Richen & Eder (1991). Explanation and interpretation of this diagram and data are as follows.

Fig. 108 graphically shows three data sets for $\delta^{13}C$ and $\delta^{18}O$ values of samples: data from Richer & Eder (1991), data from Hudson and Friedman (1976); and sample data from our analyses (Table VIII). The large data set by Ricken & Eder (1991) demonstrates a range of isotopic values published for carbonate concretions from many ages and locations, and by many authors. Imprinted on this data set are clusters of values reported by Hudson & Friedman (1976) which include isotopic value designations for marine fossils, "early" calcite, and "late" calcite. Modern ocean water, with "0.0" values for $\delta^{13}C$ and $\delta^{18}O$, falls within the range of marine fossils. The "early" calcite of Hudson & Friedman's data represents a range of isotopic values for concretion matrix samples which they suggested represents carbonate material precipitated during early stages of concretion formation (during sulfate reduction and methanogenesis). The "late" calcite of Hudson & Friedman's data represents a range of isotopic values for calcite derived from septarian fractures

## TABLE VIII

**$\delta^{13}C$ and $\delta^{18}O$ Values** for Samples of Concretion Matrix, Bivalve Shells (*Protocardium* sp.), and Baculite Shells From Four Ammonite Range Zones in the Upper Unnamed Shale Member in the Osage Oil Field, Weston Couny, Wyoming**

| range zone | concretion matrix | | bivalve shell | | baculite shell | |
|---|---|---|---|---|---|---|
| | $\delta^{13}C$ | $\delta^{18}O$ | $\delta^{13}C$ | $\delta^{18}O$ | $\delta^{13}C$ | $\delta^{18}O$ |
| *Baculites clinolobatus* | -21.3 | -2.3 | +0.3<br>+0.3 | -1.6<br>-1.7 | -4.5 | -0.4 |
| *Baculites grandis* | -18.5 | -2.6 | -0.7 | -2.4 | -1.1 | -1.6 |
| *Baculites baculus* | -11.2 | -2.9 | +0.5 | -2.3 | -5.3 | -1.2 |
| *Baculites eliasi* | -20.0<br>-20.0 | -0.7<br>-0.7 | -1.3 | -2.7 | -1.8 | -2.9 |

**Values for $\delta^{13}C$ and $\delta^{18}O$ are adjusted to PDB standard for all samples. Testing of samples was conducted by Krueger Enterprises, Inc. in fall, 1994.

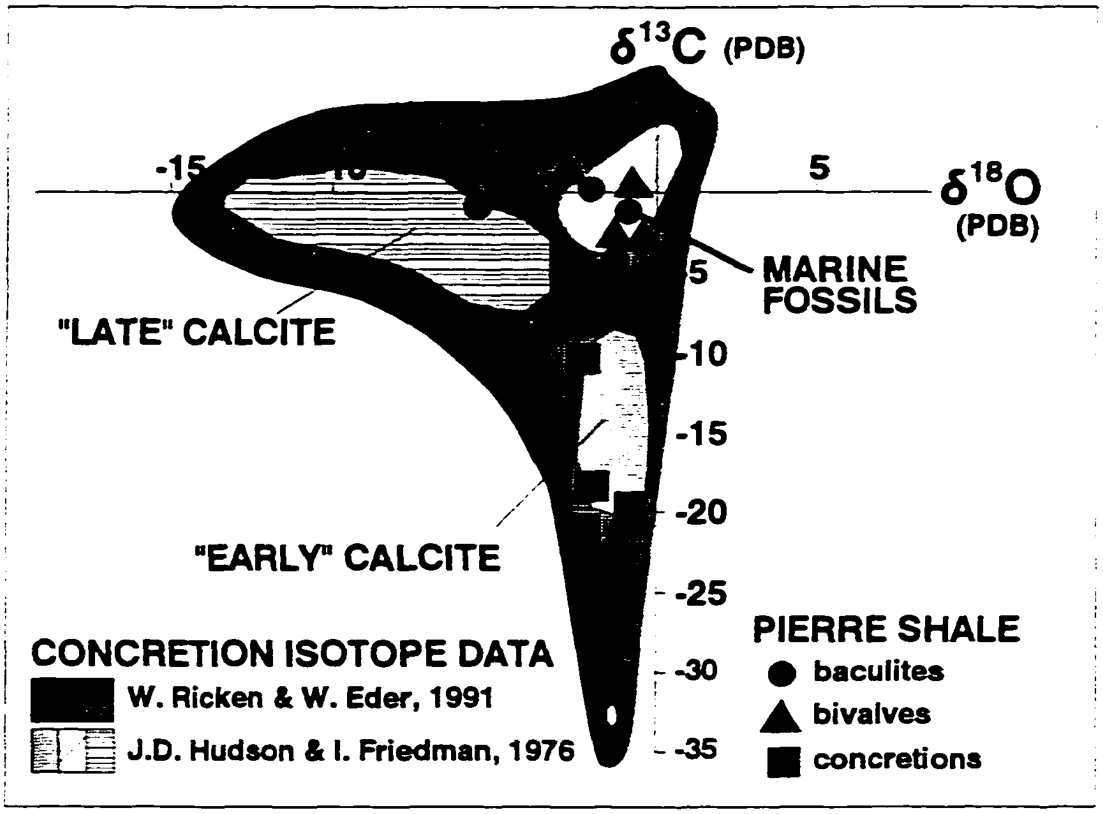


Fig. 108. Stable isotope data (carbon and oxygen) derived from concretions and marine fossils. The diagram is a combination of data from three sources: 1) Data reported by Richen and Eder (1991) which shows the total range of $\delta^{13}C$ and $\delta^{18}O$ values from concretion material reported for rocks of many ages. 2) Data by Hudson & Friedman (1976) for samples from the Pierre Shale which they interpret "cluster ranges" for $\delta^{13}C$ and $\delta^{18}O$ values for marine fossils, "early" diagenetic calcite, and "late" diagenetic calcite. 3) Data from this study which includes $\delta^{13}C$ and $\delta^{18}O$ values of baculites (circles), bivalves (triangles), and concretion matrix (squares) from samples taken from the Upper Unnamed Shale Member, Osage Oil Field, Wyoming (shown in Table VIII). Ideally, marine water should fall near the "0.0" value for both $\delta^{13}C$ and $\delta^{18}O$.

in concretion which they suggested represents carbonate material precipitated during late stages of diagenesis.

Data from our shell material (from ammonites and bivalves) is similar to the values of marine fossils reported by Hudson & Friedman (1976) which cluster near "zero" values for the PeeDee Belemnite Standard, a reference standard close to the value of seawater for both $\delta^{13}C$ and $\delta^{18}O$. Our samples of concretion matrix from the Osage Oil Field are similar to the $\delta^{13}C$ reported by both Ricken & Eder and by Hudson & Friedman.

Hudson & Friedman demonstrate that $CO_2$ in concretion matrix is derived from the oxidation of organic matter, probably accompanying the reduction of seawater sulphate to sulphide by anaerobic bacteria. Richen & Eder argued that the effects of sulfate reduction can be especially intense when additional seawater sulfate is allowed to enter the sediment via diffusion. This condition would require a very slow sedimentation rate or a still-stand, and high permeability in order for marine water to defuse into the substrate. Richen & Eder also suggest that methanogenesis generally follows the sulphate reduction phase during increased burial. They argue that bacterially induced methane production preferentially removes the lighter $\delta^{13}C$. Methane with light $\delta^{13}C$ can migrate with pore fluids toward the surface, become oxidized, and then became incorporated into the matrix of concretions. This process perhaps best explains why concretion matrix values of $\delta^{13}C$ are light, but $\delta^{18}O$ values are consistent with seawater. Hudson & Friedman (1976) demonstrated that $\delta^{13}C$ values are lightest in the sites of nucleation and grow heavier outward toward the surface of concretions.

The "late" calcite values are poorly understood. Late calcite has been interpreted as being related to processes involving increased temperatures, clay mineral dewatering, and clay mineral alteration during diagenesis (Richen & Eder, 1991). The "late calcite" contains "light" $\delta^{18}O$ values in the range typical of meteoric waters (Hudson & Friedman, 1976). These $\delta^{18}O$ values are unusual because the calcite has $\delta^{13}C$ values are similar to seawater. Hudson & Friedman (1976) and Ludvigson et al., (1994) suggested that the influx of meteoric water best explains the shift of $\delta^{18}O$ to lighter values for the late diagenetic calcite, whereas the carbon are derived from the host sediment where the concretions occur. They add that the hydrostatic head had to be strong enough to move meteoric waters long distances through low permeability marine shales. For concretions in the Badlands region and in the Weston County, Wyoming localities perhaps this hydrostatic head can be explained by early uplift in the Black Hills region when the marine sediments were still less consolidated? Meteoric water-influenced diagenesis could have also occurred as freshwater environments prograded over the concretion zones during the late Maastrichtian and later in the Tertiary. Meteoric water-influenced diagenesis is apparent in concretions exposed to Yellow Mounds-style weathering; it is also an ongoing process related to modern weathering. However, the excellent condition of the fossils and trace fossils in the concretions suggests that the concretions formed early, prior to significant burial and compaction.

The geochemical data from core sample analyses for concretions horizons (Table IV) is consistent with the interpretation that concretion horizons are associated with a slow-down or still-stand in sedimentation. The geochemical data for concretions demonstrated that although the shale around concretions is depleted in calcium (due to the growth of concretions), the shale is also is enriched in sodium, potassium, and magnesium. The concentration of these elements in sediments around concretions suggests that the processes of diffusion of seawater into the sediment occurred during a slow-down or still-stand in sedimentation. The process is analogous to how water softener systems work. Cations, such as Na, Mg, and K, from seawater enter the sediment and trapped by clays. In turn, calcium is released. This mobile calcium becomes available for concretion growth.

Additional evidence that concretions are of early diagenetic origin is the fact that shells are usually uncrushed within concretions, but may be flattened and chemically degraded in the surrounding shale. Concretions commonly preserve burrows that appear unflattened in vertical cross section and thus show a lack of load packing.

Fig. 109 illustrates a model that incorporates aspects of benthic community

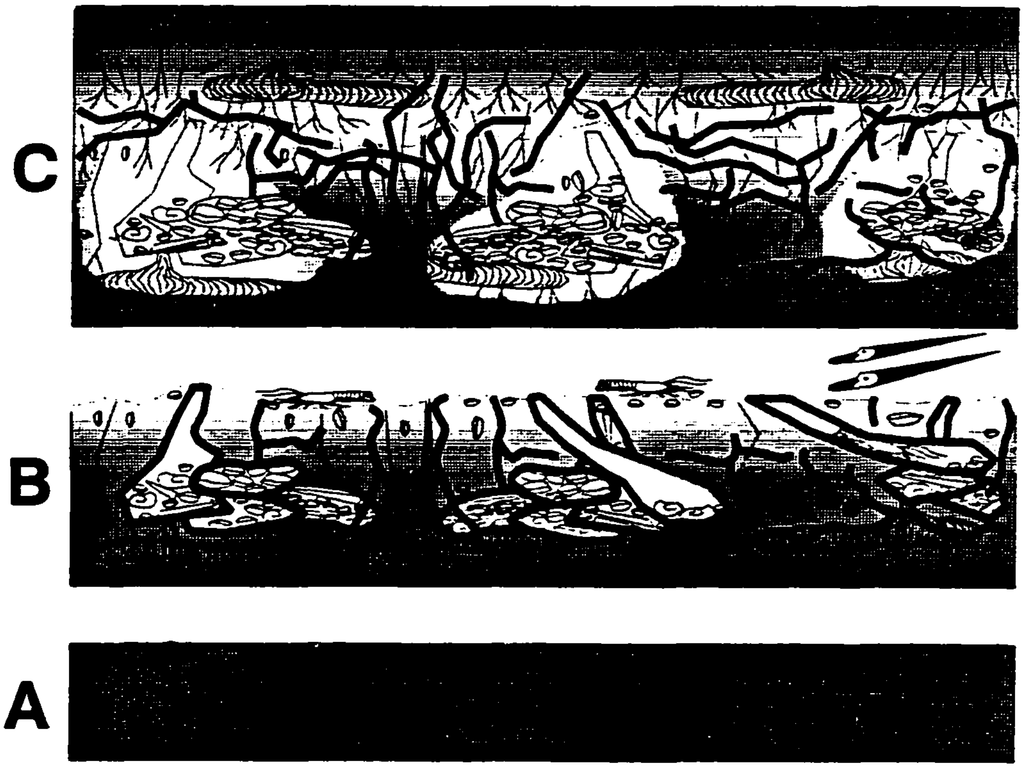


Fig. 109. A model for the origin of concretion horizons. "A" shows the sea bottom after a catastrophic storm event. "B" shows a diverse paleocommunity of organisms thriving during a period of slow deposition or still-stand when oxygen levels are high on the sea bottom. "C" show concretions beginning to form around the layer where organism had concentrated organic matter and calcareous debris into the sediment prior to being smothered by sediments from another catastrophic storm or series of storm events.

development and collapse and the concurrent early diagenetic origin of concretions. Fig. 109-A shows the top of a graded storm deposit shortly after the storm had ended. A one to two meter thick graded-bed sequence is deposited across a large portion of the seaway at the expense of submarine erosion in shallower regions and floods on-shore. Highly turbid conditions with a high organic content has depleted the available oxygen at the sea bottom. As oxygen levels increase at the sea bottom, dysaerobic tolerant species such as the organisms responsible for *Chondrites* and *Planolites* recolonized the benthic environment.

As turbidity level decreases, sedimentation rates approach still-stand rates, and oxygen levels approach normal marine conditions (shown in Fig 109-B). This allows additional benthic species to colonize the substrate, increasing both the abundance and diversity of the benthic community, in addition to supporting a greater abundance and diversity of predatory swimming species in the water column. With time, benthic organisms contribute calcareous material and organic remains in the form of shells and fecal material to the sediment, while pelagic rain of calcareous microfossils and fecal debris accumulate on the surface. Agonistic behavior of crustaceans allow stabilized burrows to remain stationary for extended periods of time (Reback & Duncan, 1983). The early phase concretions diagenesis begins around nucleation sites such as shells packed with fecal material within burrows.

Fig. 109-C shows the results of an additional catastrophic storm event where

the benthic community is smothered by the rapid influx of sediments. The burial of an additional 1-2 meters of storm-deposited material separates the calcareous and organic-rich zone associated with the still-stand from the new surface after the storm event. Diffusion of marine waters into the substrate, sulphate reduction, and methanogenesis continue, which allow the concretions to grow at the expense of nutrients in the surrounding shale.

### 9.3.2.5 Clinoform-Style Mudbanks

The occurrence of clinoform-style mudbanks in the Badlands National Park region are perhaps the most important evidence for unraveling the sequence stratigraphy and general regional geology of the Late Cretaceous in the area. There are three clinoform-style mudbanks preserved in the Badlands region. One in the *Baculites reesidei* Zone interval (late Campanian) in the Cedar Creek (Badlands National Park, South Unit). Two others of Maastrichtian age occur throughout large portions in the North Unit of Badlands National Park (discussed below).

The orientation of clinoform bedding of the older late Campanian mudbank is in a north to northeast direction. Sand sheets, concretion beds, and bentonite beds give the strata an appearance of dipping in a northeastward direction. The dip angle of these beds preserves the ancient clinoform bedding surfaces as the mudbank prograded northward across the region. Fossils of the *Baculites reesidei* Zone and reworked material from the *Baculites compressus/cuneatus* Zones are common throughout the clinoform beds. Most shell material were broken into fragments by transport or bioturbation. The uppermost beds of this latest Campanian mudbank are truncated along an unconformable boundary giving the strata the appearance of an angular unconformity (see Fig. 38, p. 122). The clinoform unit is 12-20 meters thick beneath the Campanian-Maastrichtian boundary unconformity, and extends from near creek level upward to the unconformity (Fig. 110).

Clinoform geometry of beds in the North Unit of Badlands National Park were not recognized in the *Baculites reesidei* Zone, probably because in most fresh exposures the sediment of this zone has undergone a higher degree of bioturbation and post-depositional diagenetic alteration, and was not recognized probably because the interval is very poorly exposed. However, along the South Fork of Sage Creek several specimens of *Baculites reesidei* were observed weathering from silty shale. This silty shale has not been exposed to pervasive bioturbation, and still displays cross-stratification that dips in the north to northeast direction. This cross-bedded silty shale demonstrates that currents in the seaway transported fine-grained sediment in a northward direction in this locality. This is consistent with interpretation of the orientation of the larger clinoform structure in the South Unit of the park.

A second clinoform-style mudbank of Maastrichtian age is represented by the sediments of the Interior Zone in the North Unit of Badlands National Park. Perhaps

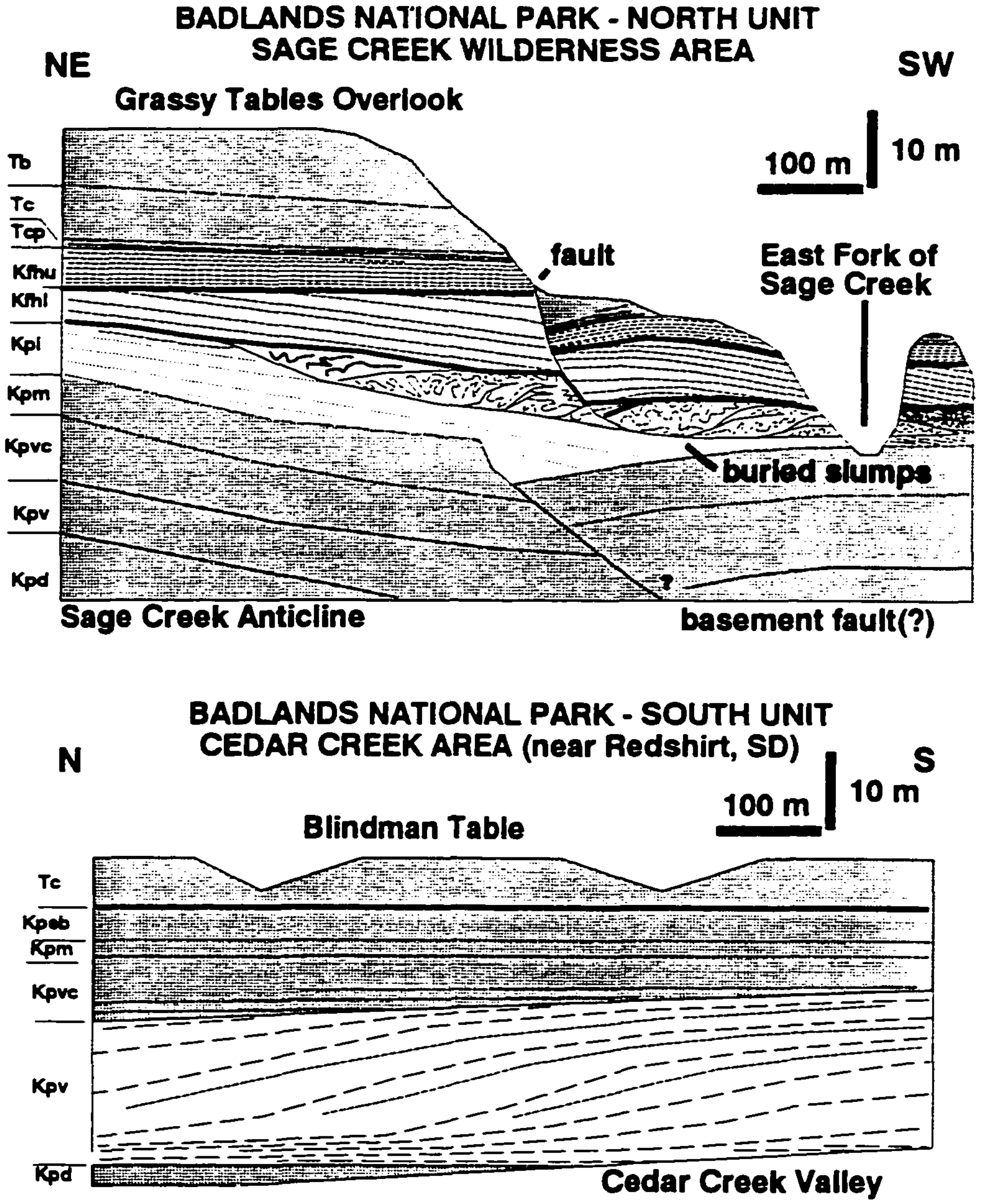


Fig. 110. Clinoform-style mudbanks in Badlands National Park. UPPER FIGURE (North Unit): NW-SE cross section through the Grassy Tables Overlook area showing mudbank features in the Interior Zone and Lower Unit of the Fox Hills Formation, including buried slumps. LOWER FIGURE (South Unit): N-S cross-section profile along the hillside below Blindman Table along Cedar Creek showing the geometry of beds in a mudbank in the Verendrye Member (truncated on top along the Campanian/Maastrichtian boundary unconformity). Symbols: Kpd-Degrey Mbr.; Kpv-Verendrye Mbr.; Kpvc-Virgin Creek Mbr.; Kpm-Mobridge Mbr.; Kpi-Interior Zone; Kfhl-Lower Und@

thickest and most accessible exposures of this sequence of clinoform beds are along the Badlands Loop Road in the Dillon Pass area (see Fig. 58, p. 172). This mudbank displays a progradation direction towards the south in exposures throughout the North Unit of Badlands National Park. Sedimentary structures in the Interior Zone in the Grassy Tables Overlook area demonstrate that buried slumps moved along over-steepened bedding surfaces in a southwestward direction (Fig. 110). The variable thickness of the Interior Zone throughout the North Unit of Badlands National Park suggests that contemporaneous movement of structures related to the Sage Creek anticline/fault system occurred while sediments of the Interior Zone and the overlying Fox Hills Formation were being deposited.

The Maastrichtian-age clinoform sequence occurs in the Lower Unit of the Fox Hills Formation with its maximum exposure occurring in the Grassy Tables Overlook area. This mudbank is limited in its occurrence between the vicinity of the Roberts Prairie Dog Town area and the Grassy Tables Overlook area. This mudbank sequences tends to pinch out to the east, to the west, and to the south, suggesting that it represents a localized "lobe-like" occurrence. Its extent in the subsurface north of the park is unknown. This younger mudbank overlies the mudbank sequence in the Interior Zone (see the upper diagram in Fig. 110).

The occurrence of mudbanks demonstrates that the sea bottom of the Western Interior Seaway in the Badlands region displayed considerable relief. In both examples the tops of the mudbanks display truncation along unconformable surfaces (the Campanian/Maastrichtian boundary unconformity, and the unconformity between the Pierre Shale and the Fox Hills Formation). These structures fit into a model for sequence stratigraphy representing lowstand wedge-prograding complexes prior to exposure when the seas temporarily withdrew from the Badlands area (Bally, 1986; Haq et al., 1987).

The reason for the opposing orientation of these clinoform-style mudbanks is unclear. Perhaps the geometry of these clinoform wedges in the Badlands region is an indication that uplift in the Black Hills region blocked the eastward progradation of sediments from source areas to the west, causing progradational sequences of sediments to "wrap around" the uplift. In addition, the uplift itself could have been supplying reworked sediments.

#### 9.3.2.6 Weathering Profiles

Meteoric weathering has affected the Pierre Shale during periods of subaerial exposure starting in Cretaceous time, and is continuing today in the manner of modern soil development. It is apparent, however, that ancient soil profiles are preserved within the Pierre Shale and Fox Hills Formations, and that the ancient weathering profiles formed on subaerially exposed surfaces while sediments of these formations were accumulating in the Badlands National Park region. Most notable is the Yellow Mounds Weathering Profile described by Dunham (1961), Pettijohn (1965), Retallack (1983), and Retallack (1985). To differentiate between the original marine strata and the effects of meteoric weathering on marine strata the phrase "Yellow Mounds-Style Weathering" is used in this report to describe weathered Cretaceous outcrops with disregard for actual age of the weathering features (whether latest Cretaceous, Tertiary, or modern in age).

Examination of core samples affected by meteoric weathering show enrichment in oxides of iron and aluminum, but depletion in silica and alkaline metals (Na, K) and alkaline earth metals (Mg, Ca). The data for calcium-depleted samples in Table IV perhaps best illustrates this trend. Such elemental depletion is consistent with laterite soil formation in warm, humid climates (Tourtelot, 1962; Friedman et al., 1992). However, not all paleosol features are consistent with lateritic weathering. For instance, some horizons are enriched in calcite; calcite is concentrated in soils during arid conditions. Perhaps both humid and arid weathering conditions affected the same sediments at different times. Whether these conditions can be differentiated in the Yellow Mounds Weathering Profile is unclear. However, the episodic switch from arid to humid weathering conditions might explain the complexity and intensity of the pre-Chadron weathering profiles.

Features we observed in outcrops that are attributable to meteoric weathering include leached mudrocks, degraded concretions, weathered bentonite beds, caliche crusts, and root structures. Degraded mudrocks are any marine sediments that have been exposed to meteoric weathering, and may range from a slight coloration change to pervasive leaching and replacement where all original bedding structures are unrecognizable. Heavily leached sediment consists of residuum of mostly iron and aluminum oxides (laterite). In most areas the leaching of mudrock along fractures, joints, permeable layers and root traces gives the rock a mottled appearance with colors typical of iron minerals (ranging from red, orange, yellow, purple, white, and everything in-between).

Degraded concretions are concretions with rind coverings that lack evidence of original bedding, bioturbation or fossils, and are stained brown from impregnation with limonite. Heavy leaching in some cases completely replaces original calcite with hydrous silica (opal) and hematite and limonite. Crusts are thickest on the top of concretions, and may display cone-in-cone structure where calcite is still present.

Degraded bentonite layers in the Badlands National Park region display an abundance of jarosite (undifferentiated mineral salts) and pervasive replacement or cementation by cone-in-cone calcite. Pods of caliche were observed along unconformable surfaces, particularly along the Pierre/Fox Hills boundary unconformity along the South Fork of Sage Creek (see Fig. 46, p. 142).

At least four weathering profiles were observed within the Cretaceous section in Badlands National Park. The oldest occurs on top of the Verendrye Member along the South Fork of Sage Creek. This weathering profile is expressed in the sediments beneath the Campanian-Maastrichtian boundary unconformity. It is very limited in its outcrop occurrence and is only about one meter thick (see Fig. 45, p. 138). Similar weathering profile features were observed on the top of the Verendrye Member along Elk Creek on the Tom Trask Ranch. In the Cedar Creek locality in the South Unit of Badlands National Park sediments above the Campanian/Maastrichtian boundary unconformity display a reddish color, possibly from the reworking of weathered sediments from subaerially exposed source areas nearby.

A second weathering profile occurs along the boundary between the upper Pierre Shale and the lower Fox Hills Formation, but was observed only in the Grassy Tables Overlook area (see Fig. 55, p. 163) and possibly in the Roberts Prairie Dog Town area (see Fig. 49, p. 153). A third weathering profile is exposed beneath the boundary of the Lower and Upper Units of the Fox Hills Formation. This weathering profile is very well developed throughout the region along the East Fork of Sage Creek, particularly in the area of the Grassy Tables Overlook (see Fig. 56, p. 165). These weathering profiles appear to be limited in their extent along the crest of the Sage Creek Anticline. Elsewhere, these weathering profiles cannot be differentiated from the fourth, most prominent weathering profile, the Yellow Mounds Weathering Profile, which is associated with the unconformity at the top of the Cretaceous sequence and beneath the White River Group.

Detailed discussion about the history of the interpretation of the Yellow Mounds Weathering Profile is included in an introduction to the history of stratigraphic interpretation in Badlands National Park region that begins in Chapter 6 (p. 111). Dunham (1961) and Pettijohn (1965) demonstrated that the Yellow Mounds Weathering Profile is a relict weathering profile imprinted on the sediments of Cretaceous age (Pierre Shale and Fox Hills Formation) in the Badlands National Park area and on older formations (the Niobrara Formation) and younger formations elsewhere in the region: Hell Creek (Maastrichtian/Danian), Fort Union (Paleocene), Golden Valley (Eocene), and Slim Buttes (Latest Eocene) formations. The Yellow Mounds Weathering Profile gets its name from the "yellow mounds" - rounded hills of yellowish sediment in exposures of Late Cretaceous strata throughout the North Unit of Badlands National Park (see Fig. 51, p. 156).

Retallack (1983) and Retallack (1985) demonstrated that the Yellow Mounds Weathering Profile is similar to other weathering profile exposures in the upper Eocene horizons of the Badlands and elsewhere. He provides supporting evidence that many of the characteristic structures in the Yellow Mound Weathering Profile are related to root structures and pedogenetic processes. Retallack (1983) established a type locality for the Yellow Mounds Weathering Profile in Badlands National Park with descriptions prepared along a ravine in the Dillon Pass area approximately one mile northwest of the intersection of Conata Road with Badlands Loop Road in NE, NW, Sec. 20, T2S, R16E in the "Pinnacles" section of the North Unit (close to the location of the photograph in Fig. 59, p. 174).

Retallack (1997) implied that the Yellow Mounds Weathering Profile formed from pedogenic (soil-forming) processes in humid climates occurring during the long period of exposure prior to a significant change to a drier climate which began in Late Eocene time when Chamberlain Pass and Chadron age deposits began to accumulate in the region. The occurrence of unconformable surfaces between the Pierre Shale and overlying Fox Hills, between the Lower and Upper Units of the Fox Hills, and between the Fox Hills and the overlying Chamberlain Pass Formation suggest that Yellow Mounds-style weathering profiles began to develop as early as middle to late Maastrichtian time when deposits were first exposed to subaerial exposure.

# CHAPTER 10

## GEOLOGIC HISTORY

This chapter integrates information from previous chapters to review the geologic history of the study area. Perhaps the most critical question of this research is how eustatic changes in sea level or pulses of tectonism affected sedimentation patterns in the greater Black Hills region and specifically in the Badlands National Park area. Discussion begins with an interpretation of sequence stratigraphy in the Badlands National Park area. This is followed by a discussion about the influence of tectonism on sedimentation patterns in the Western Interior region and within the study area, including an examination of what can be inferred about early stages of uplift in the Black Hills region. A summary of the geologic history is presented using a series of schematic cross-sections and maps showing the progression of shorelines and sedimentary facies around the ancestral uplift in the Black Hills region. The chapter concludes with suggestions for future research.

### 10.1 SEQUENCE STRATIGRAPHY OF BADLANDS NATIONAL PARK

Fig. 111 is a generalized columnar section representing the Sage Creek

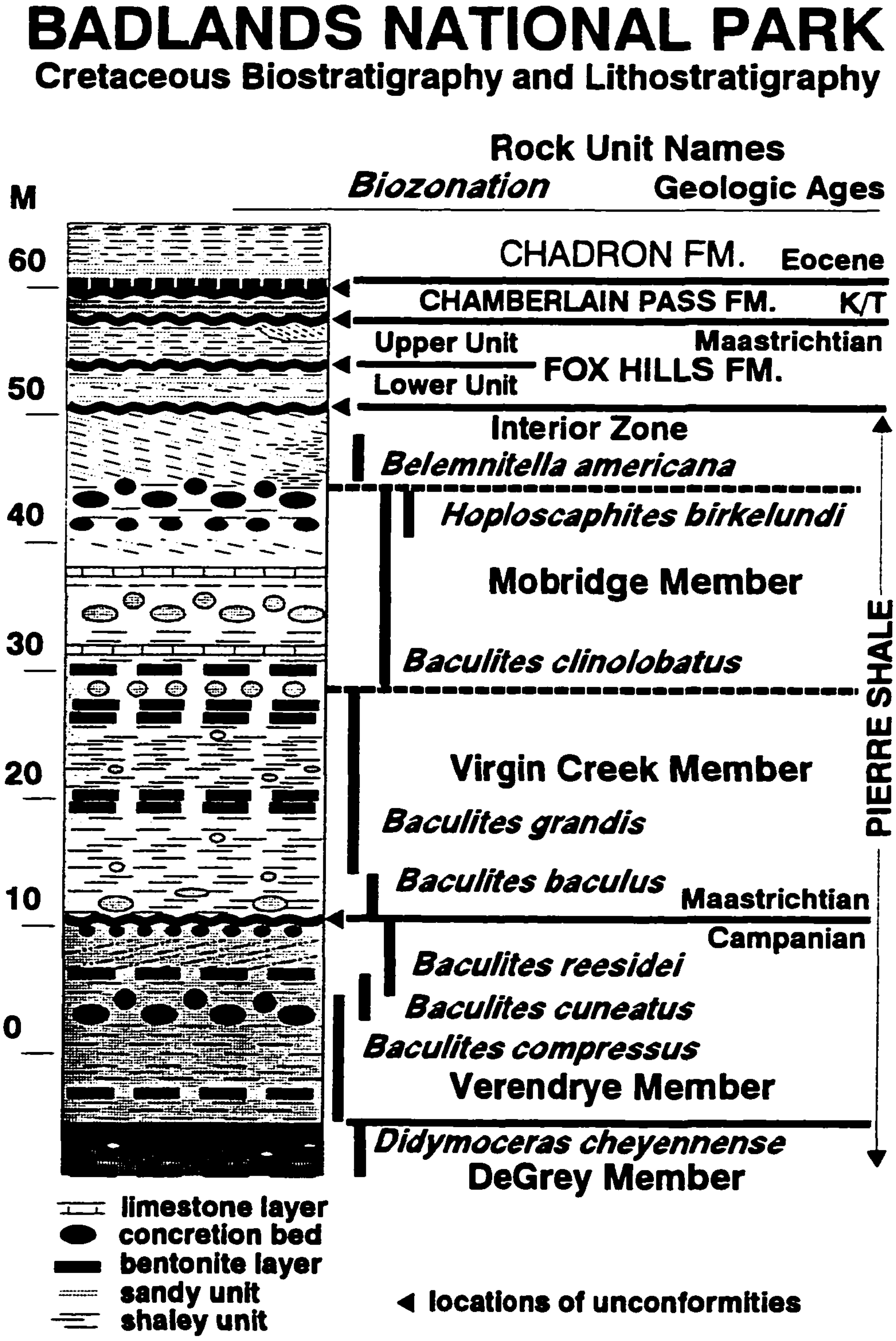


Fig. 111. A generalized composite columnar section for the Sage Creek Wilderness Area in the North Unit of Badlands National Park.

Wilderness Area in Badlands National Park. This section illustrates the general lithologic characteristics which are incorporated into the interpretation of sequence stratigraphy presented below. In interpreting sequence stratigraphy, it should be recognized that both gradual regional uplift and a eustatic fall in sea level will produce similar effects on the geometry of sedimentary facies. Correlation over long distances across a basin and to other regions around the world must be used to differentiate whether transgressive/regressive patterns in sedimentary sequences are a result of tectonism or eustacy.

Fig. 112 outlines an interpretation of the occurrence of sedimentary features associated with stages of transgressive-regressive cycles observed in the upper Pierre Shale and Fox Hills Formation in the Badlands National Park area. This figure represents a sea level curve model that places sedimentary features observed in outcrops in the context of sequence stratigraphy after Bally (1986) and Haq et al., (1987). It is important to emphasize that the science of sequence stratigraphy interpretation evolved from the study of coastal margins, and that these models apply to the Western Interior Seaway with some modification. For example, when sea level falls along a coastal margin, rivers and streams cut down into their flood plains, and sediments are reworked and deposited on deep-sea fans beyond the shelf edge. However, the Western Interior Seaway had no significant shelf break or deep basin area. There was no place where the sediments of a lowstand system tracts could

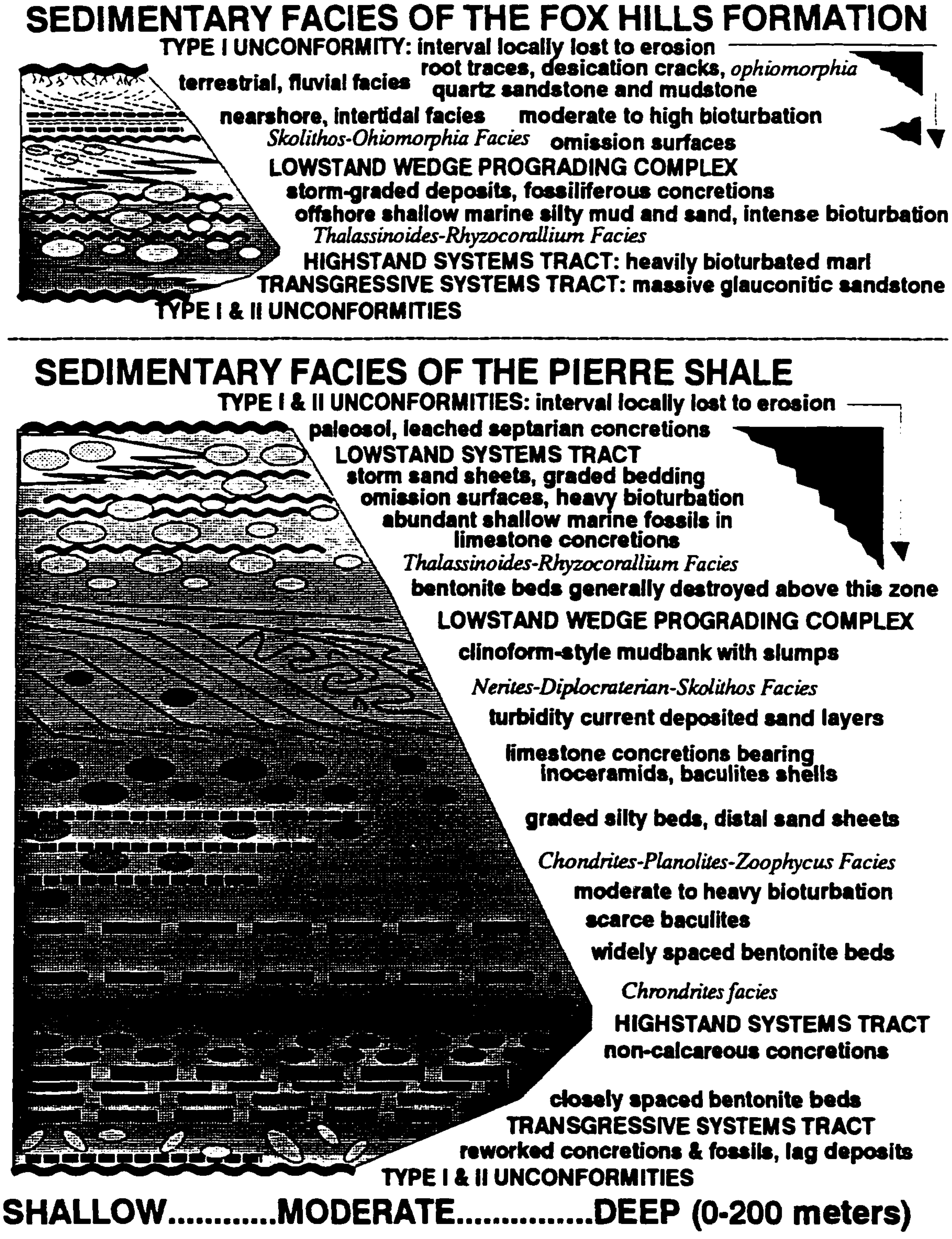


Fig. 112. Sedimentary facies models for the Pierre Shale and Fox Hills Formation. The occurrence of lithological and paleontological features are used in the interpretation of relative changes in sea level in the Western Interior study area.

accumulate in a deeper water setting. Rather, very rapid regression must have occurred over long distances in regions of little or no relief on the sea bottom. This would have forced rivers to expand their flood plains into great coastal swamplands. In addition, with an abundance of fine-grained sediment trapped in extensive shallow marine environments the water must have become very turbid during storm events when wave energy affected the sea bottom across large portions of the shallow seaway. Unidirectional current transport of sediments by basin currents resulted in the development of submarine mudbanks which relatively quickly would fill in accomodation space below wave base.

Not all features in Fig. 112 were observed in individual outcrops, however, this generalized sedimentary facies model is an interpretation based on the examination of numerous outcrops throughout the study area. The term, sedimentary facies, is defined as any aerially restricted part of a designated stratigraphic unit that exhibits characters significantly different than those of other parts of the unit (*AGI Dictionary of Geological Terms*). Within the context of this sequence stratigraphy model, the term, sedimentary facies, perhaps applies to the collective grouping of sedimentary features, such as concretion horizons, trace fossils, or bentonite beds, which are used to interpret characteristics of systems tracts. Explanation for this model is as follows.

The bottom of Fig. 112 shows hypothetical water depths, ranging from shallow to deep, with "deep" meaning a maximum water depth of about 200 meters as suggested by Gill & Cobban (1966), and "shallow" meaning intertidal to slightly above sea level. The base of the model for the Pierre Shale is a Type I or II unconformity. The occurrence of a weathering profile beneath an unconformable surface indicates a Type I unconformity. A Type II unconformity is an erosional surface that reflects submarine erosion which occurred within the depth range above storm wave base. A Type II unconformity may be difficult to recognize within a sequence of mudrocks. However, in the Pierre Shale unconformable boundaries can be expressed as lag deposits consisting of reworked materials (including phosphatic pebbles, fossils, and concretions). In fresh outcrops they are represented as a locally scoured surface, or simply a color change in the sediment. In Fig. 112, the Type II unconformity represents the base of a thin transgressive systems tract. The Campanian-Maastrichtian boundary unconformity displayed all of these characteristics in different locations.

Once water depths have increased to about 40 meters the sea bottom is rarely affected by storm wave-generated currents. Without wave energy bentonite beds are more likely to be preserved. Closely spaced bentonite layers may represent volcanic eruptions in rapid succession. However, within the context of sequence stratigraphy, these closely spaced bentonite beds may be interpreted differently. If it is assumed that volcanic eruptions capable of generating bentonite beds occur in a random but consistent pace through time, then the general spacing of bentonite beds provide an indication of changing sedimentation rates. Closely spaced bentonite beds suggest that the flux of sediment derived from the western margin of the seaway and transported to the central basin area was slowed by the generation of accommodation space along the margins of the seaway during a transgression. In this manner the later stage of a transgressive systems tract would be represented by closely-spaced bentonite beds. A highstand systems tract is perhaps represented by an inflection in the spacing of bentonite beds. Other features associated with a highstand systems tract would include biofacies consistent with more dysaerobic or anoxic deeper-water conditions (such as *Chondrites* ichnofacies and/or a general lack of fossil material). Reduced oxygen supply would allow more organic matter to become incorporated into the sediment. The lower eH/pH conditions would prevent calcareous concretions from forming, but would allow the formation of siderite and phosphorite concretions (Gautier, 1982; Curtis & Coleman, 1986).

In the Pierre Shale model shown in Fig. 112, regression proceeding toward a lowstand in sea level is represented by sedimentary units formed in part by episodic sedimentation events, probably as a result of storms. Where bioturbation hasn't completely destroyed the original bedding features these deposits are expressed as silty-to-shaley graded-bedding. In Fig. 112 a regression sequence overlies the highstand systems tract, beginning with concretion-bearing, graded-bedding units formed in deep to moderate depths below wave base. This is overlain by rapid sedimentation features associated with a lowstand wedge prograding complex in the transition from moderate to wave-base depths. This is expressed in the form of prograding clinoform-style mudbanks where a unidirectional sediment supply progressively fills accommodation space below wave base. The uppermost portion of a depositional cycle consists of shallow water, storm-dominated facies. This represents a lowstand systems tract where these deposits have not been removed or destroyed by submarine or subaerial erosion (representing a Type I or Type II unconformity at the top of the sequence).

In Fig. 112 the cycle representing the Fox Hills is slightly different because water depths during Fox Hills deposition rarely exceeded wave base during storms. In Badlands National Park the transgressive and highstand systems tracts in the Fox Hills consists of reworked intraformational materials, mainly pelletal material converted to glauconite. In the Mobridge/Grand River area, however, the bioturated marl of the lower Trail City Member indicates that the water depths were greater. These marly facies represent a highstand systems tract in that region. Beds of fossiliferous concretions representing "rapid kill events" in the middle and upper Trail City Member suggest that massive amount of sediments were deposited during storm events (Waage, 1964). The Trail City and Timber Lake Members represent a shallowing-upward sequence. Within the Fox Hills Formation throughout the Western

Interior region the lowstand systems tract of the upper Fox Hills is represented by the rapid progradation of quartz sand-bearing nearshore, littoral, and coastal terrestrial facies across the region as the seaway withdrew eastward and southward. In the Badlands National Park area, the unconformable surface between the Lower and Upper Units of the Fox Hills probably represents a scoured surface created as the high-energy surf zone migrated eastward and southward across the crest of the Sage Creek Anticline. The Upper Unit probably represents intertidal to fluvial facies as sea level continued to fall.

Fig. 113 is an interpretation of the sequence stratigraphy for the study interval in the Badlands National Park area. Portions of three cycles of transgression and regression are represented in the upper Pierre Shale, with an additional cycle represented by the Fox Hills Formation. The figure includes an interpretation of the Western Interior ammonite zones after Cobban (1993) in relation to named stratigraphic units. The arrangement of sedimentary facies associated with systems tracts is intended to demonstrate that sediment source areas were to the west. This includes both the riverine input from the western margin of the seaway and probably from the reworking of sediments derived from the rising uplands in the Black Hills area. The reasons for this interpretation of sequence stratigraphy is as follows.

The DeGrey Member consists of dark gray bentonitic shale bearing non-calcareous concretions and deep water fauna (suggested by the presence of

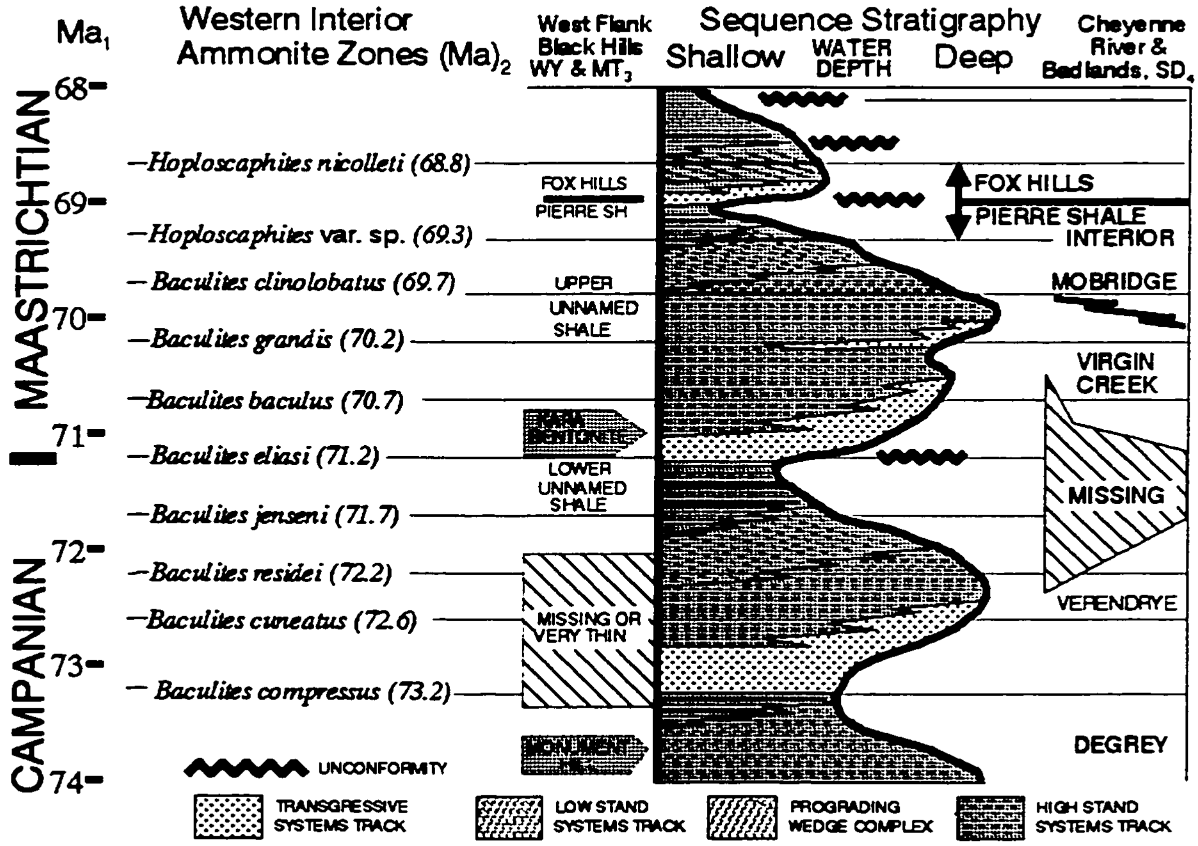


Fig. 113. Interpretation of the Cretaceous sequence stratigraphy of the Sage Creek Wilderness Area in the North Unit of Badlands National Park.

*Didymoceras*), whereas the overlying Verendrye Member contains abundant marine fauna and limestone concretions bearing *Thalassinoides-Rhizocorallium* ichnofacies in the *Baculites compressus* Zone. This suggests that in the Badlands area water depths grew increasingly shallower to a lowstand during *Baculites compressus* time. The lack of abundant fossils and the occurrence of several thin bentonite beds in the overlying *Baculites reesidei* Zone suggests that water depths increased again during a transgression. However, the occurrence of clinoform-style mudbank in the *Baculites reesidei* Zone in the South Unit of Badlands National Park suggests that sea level fell again, creating a lowstand wedge prograding complex before the seas receded or withdrew from the Badlands region during *Baculites jenseni* and *Baculites eliasi* time. Supporting evidence of this interpretation includes the local occurrence of a paleosol beneath the Campanian-Maastrichtian boundary unconformity along the South Fork of Sage Creek, and similar weathering features in along Cedar Creek (in the South Unit), and in exposures on the Tom Trask Ranch area.

Fig. 35 (p. 118) perhaps best illustrates the features used for interpretation of a halting transgression across the region during *Baculites baculus* into *Baculites grandis* time. This photograph shows several closely-spaced, well-preserved bentonite beds which suggest that the sediment supply rate was slow between ash fall events. These facies suggest a transgression occurred with maximum high-standing seas in *Baculites grandis* time. The occurrence of bentonite beds within the *Baculites* *clinolobatus* Zone suggests that high-standing seas persisted in the region until that time. The extensive concretion-bearing horizons at the top of the *Baculites clinolobatus* Zone suggests that regression occurred as a series of massive storm-generated sedimentation events between extended quiescent periods. The quiescent periods lasted long enough for diverse benthic communities to become re-established after each catastrophic storm. Progradation of a clinoform-style mudbank across the Badlands area preceded the withdrawal of the seaway during *Hoploscaphites birkelundi* time. The mudbank of the Interior Zone represents a lowstand wedge prograding complex with a geometry influenced by contemporaneous movement along the Sage Creek anticline/fault system. A period of subaerial exposure occurred prior to the return of the sea is indicated by the weathering profile and scoured surface along the Pierre Shale-Fox Hills boundary unconformity.

Fig. 58 (p. 172) shows the basal massive glauconitic sandstone at the base of the Fox Hills Formation (representing the Lower Unit). The occurrence of this glauconitic sandstone unconformably overlying the top of the Pierre Shale suggests that a transgression occurred across the region. The abundance of glauconite, but the lack of extraformational sand materials (i.e., quartz) suggests that winnowing action of waves energy concentrated the intraformational sand fraction from local sediments as transgression proceeded. However, the occurrence of the clinoform-style mudbank in the Lower Unit of the Fox Hills in the Grassy Tables Overlook area suggests that sedimentation rates in that location were faster than the development of accommodation space during transgression in that area. In Fig. 58, the Upper Unit of the Fox Hills Formation contains quartz sandstone layers consistent with an interpretation of regression at the close of Fox Hills time.

Fig. 114 is a comparison of the sea level curve from this investigation with the global sea level curve reported by Haq et al., (1987) and a curve for Western Europe defined by Hancock (1993). Whereas the overall pattern of sea level rise and fall are similar, the resolution to specific time boundaries are significantly different. The reason for the differences is unclear. Detail about the Campanian and Maastrichtian data were not included in the Haq article. In general, the curve presented in this report most closely matches the curve by Hancock for Western Europe. Where the curves closely parallel is a good indication that sea level fluctuation was a global event. The fall in sea level at the end of the Campanian (~72 Ma) and again at the end of the Early Maastrichtian (~69.5 Ma) are recorded in both Western Europe and in the Western Interior. Peak transgressions occurred within the ranges of ***Baculites cuneatus*** to ***Baculites reesidei*** (~72.5 Ma), during ***Baculites grandis*** to ***Baculites clinolobatus*** time (~70 Ma), and during ***Hoploscaphites nicolletii*** time (~68.5 Ma).

The greatest difference between the three curves is in my interpretation of a lowstand having occurred during ***Baculites compressus*** time in the Badlands region. Gill & Cobban (1973) also suggested that sea level was rising during ***Baculites***

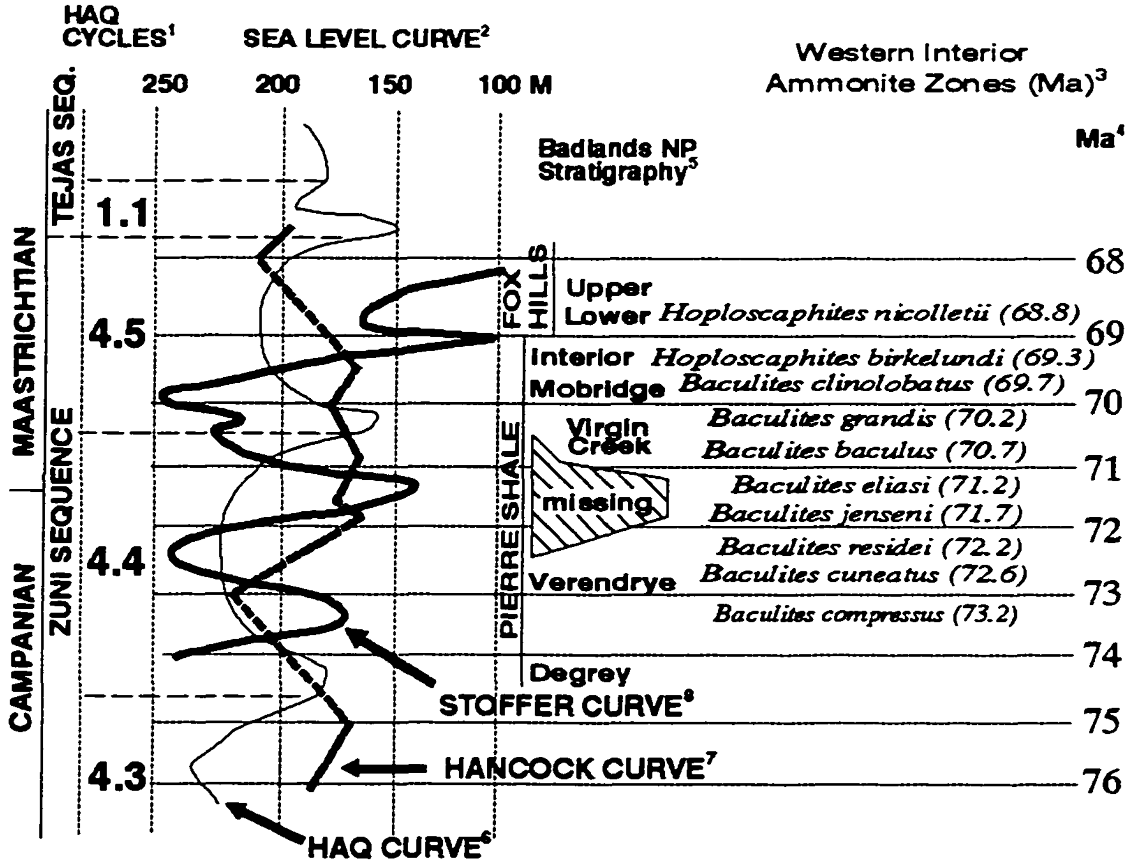


Fig. 114. Comparison of Late Campanian and Maastrichtian sea level curves. Numbered superscripts: 1: global sea level cycles from Haq et al., (1987); 2: water depths relative to modern sea level (higher) from Haq et al, (1987); 3: Western Interior ammonite range zones (Cobban, 1993; with dates from McArthur et al., 1994); 4: age in millions of years before present based on dates by Haq et al., (1987) and McArthur et al., (1994); 5: stratigraphy of Badlands National Park (this report); 6: global sea level curve from Haq et al., (1987); 7: sea level curve for western Europe from Hancock, (1993); 8: sea level curve (this report).

*compressus* time as indicated by the westward migration of marine facies onto the western margin of the seaway. Perhaps the differences in interpretations is that a pulse of tectonic uplift occurred in the Black Hills/Badlands region during *Baculites compressus* time. Fossiliferous concretions bearing *Thalassinoides/Rhizocorallium* ichnofacies occur in the Badlands region, but vanish eastward in the Missouri River Valley where probably deeper water conditions persisted. Deeper water conditions also persisted during *Baculites compressus* time in the Powder River Basin region as indicated by the thick sequence of dark shale within the zone in the Casper, Wyoming area. Gill & Cobban (1966) suggest that the zone was either not deposited or was eroded away in the Redbird area. This evidence suggests that the greater Black Hills region, including the Badlands area, was a rising tectonic bulge within the seaway. The abundant fauna preserved in the *Baculites compressus/cuneatus* Zones in the Badlands National Park area is another indication that shallower conditions existed on the eastern flank of the Black Hills at that time.

Hancock (1993) reported that a eustatic cycle represented in the Western Interior region by the *Baculites baculus/grandis/ clinolobatus* interval is better resolved and more extensive than an age-equivalent cycle in the European section. Hancock also reported that a strong pulse of transgression is recorded in the European section which culminated a highstand around 68 million years ago. This highstand probably correlates to the Fox Hills Cycle in the South Dakota region. However, the progressive uplift of the central Rocky Mountains during middle Maastrichtian time reduced the significance of this eustatic cycle in the Western Interior region in comparison with this cycle in Europe.

## 10.2 TECTONISM IN THE WESTERN INTERIOR REGION

The name, Laramide Orogeny, is referred to in textbooks as the formation of the Rocky Mountain ranges and basins on the western foreland region beginning near the end of the Cretaceous. The following discussion includes examples of Laramide tectonism associated with sedimentation processes during the Campanian-early Maastrichtian interval throughout the Western Interior region. However, it is with some difficulty that the name Laramide is applied to structures in the Pierre Shale in South Dakota. Structures affecting the Pierre Shale in the South Dakota region may be more related to reactivation of much older Precambrian and Paleozoic structures, yet the same argument of reactivation of older structures may be applied to most if not all Laramide structures. Recent seismic activity in the region suggests that many faults remain active (Shurr, Hammond & Bretz, 1994).

The oldest known occurrence of granitic cobbles from the core of the Black Hills in the Badlands National Park area are in the basal conglomerate of the Chamberlain Pass and basal Chadron Formations (middle Eocene)(Evans & Terry, 1993). This observation has been used to support an argument that uplift of the Black

Hills began much later in the Tertiary. However, the removal of unconsolidated Cretaceous sediments and erosion of older Mesozoic and Paleozoic sedimentary rocks from the core of the Black Hills uplift must have occurred well before the middle Eocene. Lisenbee (1988) proposed that synchronous development of the intra-cratonic Powder River Basin and the Black Hills uplift was initiated in the Paleocene. He conclusions are based on the work of Lewis & Hotchkiss (1981) and Flores & Ethridge (1985) who demonstrated that Precambrian rocks in the Black Hills uplift were a source of sediment for the Tullock Member of the Paleocene Fort Union Formation. These researchers demonstrated that in eastern Wyoming sand percentage increases toward the Black Hills uplift, and that paleocurrent directions based on cross-bedding orientation indicate a westerly flow away from the uplift. Lisenbee reported that in Paleocene time a large trunk stream flowed northward out of the Powder River Basin and around the north flank of the Black Hills into the Dakotas. Merin & Lindholm (1986) demonstrated that Precambrian age cores of the ranges on either side of the Powder River Basin were breached during Paleocene time, and that metamorphic debris derived from the Black Hills is incorporated in Late Paleocene sediments north of the uplift.

If Precambrian-age metamorphic materials derived from the core of the Black Hills occur first in the Paleocene sediments of the Powder River basin, then the unroofing of the sedimentary cover must have began much earlier. The thickness of the sedimentary Paleozoic and the pre-Maastrichtian Mesozoic section varies around the Black Hills region from as much as 5,000 meters in the Powder River Basin, 3,000 meters in the Williston Basin area, and around 1,800 meters in the Badlands area (AAPG *COSUNA Chart*, 1983; Rachel Benton, personal communication, 1997). Judging by the aerial extent of the Black Hills roughly 20,000 cubic kilometers of sedimentary cover were removed by erosion from the crest of the Black Hills prior to Late Paleocene time.

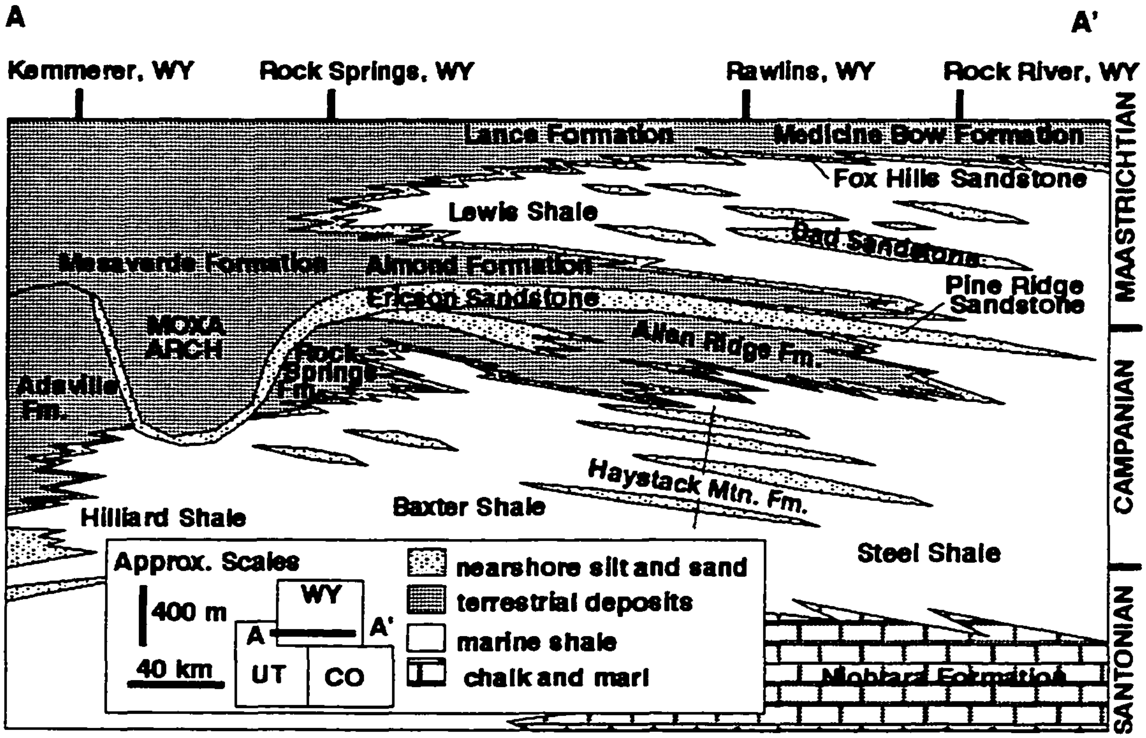
For comparison, Keefer (1965), Flemings & Nelson (1991), and Gillespie & Fox (1991) demonstrated that Laramide tectonism began during the Late Cretaceous (Campanian) in the Wind River Basin and along the Casper Arch (on the western side of the Powder River Basin) no later than Maastrichtian time. Between rising uplifts the deposition of fine-grained sediments in marine to brackish waters persisted in the Wind River and Powder River Basins though Paleocene (Fort Union) time. During latest Campanian and Maastrichtian time sedimentation patterns of deltaic sequences were controlled by uplifted obstructions. However, the first occurrence of granitic cobbles from the cores of Wyoming ranges were first incorporated into basin sediments in middle Eocene time (defining the boundary between the Indian Meadows Formation and overlying Wind River Formation - the Wyoming equivalent of the Chadron Formation)(Keefer, 1965; Keefer, 1970). The change from deltaic fine-grained sands and mud to alluvial gravels in central basin regions of the Western

Interior is probably a reflection of a wet-to-dry climate change during the transition from Late Eocene to Oligocene time (Retallack, 1997). In this view, the ranges were being eroded earlier (during the Late Cretaceous), but chemical weathering during more humid periods produced a different sedimentary sequence with less coarse clastic material being transported to the seaway.

Abundant evidence from throughout the Western Interior suggests that faults associated with Laramide structures were already active through Late Cretaceous time. Kauffman (1990) stated that "basement blocks moved in around the Denver Basin contemporaneous with sedimentation in all cycles." LaFerriere & Hattan (1989) suggested that active structures during deposition of the Fort Hayes Member of the Niobrara Formation (Santonian) in the Denver-Julesburg Basin in Colorado and western Kansas are responsible for thickness changes in the unit, and attributed the tectonism to "Cretaceous reactivation of the Transcontinental Arch."
Mereweather (1990) stated, "regional unconformities have been identified at... the base of the Teapot Sandstone Member of the Mesaverde [Formation]. The unconformities probably represent subaerial and submarine erosion associated with eustacy and regional tectonism." In Mereweather's view, the Teapot Sandstone is probably a latest Campanian low-stand systems track sandstone that underlies the Bearpaw Shale in the central and western portions of the Powder River Basin in eastern Wyoming.

Roehler (1993) described unconformable stratigraphic relations between strata along the crest of the Moxa Arch in western-central Wyoming. Fig. 115 is a redraft of Roehler's generalized cross-section across southern Wyoming (approximately along Interstate 80). It illustrates the stratigraphic framework of the Claggett and Bearpaw cycles. Of primary concern to this research is his interpretation of a rapid transgression around the time of the Campanian-Maastrichtian boundary represented by the Pine Ridge Sandstone. The equivalent units of the Pine Ridge sandstone truncate older Campanian strata uplifted along the crest of the Moxa Arch in western Wyoming. Both the Teapot Sandstone and Pine Ridge Sandstone are age-equivalent to the *Baculites cuneatus* zone (Cobban, 1965; Wyoming Geological Association, 1978; Love, Christiansen & Ver Ploeg, 1993).

Further evidence for tectonism in central Wyoming during early Maastrichtian time is presented by Winn, Bishop, & Gardner (1987) who provided evidence for tectonic control of shifting deltaic sedimentation patterns in the Wind River Basin region of Wyoming during late *Baculites grandis* time. Their theory for tectonic control of sedimentation is based on observations by Keefer (1965) and Gries (1983) who proposed that subsidence of the Wind River Basin and uplift of the Granite Mountains in central Wyoming were active at that time. Gill & Cobban (1973) discussed the importance of "local crustal instability in affecting transgression and regression" during the Bearpaw cycle. They suggest that the formation of the



(After H. W. Roehler, 1993. USGS PP 1532, p. 6.)

Fig. 115. East-to-west cross-section across southern Wyoming showing facies relations of marine mudrocks, littoral sand facies, and terrestrial deposits. Stratigraphic relations on the crest of the Moxa Arch in Western Wyoming suggest that tectonism preceded erosion and marine transgression within the vicinity of the Campanian/Maastrichtian boundary interval.

Elkhorn Mountains and Deer Creek volcanic centers in southern Montana deflected drainages into the Wyoming/Montana border region. This initiated the first phase of Fox Hills regression represented by the eastward progradation of the Sheridan Delta complex along the Wyoming-Montana border region and into the Dakotas starting during *Baculites baculus* time and lasting into *Baculites clinolobatus* time.

Kauffman (1990) described rocks of late Campanian-early Maastrichtian age in the Canon City structural embayment, a structural down-warp west of the Colorado Front Range, west of Pueblo. Regarding the Bearpaw cyclothem in that region he stated that a peak transgression is represented by the Tepee Zone in the Pierre Shale. He suggested that the origin of tepee buttes, which are essentially bus-sized concretions, were "submarine spring deposits emplaced along Laramide faults." The Tepee Zone of the Pierre Shale is equivalent in age to the DeGrey Member and Verendrye members and encompasses the biozones ranging from *Baculites scotti* to the base of *Baculites compressus* (Scott & Cobban, 1986). As discussed in the previous chapter (starting on p. 350) tepee buttes-like features occur on the western flank of the Black Hills. Their occurrence in the *Baculites grandis* Zone is an indication that uplift of the Black Hills was already in progress, and giving hydrostatic pressure to submarine springs in the region during Maastrichtian time.

Weimer & Land (1975) described contemporaneous "growth-faulting" as being responsible for changes of about 200 feet in the thickness of the Pierre, Fox Hills, and Laramie Formations (Maastrichtian) across fault boundaries in the Denver region. Weimer & Land's interpretation that growth faults affected the geometry of sedimentary facies, and caused over-steepening of sediments along the front of a prograding deltaic complex. This resulted in the formation of slumps within the transition interval between the Pierre Shale and Fox Hills Formations throughout the Front Range region in Colorado. They also suggested that movement along basement faults controlled the geometry of sedimentary facies in the Pierre/Fox Hills transition. Their interpretation also applies to the faulting and slumping associated with the Interior Zone and Fox Hills Formation along the Sage Creek anticline/fault system in Badlands National Park.

The sedimentation patterns in the upper Pierre Shale/Fox Hills interval in the Badlands region suggest that uplift of the Black Hills region was already occurring in the Late Campanian, and increased during Maastrichtian time. Supporting evidence discussed in previous chapters include the following. The most obvious evidence is the general thinning of members on the eastern flank of the Black Hills, and the occurrence of well-defined unconformities in the Badlands National Park Region (Fig. 116). In addition, uplift in the Badlands region resulted in shallower water depths which caused the enriched concentration of intraformational clastic materials by the winnowing action of wave energy. If uplift raised the seabed in the Black Hills and Badlands National Park region within the range of wave base, then wave energy and

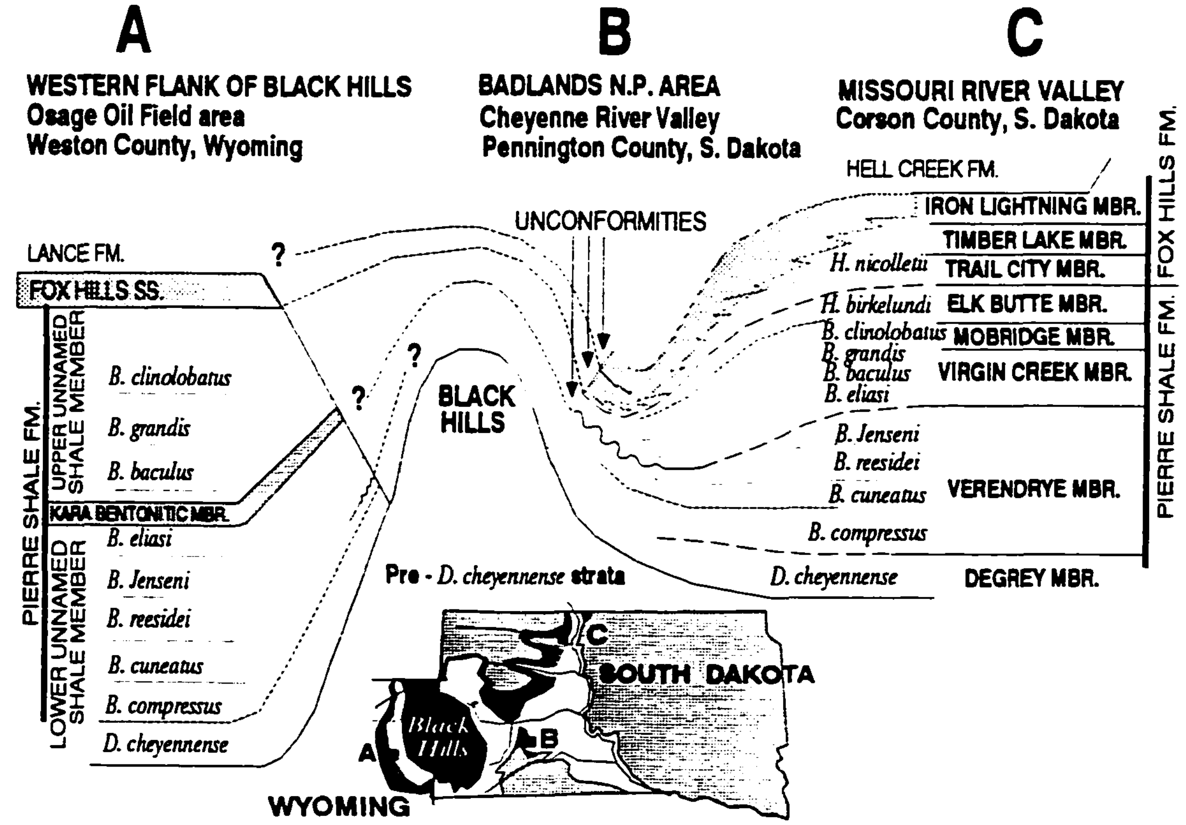


Fig. 116. Cross-section of the upper Pierre Shale and Fox Hills Formation across the study area showing the thinning of lithologic units along the eastern flank of the Black Hills.

currents would have redistributed sediments, particularly the finer materials, to deeper water settings beyond the influence of wave-generated currents.

Obstruction of the eastward flow of clastic debris from western sources by uplift in the Black Hills may also explain the geometry of the clinoform-style mudbanks in the Badlands region. For instance, Gill & Cobban (1966) reported that the zones of *Didymoceras cheyennense*, *Baculites compressus*, and *Baculites cuneatus* are missing from the Redbird, Wyoming type area. Our observation that these fossils and sediments from these zones were reworked into the upper *Baculites reesidei* Zone and into the base of the *Baculites baculus* Zone suggests that uplift and erosion occurred in that region and perhaps across and around the crest of the Black Hills. The combined effects of uplift and falling sea level could explain the development of the northeastward prograding mudbank in the Cedar Creek area of the South Unit during *Baculites reesidei* time and the well-developed unconformity in along the Campanian/Maastrichtian boundary unconformity throughout the Badlands region. Perhaps uplift of the Black Hills region began as a broader structural up-warp during Late Cretaceous time, with the more restricted uplift that defines the modern Black Hills having developed later in the Tertiary.

The occurrence of uplift in the Black Hills region perhaps best explains the geometry of the Sheridan Delta complex described by Gill & Cobban (1973). They show that the shoreline migrated eastward along the Wyoming/Montana border into

South Dakota starting during *Baculites grandis* time, and proceeding eastward into South Dakota during *Baculites clinolobatus* time. The occurrence of the southward-prograding clinoform-style mudbanks of the Interior Zone and Fox Hills Formation in the North Unit shows that progradation proceeded southward in the Badlands area after *Baculites clinolobatus* time. This arrangement of facies suggests that structural obstruction in the Black Hills region forced the flow of sediments around an upland area in the Black Hills region. Supporting evidence for this interpretation is suggested by the regional distribution of the sandstone facies of the Fox Hills Formation. The Fox Hills Sandstone exposed along the western flank of the Black Hills and in the Redbird, Wyoming area is more than 100 meters thick. This sandstone sequence is also about 100 meters thick in the region along the North Dakota/South Dakota border as far east Mobridge. However, these sandy facies are not present in the Badlands Region. The occurrence of fine-grained sediments of Fox Hills age in the Badlands National Park area suggests that obstruction by structural uplift of the Black Hills region blocked the eastward progradation of shoreline facies away from western source areas. Uplift along the eastern flank of the Black Hills prevented the massive accumulation of Fox Hills sediments in the Badlands region, and subaerial exposure resulted in the formation of the weathering profiles along the unconformities beneath, within, and above the limited exposures of the Fox Hills Formation in the Badlands area. Whether the sand in the Fox Hills Formation is derived, in part, from the erosion of sedimentary formations exhumed from the crest the Black Hills is undetermined.

The existence of weathering profiles demonstrates that subaerial exposure occurred several times in the Badlands region in Early Maastrichtian time. The lateritic weathering profiles suggest that humid conditions existed in the region, and therefore, upland areas were probably forested. Tropical to subtropical conditions in the seaway region reduced mechanical erosion and increased chemical weathering. This perhaps explains why there is a lack of sand derived from the unroofing of the Black Hills. In addition, the geometry of the southward prograding mudbanks in the Interior Zone and Fox Hills suggests that sediments derived from the Black Hills area would have been transported southward by coastal marine currents, away from the Badlands region.

Structural features affecting sedimentation pattern in the members of the Pierre Shale have been documented throughout the Missouri Valley region. In central South Dakota in a region encompassing the Pierre and Hayes area many faults have been mapped by Crandall (1958) and Nichols et al., (1994). These researchers demonstrated that numerous normal faults display offset along the "base" of the Virgin Creek Member. Nichols et al., (1994) observed twenty four faults in the region that display a range of offset of 2 to 30 meters along the base of the Virgin Creek Member. Seismic reflection profiles across selected faults in this vicinity indicate that these faults correspond to deep basement faults that display as much as 340 meters of offset (Nichols et al., 1994). Both Crandall and Nichols concluded that the faults display evidence of tectonism which occurred in Late Cretaceous time, but the faults also display evidence of continuous activity through Tertiary time into the present. For instance, Nichols et al., (1994) reported that recent seismic activity along deep basement faults have earthquake focus depths of 17 to 23 kilometers. They also illustrated examples of surface scarps in the Pierre Shale that have offset roads and fields, and demonstrated that these faults are not associated with modern slumps.

Searight (1937) was first to document thickness variations in stratigraphic units in the Pierre Shale in exposures along the Missouri River valley. Within South Dakota, tectonism contemporaneous with sedimentation was illustrated for the upper Niobrara and lower Pierre Shale by Shurr, Hammond & Bretz (1994). They stated that paleotectonic movements of regional structural blocks are documented by thickness and lithologic variation in most Cretaceous depositional cycles. They suggested that differences in the texture and composition of sediments correspond to differences in block position, particularly in regard to the Crow Creek Member of the Pierre Shale (below the DeGrey Member) in the Missouri Valley region. They provided a generalized map of structural lineaments for central South Dakota and suggested that mapped linear features correspond with separate broad anticlinal blocks. They also suggested that basement faults and structures in central South Dakota were active before, during, and after Cretaceous sedimentation.

Post-Cretaceous uplift and tectonism is obvious throughout South Dakota. Most obvious is the occurrence of granitic gravels derived from the Black Hills uplift in the Chamberlain Pass and Chadron Formations (Terry & Evans, 1993). Within Badlands National Park a particularly spectacular example of tectonism contemporaneous with sedimentation is depicted by well-exposed stratigraphic thinning and folding of Eocene and Oligocene sediments along the eastern end of the Sage Creek fault near the "pig dig" site near the intersection of Conata Road and Dillon Pass Road (Sections 27-28, T2S, R16E)(see Fig. 60, p. 170). Several small faults along the Badlands Loop Road in the Dillon Pass/Conata Basin area show erosional truncation along the base of the Tertiary strata. For instance, a small fault in NW, NW, Sec. 28, T2S, R16E displays Fox Hills Formation on the north side of the fault, but the Fox Hills has been stripped away by erosion on the south side of the fault. This indicates that fault movement occurred prior to the erosion of the Cretaceous sediments and the subsequent deposition of the basal White River Group. We observed fossiliferous freshwater limestones in the lower Chadron Formation on the south (down-thrown) side of the Sage Creek fault system. These limestone beds indicate that shallow lakes formed as a result of contemporaneous movement along the faults. These shallow lakes, and possibly springs associated with the faults, might explain the prolific occurrence of bone beds in the White River Group in the Badlands National Park area.

## 10.3 SUMMARY OF GEOLOGIC HISTORY

Sediments deposited in the Western Interior region during the Late Campanian through Maastrichtian record a series of transgressions and regressions and finally the withdrawal of the marine seaway from the region. Cobban (1993) suggested that the overall pattern for the study interval can be included within one great transgression-regression cycle, beginning with the Bearpaw transgression which began in *Baculites compressus* time. A final regression of this cycle is represented by the Fox Hills Formation with totally non-marine facies represented by the Lance and Hell Creek Formations which overly the Fox Hills throughout most of the Western Interior region. Gill & Cobban (1966) did not recognize any "clear cut example of transgression or regression that can be unquestionably related to anything other than local subsidence and uplift." However, with progress in stratigraphic investigations of the coastal margins in Europe, the Atlantic and Gulf regions, and the California coastal regions demonstrate that synchronous eustactic changes in sea level occurred around the world during late Campanian through Maastrichtian time. The sequence stratigraphy interpretation presented above is an attempt to integrate the Badlands section with established sea level curves. Future research will possibly further resolve, clarify, or differentiate the effects of local tectonism versus eustatic changes in sea level. Unfortunately, erosion has removed Late Campanian and Maastrichtian strata from most regions beyond the Western Interior making correlation difficult between the Gulf Coast and the Arctic regions. Glacial cover and poor exposure east of the Missouri River Valley hinders investigation in that region.

The molluscan fauna preserved in the Pierre Shale and Fox Hills Formation suggests that links to the open ocean occurred during periods of the Late Campanian into Maastrichtian time. Cobban (1993) suggested that the seaway sediments in the Western Interior region record a history of migration of ammonite stocks from both the Arctic region (and possibly Greenland region) and from the Gulf Coast region. The pattern in species migration and extinction described by Cobban roughly corresponds to the eustatic cycles illustrated in Fig. 113. During periods of high-standing seas migrant species replaced endemic stocks and, in turn, became endemic, flourished, diversified, then became extinct. In relation to this study, Cobban (1993) reported three intervals when endemic stocks persisted. The first is represented by an endemic center in northern Colorado that peaked during *Baculites compressus* time, but vanished before *Baculites jenseni* time. Cobban demonstrated that stocks in this endemic center were, in part, derived from migrants from the northern link to the open ocean in Canada or Greenland. He also suggested that *Baculites eliasi* represents the end member of a long lineage of baculites (including *Baculites* *compressus* through *Baculites jenseni*). Cobban (1993) suggested that *Baculites baculus* represents an introduction of a new stock from the south, and that its range extended northward into southern Canada. This corresponds to the interpretation that high-standing seas returned during *Baculites baculus* time, allowing the southern species to migrate into the northern portion of the seaway. The lineage of *Baculites baculus-grandis-clinolobatus* vanished when the seas withdrew southward. The fauna of the Fox Hills Formation is best represented in the Mobridge/Grand River region. Cobban (1993) suggested that the ammonites *Baculites columna* and *Discoscaphites* sp. represent migrants from the south which joined the endemic stocks of *Hoploscaphites* which survived from previous cycles in the seaway.

After *Hoploscaphites nicolletii* time the seaway withdrew form the study area. Although bodies of water may have persisted in some of the Laramide basins, it was the end of normal marine conditions in the Western Interior region. The Paleocene Cannonball Seaway replaced the Western Interior Seaway and was host to a brackish water fauna. Although the seaway may have persisted until mid Tertiary time in some portions of the Western Interior region, the inland seaway remained isolated from the ocean.

Gill & Cobban (1973) used maps and cross-sections to summarize their interpretations of the geologic history of the Western Interior Seaway in the region north and west of the study area for this dissertation. In the same manner, Fig. 117

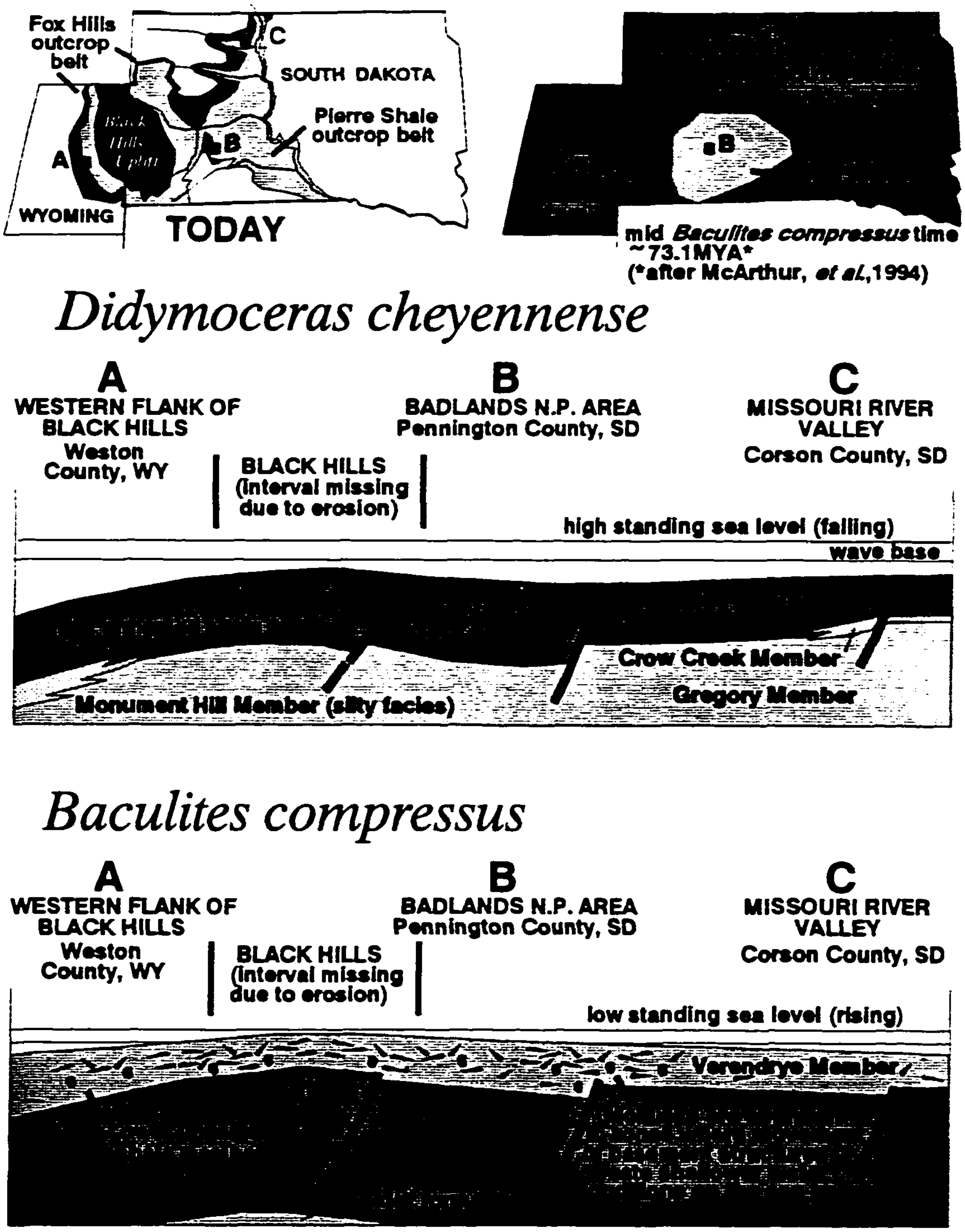


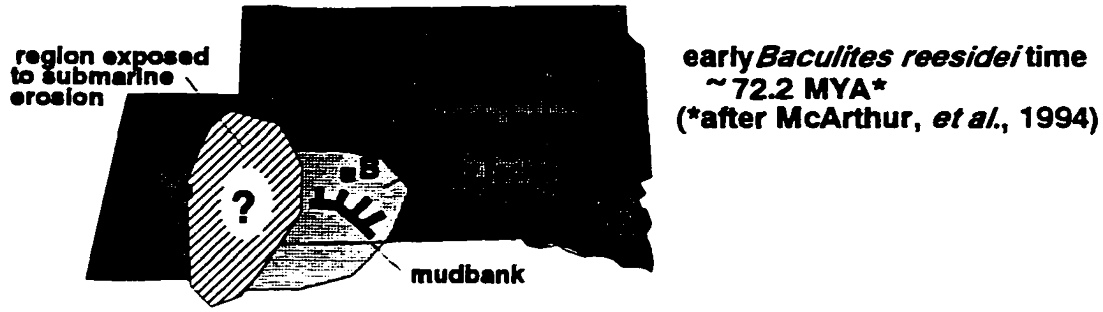
Fig. 117. Depositional setting prior to and including *Didymoceras cheyennense* time (representing the end of DeGrey deposition), and during *Baculites compressus* time (representing the beginning of Verendrye deposition). Features are not to scale. Double lines represent sea level and wave base on all diagrams. Features such as the Sage Creek Fault and faults in the Missouri River Valley are included. Uplift in the Black Hills region is inferred.

through Fig. 122 display maps and cross-sections for each ammonite zone in the study interval, and represents an interpretation of the geological history of the study area. These diagrams integrate data from the regional correlation section (Chapter 8), and the interpretation of the sequence stratigraphy presented above. This series of figures shows the chronology of changes beginning prior to *Baculites compressus* time and ending with the withdrawal of the seaway during Hell Creek time at the end of the Maastrichtian. Each page shows two cross sections of consecutive ammonite zones and a representative sedimentary facies map at the top for the two zones. The early stages of gradual uplift in the Black Hills region are assumed in these diagrams. The subsurface faults on the right side of the cross-sections are schematic representation of basement structures such as the Sage Creek Fault in the Badlands National Park area or similar faults reported by Nichols et al., (1994) in the Missouri Valley region. The direction of eustatic change is also included on each cross section (i.e., rising, stationary, or falling sea level). On each diagram two lines are used to indicate the sea surface (above) and wave base (below). Although the diagrams include the eastern South Dakota region, the Pierre Shale and Fox Hills was not examined in that region. The continuity of marine facies eastward to the Transcontinetal Arch is assumed based on the known occurrence of Pierre Shale in that region (Shurr *et al.*, 1994).

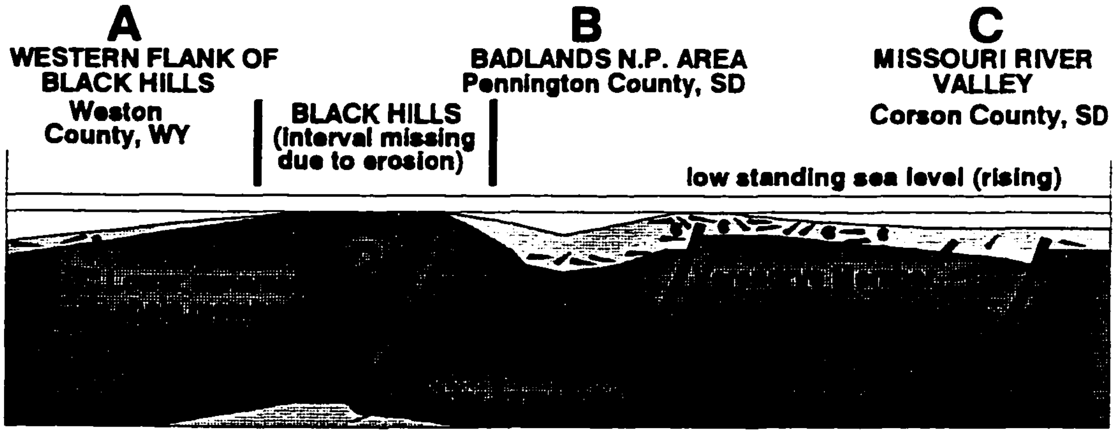
Fig. 117 illustrates the affects of falling sea level from *Didymoceras* *cheyennense* time starting at approximately 74 million years ago, culminating in a lowstand around 73.2 million years ago during *Baculites compressus* time. The fall is sea level resulted in the reworking of sediments by wave energy in the region in the Black Hills area. This increased the silt content in the sediment in the vicinity along the eastern flank of the Black Hills relative to deeper water setting in the Powder River Basin to the west, and the Missouri Valley region to the east. In the region around Badlands National Park benthic communities flourished and, in-part, supported a rich swimming molluscan fauna and the marine reptiles which preyed on them.

Fig. 118 shows that sea level rose again during *Baculites cuneatus* time resulting in a brief highstand about 72.5 million years ago. A more intense fall in sea level than the previous cycle began during *Baculites reesidei* time around 72.2 million years ago. This may have been compounded by an accelerated rate of uplift in the Black Hills region. This resulted in the stripping away of recently deposited sediments from the crest of the Black Hills region. Some of these reworked sediments, including concretions and fossil debris, became incorporated into a submarine mudbank along the eastern flank of the Black Hills.

Fig. 119 shows that sea level continued to fall to a lowstand during late *Baculites jenseni* time around 71.5 million years ago. This resulted in the development of an unconformable surface across the South Dakota portion of the study area, with subaerial exposure occurring is portions of the region around the



*Baculites cuneatus*



*Baculites reesidei*

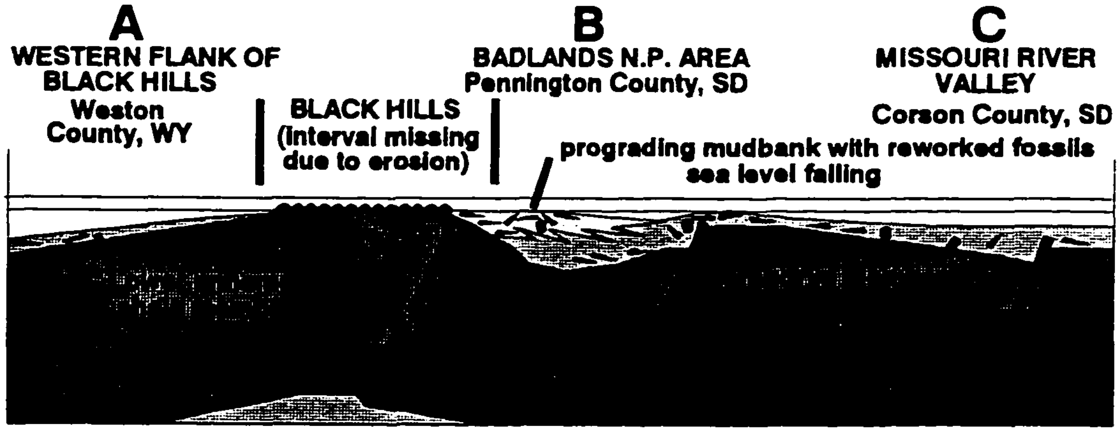
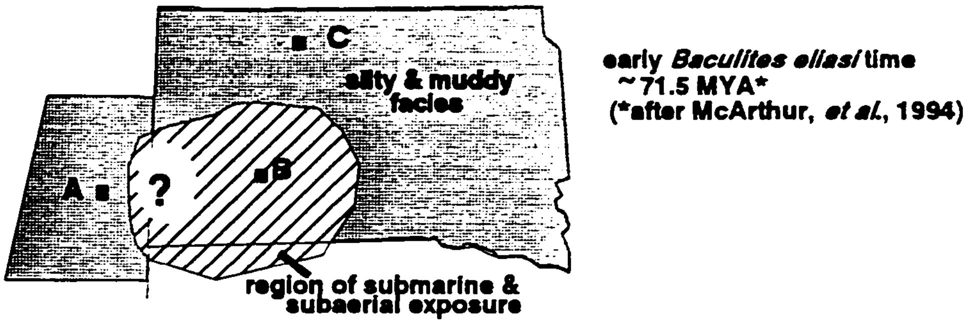
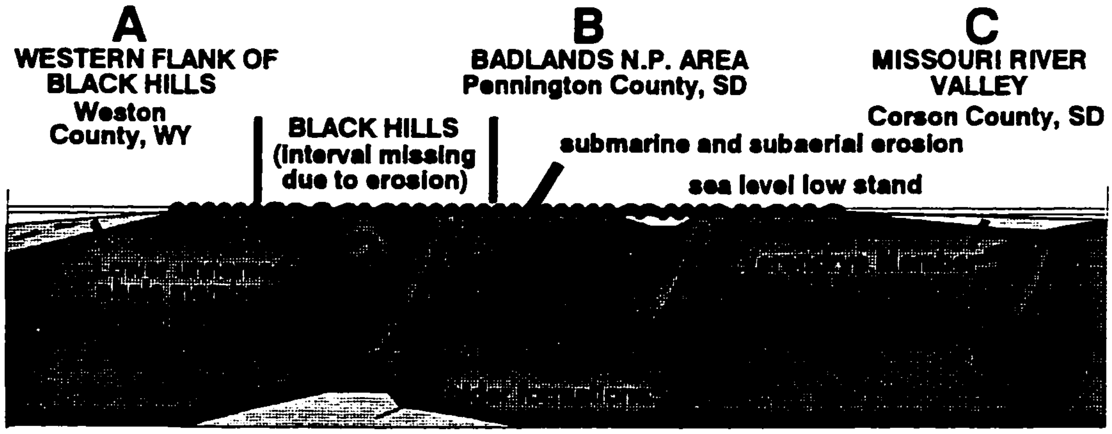


Fig. 118. Depositional setting during *Baculites cuneatus* and *Baculites reesidei* time. (Features not to scale.)



*Baculites jenseni*



*Baculites eliasi*

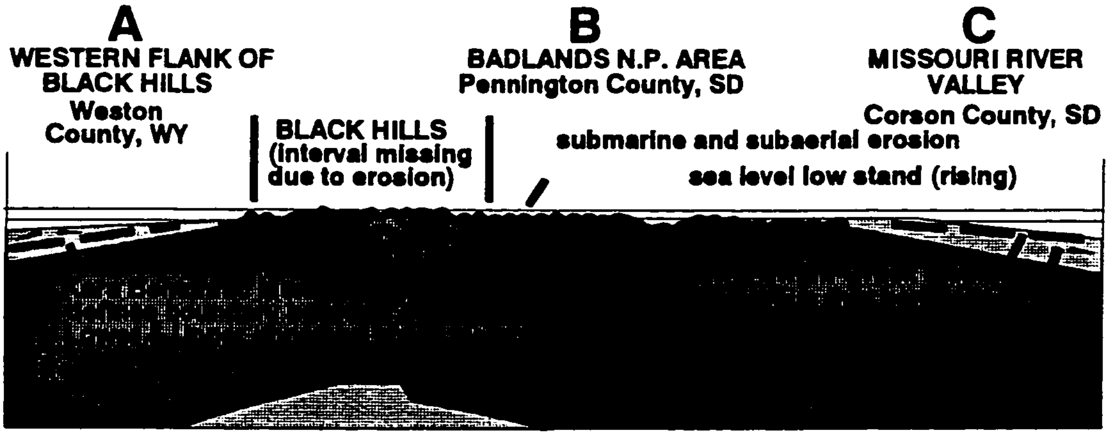


Fig. 119. Depositional setting during *Baculites jenseni* and *Baculites eliasi* time. (Features not to scale.)

eastern flank of the Black Hills. Structural downwarping of the Powder River Basin area maintained marine deposition along the western flank of the Black Hills and in the basin. Sea level began to rise during early *Baculites residei* time around 71.3 million years ago. This resulted in the gradual transgressive flooding and wave scouring of the surface exposed during the lowstand, and the continued reworking of sediments and fossils into younger deposits.

Fig. 120 show the continued progress of transgression through *Baculites baculus* time into *Baculites grandis* time. High standing seas culminated around 70 million years ago. The progress of the uplift of the Black Hills continued gradually, resulting in the maintenance of shallower water setting in the vicinity around the uplift. Exposure in the region around the crest of the Black Hills maintained a supply of fresh groundwater which emanated as springs in the marine setting fed from aquifers via fractures or faults. The freshwater influx initiated the development of Tepee Butte deposits and aided in the development of late diagenetic growth of concretions in the poorly consolidated sediment.

Fig. 121 show sea level falling during *Baculites clinolobatus* time into *Hoploscaphites burkelundi* time. The partial blockage of the flux of sediments from the western margin of the seaway by the uplift of anticlines and Laramide mountain ranges allowed calcareous facies of the Mobridge Member to accumulate. This was probably assisted by an influx of carbonate material derived from the Paleozoic rocks

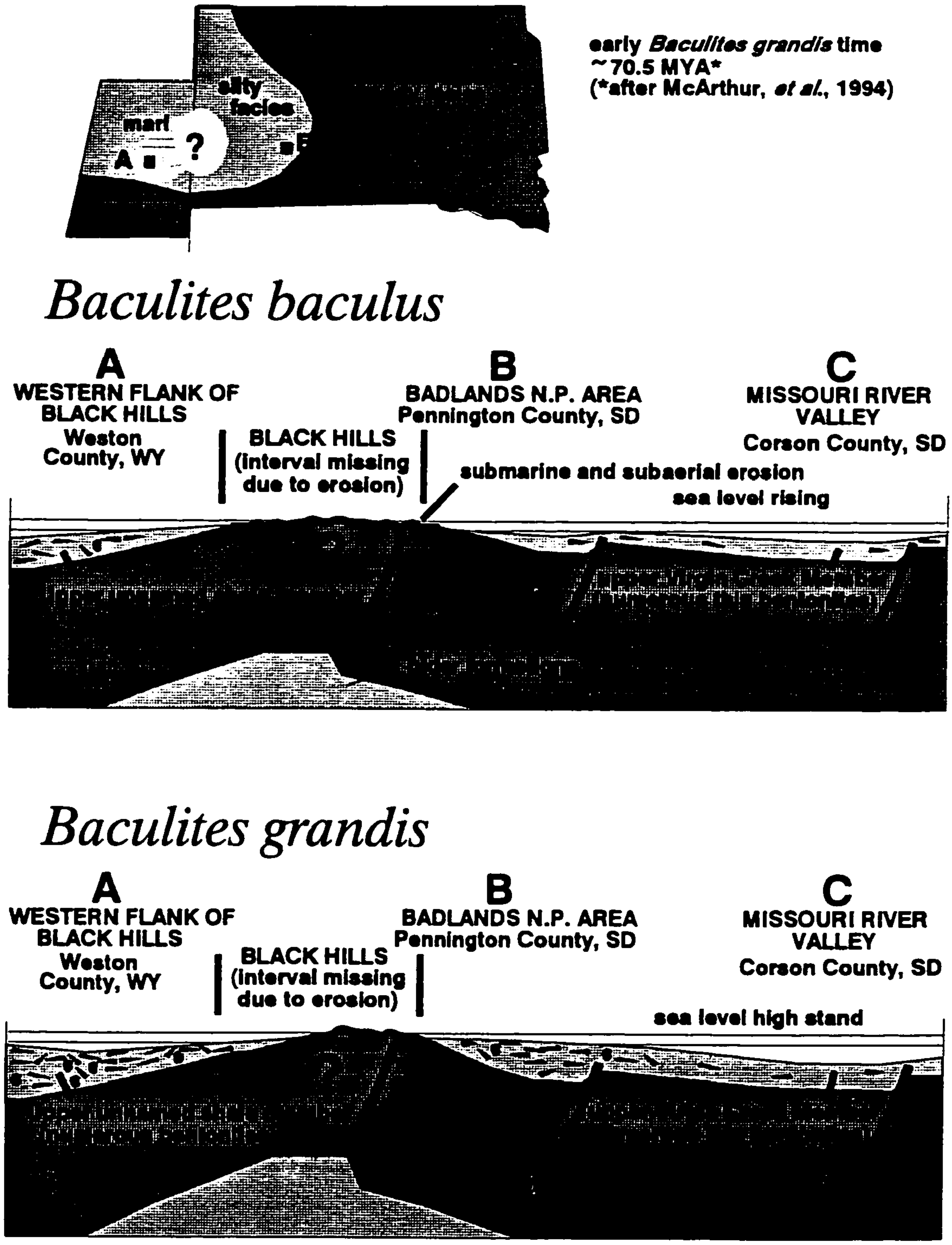


Fig. 120. Depositional setting during *Baculites baculus* and *Baculites grandis* time. (Features not to scale.)

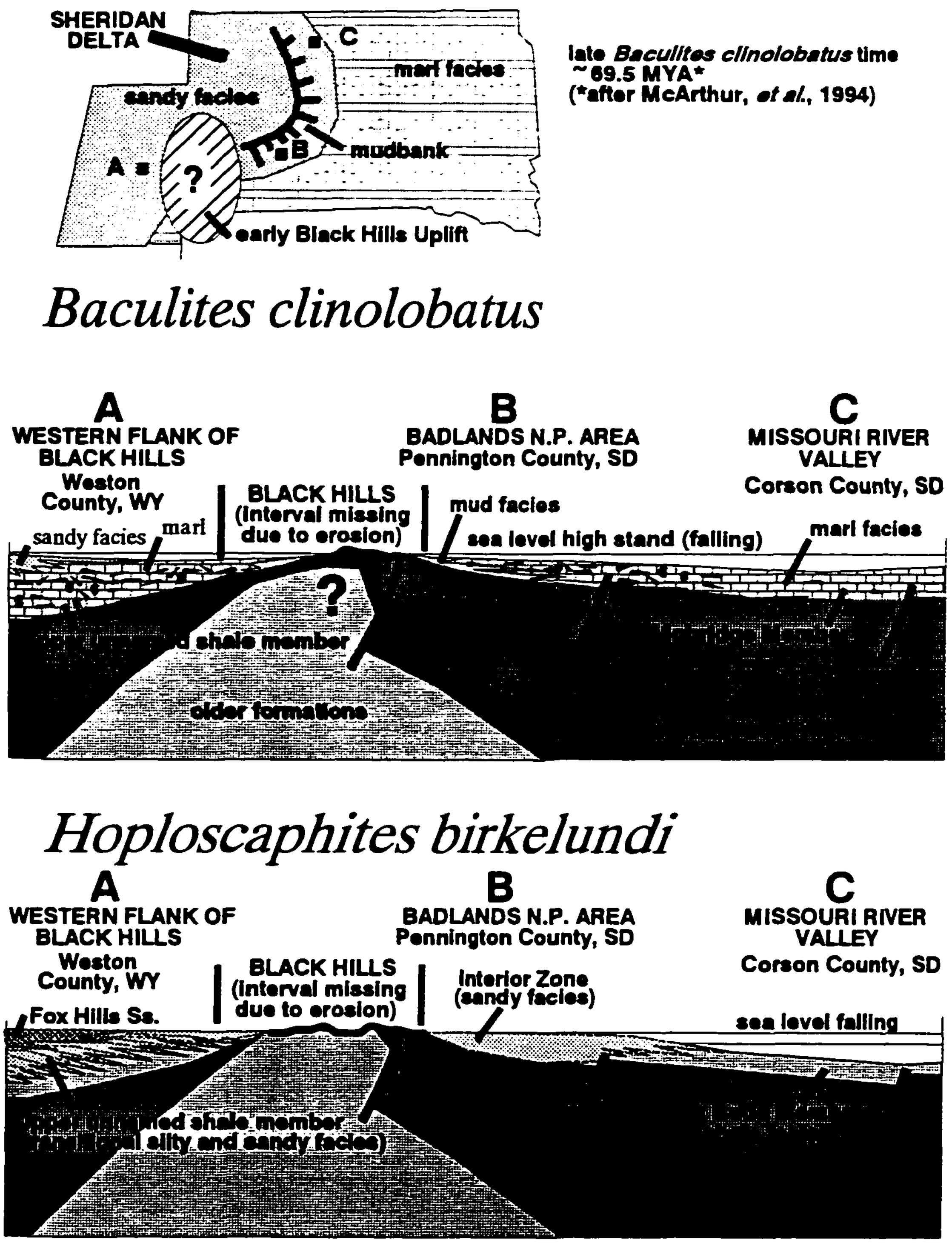


Fig. 121. Depositional setting during *Baculites clinolobatus* and *Hoploscaphites birkelundi* time. (Features not to scale.)

exposed throughout the crest of rising ranges. Whether seaway isolation or climatic factors played a role is unclear. By 69.5 million years ago sandy sediments derived from reworked sediments from the crest of the Black Hills and the crest of rising anticlines, such as the Sage Creek anticline/fault system, began to be incorporated in sediments of the Interior Zone and Fox Hills equivalent Fox Hills lithology of the Sheridan Delta in northwestern portion of the study area.

Fig. 122 shows the final marine transgression of the Cretaceous which began around 69 million years ago. This resulted in the accumulation of glauconitic sandstone facies across flood plain regions throughout western South Dakota and along the eastern margin of the Powder River Basin region in Wyoming. This transgression was short-lived in the western portion of the study area, but persisted longer in the Missouri Valley region through *Hoploscaphites nicolletii* time. The progressive downwarping of the Laramide basins (Willison, Power River, Denver/Julesburg, etc.) continued to maintain accommodation space for sediments from western source areas. The remnants of normal marine settings in the Western Interior region eventually vanished, probably around 68 million years ago, replaced by the brackish water and terrestrial setting associated with the Hell Creek, Lance and Fort Union formations. The youngest marine mudrocks of Fox Hills age are possibly preserved in the hilltop region along the Missouri Valley in south-central South Dakota.

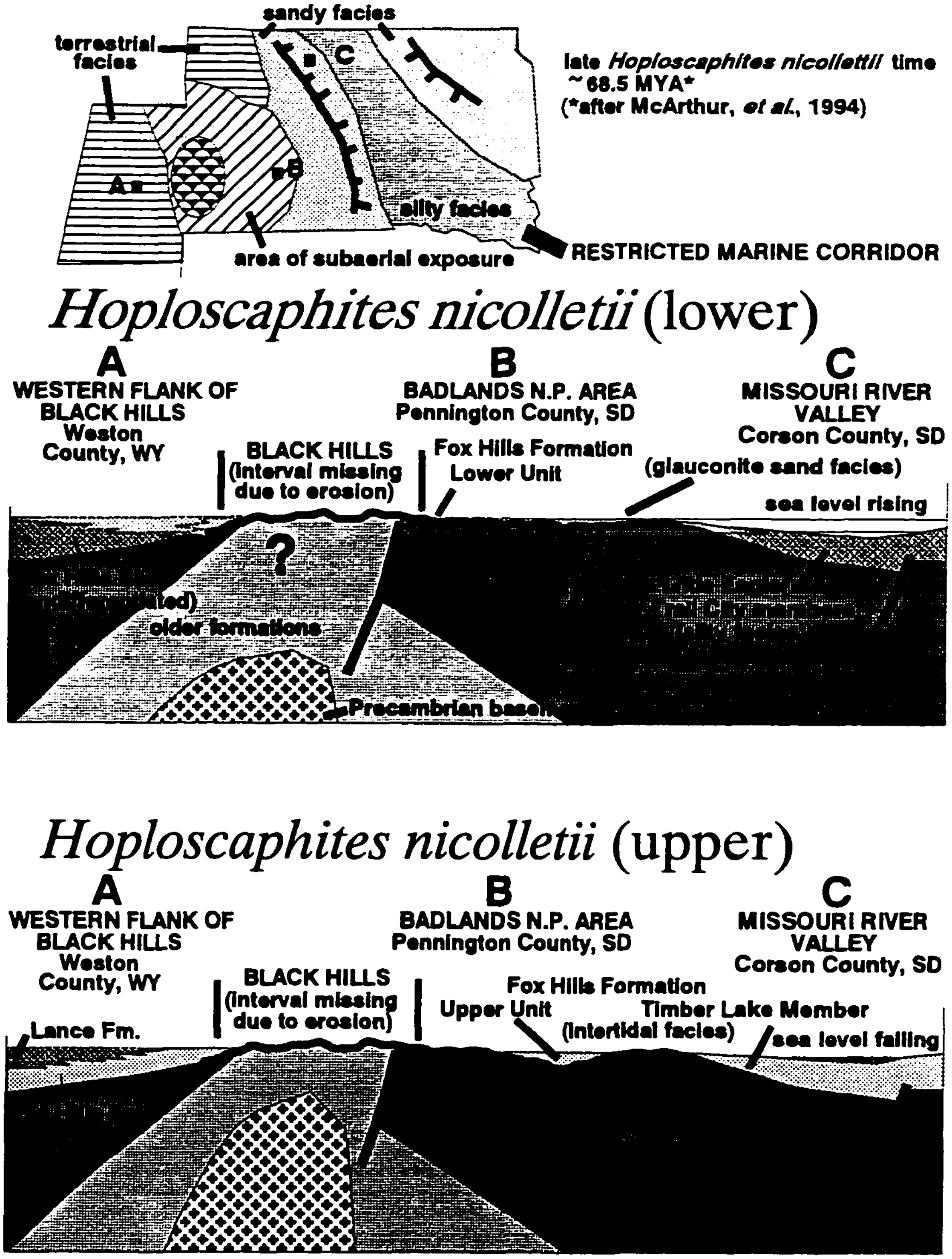


Fig. 122. Depositional setting during lower and upper *Hoploscaphites nicolletii* time. (Features not to scale.)

## 10.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Ideas are presented below that might be considered for future research in the range of perhaps simple Master's theses to higher levels of investigation. Suggestion below are projects which related to study of the Pierre Shale and Fox Hills Formations, and the early uplift of the Black Hills region.

1. Of greatest significance to this research would be the extension of detailed correlation into surrounding areas which were not included in this investigation. Perhaps of greatest interest, and perhaps most practical due to public land access, would be an investigation of the sedimentary facies on national grasslands in the area between Badlands National Park and Rapid City and southward around the eastern and southern flank of the Black Hills. Additional investigations would be of interest in the White River Valley region, along the Chadron Arch and the south flank of Black Hills, along the Belle Fourche Valley, and along the Moreau and Grand River Valleys. Unfortunately, our experience shows that gaining access to private land and reservation property is potentially very difficult.

2. A significant contribution to the study of the Cretaceous section would be the detailed analyses of bentonite beds for the establishment absolute ages and for geochemical correlation of these beds to bentonite beds to other regional locations.

3. Additional study of the Pierre Shale/Fox Hills interval is needed in the South Unit of Badlands National Park. Unfortunately, it was too hot and too wet to try to access the central region of this rugged wilderness during our visits. Additional study of the interval along the Campanian/Maastrichtian boundary might reveal additional information about the character of the unconformity in that area. A closer examination of fossils might yield information about the age range of fossils that are reworked into this interval.

4. Additional study of baculite morphology is recommended. The most problematic intervals are the zones that appear to overlap, such as the *Baculites compressus/cuneatus* Zones, the *Baculites baculus/grandis* Zones, and the *Baculites clinolobatus* and compressed variant of the same species. Is it possible that there is sexual dimorphism within these species that make identification so difficult?

5. Detailed investigations into the trace fossil assemblages in the Pierre Shale and the Fox Hills would likely yield a variety of new inchnogenera.

6. A concentrated study of the Campanian/Maastrichtian boundary unconformity (between the Verendrye and Virgin Creek Members) would probably yield fossil-rich lag deposits. The yellow-phosphatic nodules along this boundary typically contain

abundant arthropod remains an bone material.

7. A similar study of the boundary between the Fox Hills and Pierre Shale might also yield lag deposits.

8. An potentially attention-grabbing investigation, involving long hikes throughout the park and grasslands, would be a search for additional vertebrate remains in the Upper Cretaceous sediments, particularly in the diagenetically-altered beds of the Interior Zone and Fox Hills.

9. Additional research using subsurface logs might yield additional information about the subsurface changes, particularly in the region in western Nebraska and Wyoming. Unfortunately, our limited investigation into the availability of well logs through the South Dakota Geological Survey demonstrated that both shallow and deep well records are scarce or are widely dispersed for the region west of the Missouri River.

10. Additional research into aspects of micropaleontology might reveal additional detail to the cycles of sea level fluctuations and marine circulation patterns in the seaway. Unfortunately, my limited examination of sand fractions show that, in general, calcareous microfossils are generally very scarce or are very poorly

preserved due to diagenetic alteration. Perhaps the study of palynomorphs derived from the disaggregation and acid processing of concretion material or fresh shale samples migh be helpful. Palynomorphs might reveal valuable information about climatic change in relation to the cycles of transgression and regression.

11. An investigation into palynomorphs might be conducted in conjunction with an investigation into stable isotope compositions of shell material to reveal whether paleothermometric determinations correlated with changes in palynomorph faunas.

12. Additional questions relating to geochemistry of concretions include the following. Do concretions record diagenetic histories that support a model of groundwater flow away from the Black Hills? Are strontium isotopic values enriched in the Sage Creek Fault area and in other fault zones due to groundwater flow from ancient springs? Can absolute dating methods be used to date the stages of concretion growth and the formation of cone-in-cone overgrowths on concretions?

13. Studies on the early evolution of the Black Hills uplift might include a detailed study of the Fox Hills Formation. How does the Fox Hills Formation correlate in the subsurface westward into the northern, central, and southern portions of the Powder River Basin, and southward into the Denver-Julesburg basin? What happens to Fox

Hills facies in the subsurface on a trend from the margins to the center of the Williston Basin? Would subsurface studies indicate that these structural basins were deeper water settings during Fox Hills (*Hoploscaphites nicolletii*) time? And, is the occurrence of sandstone facies Fox Hills Formation is limited to the margins of theses basins and around uplifts? Perhaps tilt-meter analyses on wire-line logs could be used in conjunction with outcrop studies to map the general marine circulation pattern in the seaway.

14. A detailed study of the provenance of the sandstones in the Interior Zone, the Fox Hills Formation, and several sand sheets in the *Baculites grandis* Zone in the Tom Trask Ranch area might yield information about the early unroofing of the Black Hills. The occurrence of lithic clasts might be linked to Paleozoic chert horizons in the Black Hills. Heavy mineral concentrates might yield other sedimentological patterns.

15. Relating to the early uplift of the Black Hills, are calcite cements within fractures of the limestones and in the "boxwork" in the Mississippian limestones in the Wind Cave area dateable using isotopic geochronology methods? Would any of the dates correspond with pulsed of tectonism in the Late Cretaceous?

# APPENDIX A

## CORE SAMPLE LOCALITY INFORMATION

Information listed below includes information about core number, latitude and longitude of location of core using a hand operated GPS locator device (~30 accuracy), position (either elevation or relative position in meters), and notes about cores taken in the field. An asterisk (*) next to the sample number indicates that a portion of the sample was tested for geochemical analysis.

| CORE | LATITUDE | LONGITUDE | ZONE | POSITION (M) | NOTES ABOUT CORES |
|---|---|---|---|---|---|
| MOBRIDGE/GRAND RIVER AREA, SD; US Highway 12 Rest Area | | | | | |
| A01* | 45.39.24 | 100.38.26 | VIRGINCR | 450 | WATER LEVEL (DISPLAYS BIOTURBATION) - UPPER VIRGIN CREEK MBR |
| A02 | 45.39.23 | 100.38.24 | VIRGINCR | 453 | 3 METERS ABOVE WATER LEVEL (ABOVE CORE 18) |
| A03* | 45.39.28 | 100.38.19 | VIRGINCR | 455 | 1ST CORE FROM UPPER VIRGIN CREEK MBR. AT MOBRIDGE REST AREA |
| A04* | 45.39.27 | 100.38.19 | VIRGINCR | 460 | VIRGIN CREEK/YELLOW PEBBLES/B.ELIASI? |
| A05* | 45.39.28 | 100.38.19 | VIRGINCR | 463 | VIRGIN CREEK - 3 METERS ABOVE #12 |
| A06* | 45.39.27 | 100.38.17 | VIRGINCR | 465 | INCLUDES BENTONITE BED (JUST ABOVE CONC. BED) |
| A07 | 45.39.28 | 100.38.17 | VIRGINCR | 467 | 2 M ABOVE BENTONITES/CONTAINS "WHITE SPECKS" |
| A08 | 45.38.28 | 100.38.17 | VIRGINCR | 468.5 | 3.5 M ABOVE BENTONITE; CONTAINS GYPSUM |
| A09* | 45.39.28 | 100.38.16 | VIRGINCR | 470 | SELENITE XTALS; B. ELIASI? FRAGMENTS/YELLOW PHOSPHATE PEBBLES |
| A10* | 45.39. 7 | 100.38.22 | MOBRIDGE | 475 | 1 M BELOW "LOWER BENTONITE" BED: SLUMP SCARP NEAR BAY |
| A11 | 45.39. 7 | 100.38.22 | MOBRIDGE | 476 | LOWER BENTONITE BED IN MOBRIDGE MBR: 1 M ABOVE #39 |
| A12 | 45.39. 7 | 100.38.22 | MOBRIDGE | 477 | SMALL BENTONITE ABOVE "LOWER BENTONITE": .8 M ABOVE #40 |
| A13* | 45.39. 7 | 100.38.22 | MOBRIDGE | 479 | 2 M ABOVE #41; THROUGH CONCRETION LAYER: LIGHT-COLORED LAYER |
| MOBRIDGE/GRAND RIVER AREA, SD: Ray Johnson Ranch | | | | | |
| A14* | 45.37.32 | 100.41.51 | MOBRIDGE | 485 | RAY JOHNSON RANCH, BELOW POND DAM NEXT TO UPPER BENTONITE |
| A15 | 45.37.32 | 100.41.51 | MOBRIDGE | 485 | BELOW CORE 20 (SAME HOLE), UPPER BENTONITE; RAY JOHNSON RANCH |
| A16 | 45.37.30 | 100.41.47 | MOBRIDGE | 487 | 2 M ABOVE #20; BASE OF POND DAM ON RAY JOHNSON RANCH |
| A17* | 45.37.20 | 100.41.38 | MOBRIDGE | 500 | CUT BANK ABOVE POND ON RAY JOHNSON RANCH; MOBRIDGE/ELK BUTTE |
| A18* | 45.37.22 | 100.41.42 | MOBRIDGE | 503 | 3 M ABOVE #23; MOBRIDGE/ELK BUTTE; RAY JOHNSON RANCH |
| A19* | 45.37.20 | 100.41.42 | ELKBUTTE | 506 | GRAY BARREN CONC. ZONE (.6 M DIAMETER) |
| A20 | 45.37.19 | 100.41.40 | ELKBUTTE | 510 | INTERSECTION OF GULLY WITH FENCE NEAR ROAD. |
| A21* | 45.37.19 | 100.41.38 | ELKBUTTE | 515 | FOSSIL SCAPHITE FRAGMENT; COLLECT. BAG 97508 |

| | | | | | |
|---|---|---|---|---|---|
| A22 | 45.37.19 | 100.41.36 | ELKBUTTE | 518 | CONTAINS SELENITE; 2 M ABOVE #27 |
| A23* | 45.37.19 | 100.41.35 | ELKBUTTE | 520 | 2 M ABOVE #28 |
| A24 | 45.37.18 | 100.41.34 | ELKBUTTE | 522.5 | 2 M ABOVE #29 |
| A25* | 45.37.19 | 100.41.35 | ELKBUTTE | 525 | JUST BELOW BENTONITE LAYER |
| A25 | 45.37.19 | 100.41.35 | ELKBUTTE | 525 | JUST ABOVE #32, INCLUDES TOP OF BENTONITE? BED |
| A26 | 45.37.18 | 100.41.37 | ELKBUTTE | 529 | 4 M ABOVE CORE #32; ABUNDANT GYPSUM PRESENT |
| A27* | 45.37.20 | 100.41.32 | ELKBUTTE | 532 | SMALL SCAPHITE FRAG: SAMPLE BAG 97508; IRON FILLED FRACTURES |
| A28 | 45.37.21 | 100.41.32 | ELKBUTTE | 534 | 2 M ABOVE CORE #34 |
| A29* | 45.37.21 | 100.41.29 | ELKBUTTE | 536 | 2 M ABOVE CORE #35: IRON CONCRETION-BEARING HORIZON |
| A30 | 45.37.20 | 100.41.31 | FOXHILLS | 538 | TOP ELK BUTTE: INCLUDES BENTONITE BED; FOX HILLS FOSSILS |
| A31* | 45.37.20 | 100.41.31 | FOXHILLS | 538 | SAME HOLE AS #37; BASAL FOX HILLS DIRECTLY THROUGH BENTONITE |

**MOBRIDGE/GRAND RIVER AREA, SD:** Alan Johnson Ranch

| | | | | | |
|---|---|---|---|---|---|
| A32* | 45.35.31 | 100.50. 9 | FOXHILLS | 550 | FOX HILLS (TRAIL CITY MBR): D. NICOLLETTI ZONE (BAG #97509) |
| A33* | 45.35.31 | 100.50.10 | FOXHILLS | 552 | TRAIL CITY MBR: LOWER D. NICOLLETTI CONC. ZONE: 2 M ABOVE #4 |
| A34* | 45.35.31 | 100.50.10 | FOXHILLS | 555 | 3 M ABOVE #44: IN "BLANK" CONC. ZONE (TRAIL CITY MBR.) |
| A35* | 45.35.31 | 100.50.10 | FOXHILLS | 558 | 3 M ABOVE #45: POSSIBLE BENTONITE BED PRESENT |
| A36* | 45.35.31 | 100.50. 9 | FOXHILLS | 562 | 4 M ABOVE #46: UPPER D. NICOLLETTI ZONE (TRAIL CITY MBR.) |
| A37 | 45.35.31 | 100.50. 8 | FOXHILLS | 565 | NEAR TRAIL CITY/TIMBER LAKE LITHOLOGY CHANGE (SANDSTONE BED) |

| CORE | LATITUDE | LONGITUDE | ZONE | POSITION (M) | NOTES ABOUT CORES |
|---|---|---|---|---|---|
| **BAADLANDS NATIONAL PARK:** South Unit, Cedar Creek Area (Redshirt) | | | | | |
| B01 | 43.37.24 | 102.52.38 | COMPRESS | 0 | 1 M ABOVE CEDAR CREEK; B. COMPRESSUS ZONE: BADLANDS N.P. |
| B02 | 43.37.24 | 102.52.38 | CUNEATUS | 3 | 3 M ABOVE CORE #52; B. CUNEATUS; BADLANDS STRONGHOLD UNIT |
| B03* | 43.37.24 | 102.52.38 | CUNEATUS | 7 | 4 M ABOVE CORE #53; B. CUNEATUS ZONE; BADLANDS STRONGHOLD |
| B04 | 43.37.24 | 102.52.38 | CUNEATUS | 8 | CONC. ZONE; B CUNEATUS; 1 M ABOVE #54; STRONGHOLD AREA |
| B05* | 43.37.25 | 102.52.45 | CUNEATUS | 10 | 2 M ABOVE #55; .5 M BELOW CONC. ZONE (#2); SEE SAMPLE BAG "A |
| B06* | 43.37.25 | 102.52.45 | CUNEATUS | 11.5 | 1 M ABOVE CONC. BED (SAMPLE BAG "A"); 1.5 M ABOVE #70 |
| B07* | 43.37.25 | 102.52.45 | BROWN | 12.5 | 1 M ABOVE #71; .5 M ABOVE UNCONF. BELOW BROWN BARREN ZONE |
| B08* | 43.37.25 | 102.52.45 | REESIDEI | 13.5 | 1 M ABOVE #72; CONTAIN JAROSITE BED. BROWN, D. CHEYENNENSE |
| B09* | 43.37.25 | 102.52.45 | REESIDEI | 17.5 | 2 M ABOVE #73; CONC. BED W/B. ; BROWN BARREN SHALE |
| B10* | 43.37.28 | 102.52.46 | REESIDEI | 22.5 | 5 M ABOVE #74; ZONE OF BACULTE-RICH CONCS.; N. SIDE CUTBANK |
| B11* | 43.37.28 | 102.52.46 | REESIDEI | 25.5 | 3 M ABOVE #75; 3 M ABOVE CONC. ZONE |
| B12* | 43.37.28 | 102.52.46 | REESIDEI | 29.5 | 4 M ABOVE #76; NORTH SIDE OF CUT BANK ON SLOPE NEAR CHURCH |
| B13* | 43.37.29 | 102.52.51 | REESIDEI | 31.5 | 2 M ABOVE #77; JAROSITE/CONC. REESIDEI/GRANDIS BOUNDARY |
| B14* | 43.37.28 | 102.52.51 | CLINO | 33.5 | B. GRANDIS ZONE(?); GRAY SHALE BELOW YELLOW MOUNDS |
| B15* | 43.37.28 | 102.52.51 | MOUNDS | 36 | YELLOW MOUNDS IN B. GRANDIS BEDS; BELOW CHURCH |
| B16* | 43.37.28 | 102.52.51 | MOUNDS | 38 | 2 M ABOVE #80; BRIGHT YELLOW MOUNDS: WEATHERED SHALE PROFILE |
| B17* | 43.37.28 | 102.52.51 | MOUNDS | 40 | 2 M ABOVE #81: "RED ZONE OF YELLOW MOUNDS: STRONGHOLD UNIT |

| CORE | LATITUDE | LONGITUDE | ZONE | POSITION (M) | NOTES ABOUT CORES |
|---|---|---|---|---|---|
| **BADLANDS NATIONAL PARK:** North Unit, Sage Creek Campground area | | | | | |
| C01 | 43.54.39 | 102.24.47 | COMPRESS | 0 | 4 M ABOVE SAGE CREEK NEAR BRIDGE; BADLANDS N.P. |
| C02 | 43.54.39 | 102.24.47 | COMPRESS | 2 | 2 M ABOVE #56; B. COMPRESSUS/CUEATUS ZONE; SAGE CREEK LOC. 3 |
| C03* | 43.54.39 | 102.24.47 | COMPRESS | 4 | 2 M ABOVE # 57; B. COMPRESSUS/CUNEATUS ZONE; SAGE CREEK LOC3 |
| C04 | 43.54.39 | 102.24.47 | COMPRESS | 6 | 2 M ABOVE #58; CONC. ZONE; B. COMPRESSUS/CUNEATUS ZONE |
| C05* | 43.54.39 | 102.24.47 | COMPRESS | 6.5 | .5 M ABOVE #59; BENTONITE BED; B. COMPRESSUS/CUNEATUS ZONE |
| C06 | 43.54.39 | 102.24.47 | COMPRESS | 8.5 | 2 M ABOVE #60; UPPER B. COMPRESSUS/CUNEATUS ZONE |
| C07 | 43.54.39 | 102.24.47 | COMPRESS | 10.5 | 2 M ABOVE #61; TOP OF CREEK BANK NEAR BRIDGE; SAGE CREEK |
| C08 | 43.53.53 | 102.24.53 | BROWN | 13 | "BROWN BARREN"/B. REESIDEI ZONE; 5 M ABOVE #63 |
| C09 | 43.53.53 | 102.24.53 | BROWN | 16 | 3 M ABOVE #64; "BROWN BARREN" ZONE: SAGE CREEK CAMPGROUND #1 |
| C10 | 43.53.53 | 102.24.53 | GRANDIS | 20 | 4 M ABOVE #65; "COLOR TRANSITION TO YELLOW MOUNDS" |
| C11* | 43.53.53 | 102.24.53 | CLINO | 23 | SILTY ZONE ABOVE INTRACLAST BEARING CONC.; SAGE CREEK CAMP. |
| C12* | 43.53.53 | 102.24.53 | CLINO | 25.5 | 2.5 M ABOVE #67; YELLOW MOUNDS ABOVE CONC./SAGE CREEK CAMP |
| C13* | 43.53.53 | 102.24.53 | MOUNDS | 27.5 | 2 M ABOVE #68; YELLOW MOUNDS; SAGE CREEK CAMPGROUND LOC. #1 |
| C14* | 43.54. 5 | 102.19.41 | FOXHILLS | 0 | SHALE BED BELOW FIRST FOX HILLS SANDSTONE BED. |
| C15* | 43.54. 5 | 102.19.41 | FOXHILLS | 1 | SHALE BED ABOVE FIRST FOX HILLS SANDSTONE BED. |
| C16 | 43.54. 5 | 102.19.41 | FOXHILLS | 2 | SILTY BED ABOVE FIRST FOX HILLS SANDSTONE BED. |
| **TOM TRASK RANCH,** Pennington County, SD | | | | | |
| D01* | 44.13.57 | 102.25.39 | PEBBLES | 0 | 6" BELOW YELLOW PEBBLES HORIZON, TRASK RANCH LOCALITY #2 |
| D02* | 44.13.57 | 102.25.39 | PEBBLES | 0 | 6" ABOVE PEBBLE BOUNDARY BETWEEN B. COMPRESSUS/CLINOLOBATUS |
| D03* | 44.12.17 | 102.25. 3 | GRANDIS | 20 | 20 M ABOVE YELLOW PEBBLE ZONE; BASE OF RAVINE ON TRASK RANCH |
| D04* | 44.12.17 | 102.25. 3 | GRANDIS | 25 | 5 M ABOVE #87; SAMPLE BAG 97518; TRASK RANCH RAVINE |
| D05* | 44.12.17 | 102.25. 3 | CLINO | 29 | 4 M ABOVE #88; 1 M ABOVE CONC. BED; 29 M ABOVE PEBBLES |
| D06* | 44.12.17 | 102.25. 3 | CLINO | 34 | 5 M ABOVE #89; 6 M ABOVE CONC. BED; TRASK RANCH RAVINE |
| D07* | 44.12.17 | 102.25. 3 | CLINO | 38 | 4 M ABOVE #90; 2 M BELOW SCAPHITE-BEARING YELLOW CONC. BED |
| D08* | 44.12.17 | 102.25. 3 | CLINO | 40 | 2 M ABOVE #93; IN YELLOW SCAPHITE-BEARING CONC. BED. |
| D09* | 44.12.17 | 102.25. 3 | CLINO | 43 | 3 M ABOVE #94; IN SILTY BACULITE-BEARING CONC. BED; C-IN-C |
| D10* | 44.12.17 | 102.25. 3 | CLINO | 48 | 5 M ABOVE #95; C-IN-C COVERED CONCS W/INOCERAMIDS: BAG 97521 |
| D11* | 44.12.17 | 102.25. 3 | CLINO+ | 53 | 5 M ABOVE #96 IN BARREN GRAY SHALE INTERVAL. |
| D12* | 44.12.17 | 102.25. 3 | CLINO+ | 58 | ZONE OF LARGE C-IN-C RED-BUFF CONCRETIONS. |
| D13* | 44.12.17 | 102.25. 3 | CLINO+ | 63 | 5 M ABOVE #98; SILTY SHALE 1 M BELOW RED BARREN CONC. BED |
| D14* | 44.12.22 | 102.25. 0 | FOXHILLS | 64 | 1 M ABOVE #99; LARGE RED CONC BED; SAME ELEV. AS BENCHMARK |

| CORE | LATITUDE | LONGITUDE | ZONE | POSITION (M) | NOTES ABOUT CORES |
|---|---|---|---|---|---|
| **WESTON COUNTY, WY: Osage Oil Field** | | | | | |
| E01* | 43.57.11 | 104.31.21 | COMPRESS | 0 | LOWER BENTONITIC BED; UPPER LOWER UNNAMED MEMBER, ALONG RD. |
| E02 | 43.57.11 | 104.31.21 | COMPRESS | 6.5 | 6.5 M ABOVE #125; IRON STAINED BENTONITIC BED (VIRGIN CREEK? |
| E03* | 43.57.11 | 104.31.21 | COMPRESS | 8.5 | 2 M ABOVE #126. SHALE ONLY. |
| E04* | 43.58.18 | 104.33.20 | SUBKARA | 0 | 20 M BELOW KARA BENTONITE; YELLOW PEBBLES? SUB B. ELIASI ZON |
| E05* | 43.58.18 | 104.33.19 | SUBKARA | 9 | YELLOW LOBSTER-BEARING CONCRETION ZONE BELOW B. ELIASI ZONE |
| E06* | 43.58.11 | 104.33.20 | ELIASI | 15 | 5 M BELOW KARA BENTONITE; LOWEST OCCURRENCE OF B. ELIASI |
| E07* | 43.38.11 | 104.33.19 | ELIASI | 18 | 2 M BELOW KARA BENTONITE IN GRAY CONC. ZONE. 3 M ABOVE #104 |
| E08 | 43.58.11 | 104.33.19 | ELIASI | 20 | HARD SHALE AT BASE OF KARA BENTONITE ZONE |
| E09* | 43.58.11 | 104.33.19 | ELIASI | 23 | 3 M ABOVE #106; WITHIN KARA BENTONITE ZONE |
| E10* | 43.58.13 | 104.33.22 | ELIASI | 28 | 5 M ABOVE #3; 2 M ABOVE ZONE OF ABUNDANT B. ELIASI |
| E11* | 43.58.10 | 104.33.23 | ELIASI | 32 | 4 M ABOVE #108; RUSTY RED CONC. BED; B. ELIASI ZONE |
| E12 | 43.58.12 | 104.33.30 | ELIASI+ | 39 | 7 M ABOVE #109; BARREN SHALE ZONE BETWEEN B. ELIASI/BACULUS |
| E13 | 43.58.14 | 104.33.36 | BACULUS | 49 | 10 M ABOVE #110; LOWEST B. BACULUS ZONE EXPOSED. |
| E14* | 43.58.12 | 104.33.39 | GRANDIS | 57 | 8 M ABOVE CORE #111; LOWER GRANDIS ZONE |
| E15* | 43.58.11 | 104.33.40 | GRANDIS | 62 | 5 M ABOVE #112; LOWER B. GRANDIS FOSSILIFEROUS ZONE |
| E16* | 43.58. 8 | 104.33.44 | GRANDIS | 67 | 5 M ABOVE #113; RED WEATHERING CONC. ZONE; DEEP SOIL PROFILE |
| E17* | 43.58. 4 | 104.33.42 | GRANDIS | 75 | 8 M ABOVE #115; SELENITE, FOSSIL-BARREN SHALE, FROM DITCH. |
| E18* | 43.58. 3 | 104.33.44 | GRANDIS | 81 | 6 M ABOVE #115; UPPER B. GRANDIS FOSSIL ZONE; RESISTANT BED |
| E19* | 43.58.14 | 104.33.51 | GRANDIS | 86 | 5 M ABOVE #116; UPPER B. GRANDIS ZONE, FOSSIL. CONC. BED |
| E20* | 43.58.13 | 104.33.51 | GRANDIS | 93 | 7 M ABOVE #117; "SQUISHY" BENTONITIC MUD, WEATHERED SHALE? |
| E21* | 43.58.13 | 104.33.53 | CLIN | 103 | 10 M ABOVE #118; BASE OF B. CLINOLOBATUS ZONE |
| E22* | 43.58.18 | 104.33.51 | CLINO | 109 | 6 M ABOVE #119; CLINO CON. BED ON MAPPED PROMOTORY POINT |
| E23* | 43.58.19 | 104.34. 4 | CLINO | 110 | 1 M ABOVE #120; 2ND B. CLINOLOBATUS CONC. BED ABOVE MAPPED. |
| E24* | 43.58.19 | 104.34. 4 | CLINO | 112 | 2 M ABOVE #121; WITHIN 2ND CONC. BED 2 M ABOVE MAPPED CONCS. |
| E25* | 43.58.19 | 104.34. 4 | CLINO | 114 | 2 M ABOVE #122; .5 M BELOW UPPERMOST CONC. BED IN PIERRE SH. |
| **WESTON COUNTY, WY: Mush Creek Oil Field** | | | | | |
| E26* | 43.48. 2 | 104.25.45 | FOXHILLS | 119 | ABOUT 4 METERS ABOVE UPPERMOST PIERRE SHALE CONC. BED |
| E27* | 43.48. 2 | 104.25.45 | FOXHILLS | 131 | 12 M ABOVE CORE #129; GLAUCONITIC SAMDSTONE; LOWER FOX HILLS |

**ADDITIONAL CORES**

| CORE | LATITUDE | LONGITUDE | ZONE | POSITION (M) | NOTES ABOUT CORES |
|---|---|---|---|---|---|
| **Missouri Valley Region, SD** | | | | | |
| Z01 | 42.45. 9 | 98. 4.13 | GREGORY | 0 | 39 M ABOVE TOP OF NIOBRARA FM. - 1.5 MI. W OF NIOBRARA S.P. |
| Z02 | 42.45. 9 | 98. 4.13 | GREGORY | 1 | 40 M ABOVE TOP OF NIOBRARA. 1 MI W. OF NIOBRARA S.P. |
| Z03 | 43.41.25 | 99.31. 5 | SULLY | 0 | LIGHT BAND UNDER IRON CONCRETIONS |
| Z04 | 43.41.25 | 99.31. 3 | SULLY | 2 | N OF IONA, SD, RT 47, ABOVE SECOND IRON CONC. BAND. |
| Z05 | 44.26.12 | 100.24.39 | CROWCREE | 0 | CROW CREEK MEMBER BELOW OAHE DAM |
| Z06 | 45.12.26 | 100.22.44 | LOW_VIRG | 0 | LOWER VIRGIN CREEK MEMBER |
| Z07 | 45.12.26 | 100.22.44 | LOW_VIRG | 0 | ALONG RT 7, N OF RT212; IN THIN CONCRETION LAYER |
| Z08 | 45.35.43 | 100.57.24 | ELKBUTTE | 0 | APPROX. 5 M BELOW FOX HILLS CONCRETION |
| Z09 | 45.38.36 | 100.49.15 | ELKBUTTE | 0 | ELEVATION 580 |
| Z10 | 45.31.17 | 100.28.48 | UPP_VIRG | 0 | 2.12 MI. SW OF MOBRIDGE ON WATER LEVEL - TYPE LOCALITY |
| **Cheyenne River Valley Region, SD** | | | | | |
| Z11 | 44.31.29 | 101.55.47 | LOW_VIRG | 0 | BENTONITE BED (B. CUNEATUS ZONE) NEAR CHEYENNE R./RT 73 BRID |
| Z12 | 43.45.42 | 102.40.10 | COMPRESS | 0 | BUFFALO GAP GRASSLAND; B. COMPRESSUS/CUNEATUS ZONE |
| Z13 | 43.46.31 | 102.40.18 | BARREN 0 | B | BARREN ZONE NEAR SPLIT IN 4WD ROAD @ 6 MILES WEST OF SCENIC |
| Z14 | 43.53.53 | 102.24.53 | COMPRESS | 8 | B. COMPRESSUS/CUNEATUS ZONE; SAGE CREEK CAMPGROUND HILL BASE |
| Z15 | 44. 0.47 | 102.23. 7 | CLINO | 0 | AMNH 3210; ROAD TO WASTA; 10 M BELOW H. TRASKI CONC. ZONE. |
| Z16 | 44. 0.47 | 102.23. 7 | CLINO+ | 10 | 10 M ABOVE #83; H. TRASKI CONCRETION ZONE; ROAD TO WASTA |
| Z17 | 44.52. 6 | 102.22.43 | CLINO | 5 | PEBBLE ZONE BASE OF B. CLINO; S OF I-90 @ WASTA. BAG #975127 |
| Z18 | 44. 3.15 | 102.22.50 | COMPRESS | 0 | 5 M BELOW #85 (BELOW PEBBLE ZONE); B. CUNEATUS ZONE |
| **Western Flank of the Black Hills Region, WY** | | | | | |
| Z19 | 43.57.19 | 104.31.55 | BACULUS | 0 | B. BACULUS SAMPLE FROM HILL ALONG OIL CITY RD. INTERSECTION |
| Z20 | 43.58.29 | 104.25.45 | GAMMON | 0 | LOWEST PIERRE SHALE (GAMMON MBR) FROM HIGHWAY/OIL CITY RD. |

# APPENDIX B

## CORE SAMPLE CHARACTERISTICS

The cores were examined in the lab prior to processing them for sieve fraction studies and geochemical analyses. The table below is a summary of observations made about each sample before and during its removal from the buterate core cylander. Characteristics described include: sediment type, bioturbation characteristics, the inclusion of bentonite layers, an acid "fizz" on the surface of a sample fragement, the "visible" occurrence of gypsum crystals, the association with concretion horizons (noted in the field), and the rock color of the dried, crushed, and sieved sample prior to geochemical analyses.

Abbreviations for the column titles are as follows:

Sample: Core sample from Appendix A; an asterisk (*) means the sample was tested for geochemical analyses.

SED: Sediment type: mud (shale), silt (siltstone), sand (sandstone)

BIO: Bioturbation characteristics: no (no apparent bioturbation), yes (displays bioturbation)

BEN: Bentonites present: yes or no

CALC: Calcareous fizz reaction to acid (10% HCl): none, low, medium, and high

GYP: Gypsum in fractures: none, low, medium, high (based on "subjective" visual observation)

CONC: Core collected from shale in association with a concretion-bearing horizon.

COLOR: Based on *Geological Society of America, Rock Color Chart*:

Saturation (Hue): ()=no hue; 5=intense hue;
10=border hue with red
Color: YR=yellow-red; N=neutral gray
Intensity (lightness): 1=pure black; 5=neutral;
10=pure white

Mobridge/Grand River Area (SD)

| Sample | SED | BIO | BEN | CALC | GYP | CONC | COLOR |
|---|---|---|---|---|---|---|---|
| *A1 | mud | yes | no | no | no | no | 5YR7/1 |
| A2 | mud | no | yes | no | no | no | 5YR7/2 |
| *A3 | mud | no | no | no | low | no | 5YR7.5/1 |
| *A4 | mud | no | no | no | no | no | 5YR8/1 |
| *A5 | mud | no | no | no | no | no | 5YR7/1 |
| *A6 | mud | no | yes | no | low | no | 5YR7/1 |
| A7 | mud | no | no | no | no | no | 5YR7/1 |
| A8 | mud | no | no | no | no | no | 5YR7/1 |
| *A9 | mud | no | no | no | no | no | 5YR6/1 |
| *A10 | mud | no | no | med | no | no | 5YR6.5/1 |
| A11 | mud | no | yes | med | no | no | 5YR6.5/1 |
| A12 | mud | no | no | med | no | no | 5YR7/1 |
| *A13 | mud | no | no | med | no | yes | 5YR8/1 |
| *A14 | mud | no | no | no | low | no | N6 |
| A15 | mud | no | yes | no | low | no | 5YR8/1 |
| A16 | mud | no | no | no | no | no | 5YR6.5/1 |
| *A17 | mud | yes | no | no | no | no | 5YR7.5/1.5 |
| *A18 | mud | no | no | no | no | yes | 5YR7.5/1 |
| *A19 | mud | yes | no | no | no | no | 5YR6.5/1 |
| A20 | mud | no | no | no | low | no | 5YR7.5/1 |
| *A21 | mud | no | no | no | no | no | 5YR7.5/1 |
| A22 | mud | no | no | no | med | no | 5YR7.5/1 |
| *A23 | mud | no | no | no | low | no | 5YR6.5/1.5 |
| A24 | mud | no | no | no | no | no | 5YR6.5/1 |
| *A25 | mud | yes | yes | no | no | no | 5YR6.5/1.5 |
| A26 | mud | no | no | no | med | no | 5YR7/1.5 |
| *A27 | mud | yes | no | no | low | no | 5YR7/1.5 |
| A28 | mud | yes | no | no | med | no | 5YR7/2 |
| *A29 | mud | no | no | no | no | yes | 5YR7/2 |
| A30 | mud | yes | yes | no | med | no | 5YR7.5g |
| *A31 | mud | yes | no | low | low | yes | 5YR7 |
| *A32 | silt | yes | no | med | no | yes | 5YR7 |
| *A33 | silt | yes | no | low | no | yes | 10YR7 |
| *A34 | silt | yes | no | low | no | yes | 10YR7 |
| *A35 | silt | yes | yes | med | low | no | 10YR7.5 |
| *A36 | sand | yes | no | low | no | yes | 5YR7 |
| A37 | sand | yes | no | no | no | no | 10YR7 |

Cedar Creek Locality, Badlands National Park, South Unit

| Sample | SED | BIO | BEN | CALC | GYP | CONC | COLOR |
|---|---|---|---|---|---|---|---|
| B1 | mud | no | no | no | no | no | N5 |
| B2 | mud | yes | no | med | no | no | N6 |
| *B3 | mud | yes | no | high | no | yes | 5YR6 |
| B4 | mud | yes | no | low | no | no | 5YR6 |
| *B5 | mud | yes | yes | low | no | yes | 5YR6 |
| *B6 | mud | yes | no | low | no | no | 5YR6 |
| *B7 | mud | no | no | low | no | no | 5YR6 |
| *B8 | mud | no | no | no | no | no | 5YR6 |
| *B9 | mud | yes | no | no | no | yes | 5YR5 |
| *B10 | mud | yes | no | med | no | no | 10YR6 |
| *B11 | mud | yes | no | med | no | no | 10YR7 |
| *B12 | mud | no | no | no | no | no | 10YR7 |
| *B13 | mud | no | yes | no | no | no | N6 |
| *B14 | mud | yes | no | no | no | yes | 5YR6 |
| *B15 | mud | no | no | no | no | no | 10YR7 |
| *B16 | mud | no | no | no | no | no | 5YR7 |
| *B17 | mud | no | no | no | no | no | 5YR8 |

Sage Creek Area, Badlands National Park, North Unit

| Sample | SED | BIO | BEN | CALC | GYP | CONC | COLOR |
|---|---|---|---|---|---|---|---|
| C1 | mud | yes | no | no | no | yes | 10YR6 |
| C2 | mud | yes | no | no | no | no | 10YR6 |
| *C3 | mud | yes | no | no | no | no | 10YR6 |
| *C4 | mud | no | no | no | low | no | 10YR6 |
| C5 | mud | no | yes | no | no | yes | 10YR6.5 |
| C6 | mud | no | no | no | low | no | 10YR6.5 |
| C7 | mud | no | no | no | low | no | 10YR6.5 |
| C8 | mud | yes | no | no | no | no | 10YR7 |
| C9 | mud | yes | no | no | no | no | 10YR7.5 |
| C10 | mud | no | no | no | low | no | 10YR7 |
| *C11 | mud | no | no | no | no | no | 10YR7 |
| *C12 | mud | no | yes | no | no | no | 10YR8 |
| *C13 | mud | yes | no | no | no | no | 10YR8.5 |
| *C14 | sand | no | no | no | no | no | 10YR8.5 |
| *C15 | silt | no | no | no | no | no | 5YR8.5 |

Tom Trask Ranch, Pennington County, SD

| Sample | SED | BIO | BEN | CALC | GYP | CONC | COLOR |
|---|---|---|---|---|---|---|---|
| *D1 | mud | yes | no | no | no | no | 10YR6 |
| *D2 | mud | yes | no | no | no | yes | 10YR6.5 |
| *D3 | mud | no | no | no | no | no | 10YR7 |
| *D4 | mud | no | no | no | no | no | 10YR7 |
| *D5 | mud | no | no | no | no | no | 10YR6.5 |
| *D6 | mud | no | no | no | no | no | 10YR7 |
| *D7 | mud | no | no | no | no | no | 10YR6.5 |
| *D8 | mud | no | no | no | no | yes | 10YR6.5 |
| *D9 | mud | no | yes | no | no | yes | 10YR6.5 |
| *D10 | mud | no | no | no | high | yes | 10YR6 |
| *D11 | mud | no | no | no | no | no | 10YR6.5 |
| *D12 | silt | yes | no | no | no | yes | 10YR6.5 |
| *D13 | mud | no | no | no | no | no | 5YR6.5 |
| *D14 | silt | yes | no | no | no | no | 5YR6 |

Osage and Mush Creek Oil Fields, Weston County, WY

| Sample | SED | BIO | BEN | CALC | GYP | CONC | COLOR |
|---|---|---|---|---|---|---|---|
| *E1 | mud | no | yes | no | no | no | 10YR6 |
| E2 | mud | no | yes | no | no | no | 10YR7.5 |
| *E3 | mud | no | yes | no | no | no | 5YR6 |
| *E4 | mud | no | no | no | no | no | 5YR6.5 |
| *E5 | mud | yes | no | no | no | yes | 5YR6 |
| *E6 | mud | no | no | no | no | no | 10YR6.5 |
| *E7 | mud | no | no | no | no | yes | 10YR6.5 |
| E8 | mud | no | yes | no | no | no | 5YR7 |
| *E9 | mud | no | no | no | no | no | 5YR6 |
| *E10 | mud | no | no | no | no | yes | 10YR8 |
| *E11 | mud | yes | no | no | no | no | 10YR8 |
| E12 | mud | no | no | no | no | no | 5YR7 |
| E13 | mud | no | no | no | no | no | 5YR7 |
| *E14 | mud | yes | no | no | no | yes | 5YR7 |
| *E15 | mud | yes | no | no | no | yes | 5YR7 |
| *E16 | mud | yes | no | no | no | yes | 10YR8 |
| *E17 | mud | no | no | no | no | no | 10YR8 |
| *E18 | mud | yes | no | no | no | yes | 10YR7 |
| *E19 | mud | yes | no | no | no | yes | 10YR7 |
| *E20 | mud | yes | no | no | no | yes | 10YR7 |
| *E21 | mud | yes | no | no | no | yes | 10YR7 |
| *E22 | mud | yes | no | no | no | yes | 10YR8 |
| *E23 | mud | yes | no | no | no | no | 10YR8 |
| *E24 | mud | yes | no | no | no | yes | 10YR7.5 |
| *E25 | mud | yes | no | no | no | yes | 10YR8 |
| *E26 | silt | no | no | no | no | no | 10YR7.5 |
| *E27 | sand | no | no | no | no | no | 10YR7.5 |

# APPENDIX C

## SIEVE FRACTION ANALYSES

Data for sieve fraction analyses are presented below. Data for four statdar sieve fraction in gram (dried) were derived from .250 kiograms of original core sample. Samples were water-washed through a column of four standard seives: <63μm, <250μm, <500μm, and >1.0mm. Washed sieve fractions were oven dried and weighed. This data is presented below in the first four columns after the core identification number. Percentages of fine fractions (<63μm and <250μm) are tabulated as "%A." Percentages of coarse fractions (<500μm and >1.0mm) are tabulated as "%B." "%A" and "Total" (%A + %B) were data used on supplemental information for the columnar sections in the Field Investigation section (Chapter 5). (An asterisk (*) next to the core number shows that the sample was tested for geochemical analyses.

| # | >63 μm | >250 μm | >500 μm | >1.0 mm | >63 + >250 A | %A | >500 + >1 B | %B | Total % |
|---|---|---|---|---|---|---|---|---|---|
| *A1 | .7 | 1.0 | - | 4.3 | 1.7 | .7 | 4.3 | 1.7 | 2.4 |
| A2 | 1.8 | - | 1.5 | 2.0 | 1.8 | .7 | 3.5 | 1.4 | 2.1 |
| *A3 | 2.0 | 1.0 | 2.1 | 6.0 | 3.0 | 1.2 | 8.1 | 3.2 | 4.2 |
| *A4 | 1.8 | .5 | .7 | 1.3 | 2.3 | .9 | 2.0 | .8 | 1.7 |
| *A5 | 2.2 | 2.0 | 1.0 | 1.5 | 4.2 | 1.7 | 2.5 | 1.0 | 2.7 |
| *A6 | 2.9 | .5 | .2 | 2.0 | 3.4 | 1.4 | 2.2 | .9 | 2.3 |
| A7 | 2.5 | 1.0 | .6 | .3 | 3.5 | 1.4 | .9 | .4 | 1.8 |
| A8 | 3.5 | .9 | .2 | .1 | 4.4 | 1.8 | .3 | .1 | 1.9 |
| *A9 | 2.5 | .7 | .5 | 1.3 | 3.2 | 1.3 | 1.8 | .8 | 2.1 |
| *A10 | 2.2 | 2.0 | 1.4 | .5 | 4.2 | 1.7 | 1.9 | .8 | 2.5 |
| A11 | 5.1 | 1.2 | 3.3 | 7.8 | 6.3 | 2.5 | 11.1 | 4.4 | 6.9 |
| A12 | 4.1 | 4.0 | 1.6 | 1.6 | 8.1 | 3.2 | 3.2 | 1.3 | 4.5 |
| *A13 | 4.4 | 2.5 | 1.3 | 1.0 | 6.9 | 2.8 | 2.3 | .9 | 3.7 |
| *A14 | 1.4 | 3.0 | 3.0 | 5.3 | 4.4 | 1.8 | 8.3 | 3.3 | 5.1 |
| A15 | 6.7 | 4.9 | 9.7 | 14.1 | 11.6 | 4.6 | 23.8 | 9.5 | 13.9 |
| A16 | 4.7 | 9.3 | 5.2 | .9 | 14.0 | 5.6 | 6.1 | 2.4 | 8.0 |
| *A17 | 5.2 | 9.9 | 9.9 | 8.4 | 15.1 | 6.0 | 18.3 | 7.3 | 13.3 |
| *A18 | 6.5 | 9.6 | 5.2 | 4.7 | 16.1 | 6.4 | 9.9 | 4.0 | 10.4 |
| *A19 | 5.0 | 4.0 | 2.2 | 1.0 | 9.0 | 3.6 | 3.2 | 1.3 | 4.9 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A20 | 15.0 | 6.5 | 3.9 | .3 | 21.5 | 8.6 | 4.2 | 1.7 | 10.3 |
| *A21 | 16.1 | 9.3 | 1.7 | .5 | 25.4 | 10.2 | 1.8 | .7 | 10.9 |
| A22 | 7.1 | 3.2 | 2.7 | 1.1 | 10.3 | 4.1 | 3.8 | 1.5 | 5.6 |
| *A23 | 17.5 | 11.4 | 7.0 | 1.3 | 28.9 | 11.6 | 8.3 | 3.3 | 14.9 |
| A24 | 13.3 | 6.6 | 2.0 | .2 | 19.9 | 8.0 | 2.2 | .8 | 8.8 |
| *A25 | 12.9 | 4.1 | .9 | 1.1 | 17.0 | 6.8 | 2.0 | .8 | 7.6 |
| A26 | 7.7 | 8.7 | 16.3 | 17.6 | 16.4 | 6.6 | 33.9 | 13.6 | 20.2 |
| *A27 | 5.8 | 8.0 | .9 | 26.0 | 13.8 | 5.5 | 26.9 | 10.8 | 16.3 |
| A28 | 17.1 | 6.5 | 2.0 | 6.2 | 23.6 | 9.4 | 8.2 | 3.3 | 12.7 |
| *A29 | 1.6 | .7 | 1.4 | 1.4 | 2.3 | .9 | 2.8 | 1.1 | 2.0 |
| A30 | 2.5 | .2 | .7 | - | 2.7 | 1.1 | .7 | .3 | 1.4 |
| *A31 | 5.9 | .8 | .5 | - | 6.7 | 2.7 | .5 | .2 | 2.9 |
| *A32 | 5.4 | 2.1 | .8 | .1 | 7.5 | 3.0 | .9 | .4 | 3.4 |
| *A33 | 9.8 | 4.6 | 2.6 | 2.6 | 14.4 | 5.8 | 5.2 | 2.1 | 7.9 |
| *A34 | 6.1 | 2.7 | 1.7 | .5 | 8.8 | 3.5 | 2.2 | .9 | 4.4 |
| *A35 | 5.5 | 1.3 | 1.5 | 1.5 | 6.8 | 2.7 | 3.0 | 1.2 | 3.9 |
| *A36 | 38.0 | 3.2 | 3.7 | 5.0 | 41.2 | 16.5 | 8.7 | 3.5 | 20.0 |
| A37 | 44.5 | 17.3 | 13.9 | 123 | 61.8 | 24.7 | 136.9 | 54.8 | 79.5 |
| | | | | | | | | | |
| B1 | 23.9 | 13.4 | 13.0 | .7 | 37.3 | 14.9 | 13.7 | 5.5 | 19.2 |
| B2 | 30.1 | 16.8 | 2.0 | .2 | 46.9 | 18.8 | 2.2 | .9 | 3.1 |
| *B3 | 9.9 | 5.0 | .5 | .4 | 14.9 | 6.0 | .9 | .4 | 1.3 |
| B4 | 27.3 | 4.5 | .1 | - | 31.8 | 12.7 | .1 | 0 | .1 |
| *B5 | 40.2 | 59.4 | 15.4 | .2 | 99.6 | 39.8 | 15.6 | 6.2 | 21.8 |
| *B6 | 39.2 | 16.0 | 9.2 | .5 | 55.2 | 22.1 | 9.7 | 3.9 | 13.6 |
| *B7 | 46.8 | 18.7 | 14.0 | 1.6 | 65.5 | 26.2 | 15.6 | 6.2 | 21.8 |
| *B8 | 34.7 | 10.6 | 7.2 | .5 | 45.3 | 18.1 | 7.7 | 3.1 | 10.8 |
| *B9 | 27.8 | 21.7 | 14.5 | .6 | 49.5 | 19.8 | 15.1 | 6.0 | 21.1 |
| *B10 | 29.2 | 10.7 | 15.4 | .7 | 39.9 | 16.0 | 16.1 | 6.4 | 22.5 |
| *B11 | 44.8 | 16.1 | 4.4 | 3.5 | 60.9 | 24.2 | 7.9 | 3.2 | 11.1 |
| *B12 | 36.7 | 21.9 | 17.5 | 1.4 | 58.6 | 23.4 | 18.9 | 7.6 | 26.5 |
| *B13 | 40.5 | 19.6 | 40.5 | 36.6 | 60.1 | 24.0 | 77.1 | 30.1 | 107.1 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| •B14 | 25.7 | 15.1 | 6.1 | 8.6 | 40.8 | 16.3 | 14.7 | 5.9 | 20.8 |
| •B15 | 4.5 | 4.0 | 4.6 | 5.6 | 8.5 | 3.4 | 10.2 | 4.1 | 14.3 |
| •B16 | 6.0 | 5.0 | 3.6 | 2.4 | 11.0 | 4.4 | 6.0 | 2.4 | 8.4 |
| •B17 | 5.4 | 2.5 | 1.5 | .9 | 7.9 | 3.2 | 2.4 | 1.0 | 3.4 |
| | | | | | | | | | |
| C1 | 18.5 | 9.9 | 4.9 | 6.9 | 28.4 | 11.4 | 11.8 | 4.7 | 16.1 |
| C2 | 23.3 | 24.3 | .8 | 1.0 | 27.6 | 11.0 | 1.8 | .7 | 11.7 |
| •C3 | 29.9 | 10.9 | 19.9 | 2.1 | 40.8 | 16.3 | 22.0 | 8.8 | 25.1 |
| •C4 | 42.9 | 21.3 | 21.6 | .4 | 64.2 | 25.7 | 22.0 | 8.8 | 34.5 |
| C5 | 26.0 | 12.9 | 5.2 | .6 | 28.9 | 11.6 | 5.8 | 2.3 | 13.9 |
| C6 | 16.8 | 7.8 | 4.4 | .6 | 24.6 | 9.8 | 5.0 | 2.0 | 11.8 |
| C7 | 19.1 | 24.6 | 14.4 | 2.3 | 43.7 | 17.5 | 16.7 | 6.7 | 24.2 |
| C8 | 28.9 | 14.1 | 28.9 | 2.6 | 43.0 | 17.2 | 31.5 | 12.6 | 29.8 |
| C9 | 11.0 | 4.5 | 7.1 | 13.0 | 15.5 | 6.2 | 20.1 | 8.0 | 14.2 |
| C10 | 26.8 | 11.7 | 3.2 | 4.3 | 38.5 | 15.4 | 7.5 | 3.0 | 18.4 |
| •C11 | 9.9 | 2.0 | .7 | 5.2 | 11.9 | 4.8 | 5.9 | 2.4 | 7.2 |
| •C12 | 9.3 | 3.0 | 2.3 | 8.8 | 12.3 | 4.9 | 11.1 | 4.4 | 9.3 |
| •C13 | 14.5 | 1.0 | .8 | 6.2 | 15.5 | 6.2 | 7.0 | 2.8 | 9.0 |
| •C14 | 20.3 | 4.4 | 3.8 | 4.8 | 24.7 | 9.9 | 8.6 | 3.4 | 13.3 |
| •C15 | 17.0 | 5.8 | 3.8 | 20.0 | 22.8 | 9.1 | 23.8 | 9.5 | 18.6 |
| C16 | 88.2 | 47.9 | 28.2 | 26.3 | 136.1 | 54.5 | 45.1 | 18.0 | 72.2 |
| | | | | | | | | | |
| •D1 | 23.4 | 19.7 | 9.4 | - | 43.1 | 17.2 | 9.4 | 3.8 | 21.0 |
| •D2 | 6.5 | 6.4 | 1.5 | - | 12.9 | 5.2 | 1.5 | .6 | 5.8 |
| •D3 | 16.6 | 11.5 | 18.5 | xxx | 28.1 | 11.2 | 18.5 | 7.4 | 18.6 |
| •D4 | 11.4 | 3.5 | 2.4 | - | 14.9 | 6.0 | 2.4 | 1.0 | 7.0 |
| •D5 | 13.2 | 1.0 | .3 | - | 14.2 | 5.7 | .3 | .2 | 5.9 |
| •D6 | 22.0 | 15.0 | 8.0 | xxx | 37.0 | 14.8 | 8.0 | 3.2 | 18.0 |
| •D7 | 13.2 | 8.3 | 2.0 | - | 21.5 | 8.6 | 2.0 | .8 | 9.4 |
| •D8 | 7.6 | .9 | .3 | - | 8.5 | 3.4 | .3 | .2 | 3.6 |
| •D9 | 24.9 | 7.8 | 7.5 | xxx | 32.7 | 13.1 | 7.5 | 3.0 | 16.1 |
| •D10 | 10.8 | 3.3 | .8 | - | 14.1 | 5.6 | .8 | .3 | 5.9 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *D11 | 8.0 | 1.7 | .9 | - | 9.7 | 3.9 | .9 | .4 | 4.3 |
| *D12 | 12.9 | 1.6 | .4 | - | 14.5 | 5.9 | .4 | .2 | 6.1 |
| *D13 | 29.0 | 4.1 | 2.0 | 3.6 | 33.1 | 13.2 | 5.6 | 2.2 | 15.4 |
| *D14 | 28.0 | 1.7 | 2.8 | - | 29.7 | 11.9 | 2.8 | 1.1 | 13.0 |
| | | | | | | | | | |
| *E1 | 4.3 | 2.7 | 1.3 | 4.3 | 7.0 | 2.8 | 5.6 | 2.2 | 5.0 |
| E2 | 6.5 | 3.8 | 3.3 | 14.4 | 10.3 | 4.1 | 17.7 | 7.1 | 11.2 |
| *E3 | 3.0 | 1.8 | 1.7 | .9 | 4.8 | 1.9 | 2.6 | 1.0 | 2.9 |
| *E4 | 5.7 | 4.6 | 2.8 | 3.2 | 10.3 | 4.1 | 6.0 | 2.4 | 6.5 |
| *E5 | 2.2 | 1.4 | .8 | .9 | 3.6 | 1.4 | 1.7 | .7 | 2.1 |
| *E6 | 5.3 | 1.3 | 2.3 | 3.7 | 6.6 | 2.6 | 6.0 | 2.4 | 5.0 |
| *E7 | 1.6 | 0.5 | 0.5 | 1.0 | 2.1 | .9 | 1.5 | .6 | 1.5 |
| E8 | 1.5 | .8 | 1.0 | 2.3 | 2.3 | .9 | 3.3 | 1.3 | 2.2 |
| *E9 | 2.8 | .5 | .7 | 1.1 | 3.3 | 1.3 | 1.8 | .7 | 2.0 |
| *E10 | 4.2 | 1.8 | 1.3 | 4.9 | 6.0 | 2.4 | 6.2 | 2.5 | 4.9 |
| *E11 | 16.7 | 1.2 | 1.2 | - | 17.9 | 7.1 | 1.2 | .5 | 7.6 |
| E12 | 8.8 | .3 | .3 | - | 9.1 | 3.6 | .3 | .1 | 3.7 |
| E13 | 12.0 | .1 | .1 | - | 12.1 | 4.8 | .1 | 0 | 4.8 |
| *E14 | 12.0 | .1 | - | - | 12.1 | 4.8 | 0 | 0 | 4.8 |
| *E15 | 10.5 | 1.0 | .3 | - | 11.5 | 4.6 | .3 | .1 | 4.7 |
| *E16 | 9.5 | .7 | .5 | .6 | 10.2 | 4.1 | 1.1 | .4 | 4.5 |
| *E17 | 4.1 | .8 | 1.3 | 3.1 | 4.9 | 2.0 | 4.4 | 1.8 | 3.8 |
| *E18 | 3.0 | .14 | 1.5 | - | 3.4 | 1.4 | 1.5 | .6 | 2.0 |
| *E19 | 11.5 | 3.3 | 2.8 | - | 14.8 | 5.9 | 2.8 | 1.1 | 7.0 |
| *E20 | 11.7 | 1.7 | 2.2 | 1.0 | 13.4 | 5.4 | 3.2 | 1.3 | 6.7 |
| *E21 | 10.7 | .6 | 1.6 | - | 11.3 | 4.5 | 1.6 | .6 | 5.1 |
| *E22 | 32.0 | 1.9 | .8 | 1.2 | 33.9 | 13.6 | 2.0 | .8 | 14.4 |
| *E23 | 36.0 | 3.6 | 2.6 | - | 39.6 | 15.9 | 2.6 | 1.0 | 16.9 |
| *E24 | 13.8 | 2.4 | 3.8 | 1.7 | 15.2 | 6.1 | 5.5 | 2.2 | 8.3 |
| *E25 | 10.6 | 3.7 | 5.6 | 4.1 | 14.3 | 5.7 | 9.7 | 3.9 | 9.6 |
| *E26 | 95.0 | 21.1 | 10.5 | 36xxx | 116.0 | 46.4 | 46.5 | 18.6 | 65.0 |
| *E27 | 70.0 | 9.0 | 1.6 | - | 79.0 | 31.6 | 1.6 | .6 | 32.2 |

# APPENDIX D

## SEDIMENTOLOGICAL DATA

Grain analyses of the 250 mμ sieve fraction. Numbers represent percentages based on 300 grain count. Column headings for sample identification are listed below:

SN - sample number
CM - cemented mud grain (calcareous or silica) (gray)
CG - calcite grains (crystalline white)
OR - organic residues
MF - microfossil (foraminifera or unidentified)
PR - mollusk shell prismatic layer calcite
Fe - limonite or hematite grain
MC - mica
QZ - quartz grain
CH - chert or opal grains
GL - glauconite
SE - selenite or gypsum grains
MS - miscellaneous

COLLECTION LOCALITIES
A: GRAND R./MOBRIDGE, SD
B: BADLANDS, CEDAR CREEK
C: BADLANDS, SAGE CREEK
D: TRASK RANCH, WASTA, SD
E: OSAGE OIL FIELD, WY

| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | | | | | | | | | | | | |
| A2 | | | | | | | | | | | | |
| A3 | 22 | 75 | 3 | | | | | | | | | |
| A4 | 2 | 94 | | | | 2 | 2 | | | | | |
| A5 | 2 | 88 | 3 | <1 | | | 2 | | | | | |
| A6 | 18 | 55 | | | | | 27 | | | | | |
| A7 | | 74 | 17 | | | 1 | 8 | | | | | |
| A8 | | 51 | 24 | <1 | | | 24 | | | | | |
| A9 | | 67 | 24 | <1 | | 1 | 9 | | | | | |
| A10 | 30 | 65 | 4 | | | | 1 | | | | | |
| A11 | 22 | 74 | 2 | | | 2 | | | | | | |
| A12 | 52 | 18 | 16 | | | 8 | 2 | 1 | | <1 | | |
| A13 | 57 | 17 | 20 | 2 | | 4 | | | | | | |
| A14 | 85 | 8 | 6 | <1 | | | | | | | | |
| A15 | 89 | 6 | 5 | | | | 1 | | | | | |
| A16 | 94 | 3 | 3 | | | | | | | | | |
| A17 | 96 | 3 | 1 | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A18 | 6 | 74 | | 20 | | | | | | | | |
| A19 | 28 | 66 | 5 | 1 | | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | ME |
| A20 | 92 | 6 | 2 | | | | | | | | | |
| A21 | 87 | 12 | | | | 1 | | | | | | |
| A22 | 94 | 3 | | | | 3 | | | | | | |
| A23 | 92 | | 8 | | | | | | | | | |
| A24 | 20 | 74 | 5 | | | | | | | | | |
| A25 | 95 | | 5 | | | | | | | | | |
| A26 | 94 | 2 | 4 | | | | | | | | | |
| A27 | 98 | | 2 | | | | | | | | | |
| A28 | 79 | 19 | 2 | | | | | | | | | |
| A29 | 65 | 22 | 12 | <1 | | | | | | | | |
| A30 | 60 | | 40 | | | | | | | | | |
| A31 | 89 | | 8 | | | 3 | | | | | | |
| A32 | 60 | 20 | 20 | | | | | | | | | |
| A33 | | 65 | 5 | | | | | 30 | | | | |
| A34 | | 30 | | | | | | 70 | | | | |
| A35 | | 81 | 3 | | | | | 16 | | | | |
| A36 | | 25 | 5 | | | | | 70 | | | | |
| A37 | | 2 | | | | | | 90 | | 8 | | |
| | | | | | | | | | | | | |
| SN | CM | CG | OR | MF | PR | fE | MC | QZ | CH | GL | SE | MS |
| B1 | 97 | 1 | | <1 | | | | >1 | | | | |
| B2 | 96 | 1 | | | 1 | | 1 | 1 | | | 1 | |
| B3 | 82 | 14 | 1 | <1 | | | 1 | 1 | | | | |
| B4 | 99 | <1 | <1 | | | | | <1 | | | | |
| B5 | 85 | 14 | 1 | | | | | | | | | |
| B6 | 97 | 1 | 2 | | | | | | | | | |
| B7 | 98 | 1 | 1 | <1 | | | | | | | | |
| B8 | 97 | 2 | 1 | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B9 | 91 | 7 | 1 | | 1 | | | | | | | |
| B10 | 86 | 12 | 1 | | 1 | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| B11 | 94 | 5 | 1 | | | | | | | | | |
| B12 | 92 | 7 | <1 | | | | | | | | | |
| B13 | 82 | 12 | | | | 2 | | | | 4 | | |
| B14 | 94 | 2 | | | | 4 | | | | | | |
| B15 | 16 | 2 | | | | 80 | | 2 | | 1 | | |
| B16 | 10 | 2 | | | | 85 | | | | 3 | | |
| B17 | 6 | | | | | 75 | | | 19 | | | |
| | | | | | | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| C1 | 83 | 15 | 1 | | | 1 | | | | | | |
| C2 | 96 | | 4 | | | | | | | | | |
| C3 | 93 | 4 | 2 | | <1 | 1 | | | | | | |
| C4 | 93 | 5 | 2 | | | | | | | | | |
| C5 | 91 | 6 | | | | 3 | | | | | | |
| C6 | 86 | 12 | 1 | | | 1 | | | | | | |
| C7 | 95 | 5 | | | | | | | | | | |
| C8 | 92 | 3 | 2 | | | 3 | | | | | | |
| C9 | 6 | 90 | 4 | | | | | | | | | |
| C10 | 90 | 5 | 2 | | | 3 | | | | | | |
| C11 | 90 | 3 | 6 | <1 | | | | | | | | |
| C12 | 40 | 50 | 1 | | | 9 | | | | | | |
| C13 | 40 | 46 | 1 | | | 1 | | 2 | | | | |
| C14 | | 34 | | | | 50 | | 6 | | 10 | | |
| C15 | | | | | | 10 | | 90 | | | | |
| C16 | | 23 | | | | 52 | | 20 | | | | |
| | | | | | | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| D1 | 93 | 2 | 1 | 1 | 1 | 2 | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D2 | 17 | 80 | | <1 | | 2 | | | | | | |
| D3 | 98 | 2 | <1 | | | | | | | | | |
| D4 | 97 | 3 | 1 | | | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| D5 | 28 | 70 | 2 | | | | | | | | | |
| D6 | 97 | 3 | | | | | | | | | | |
| D7 | 81 | 17 | 1 | | | | 1 | | | | | |
| D8 | 4 | 90 | 6 | | | | | | | | | |
| D9 | 59 | 39 | 1 | | | | <1 | 1 | | | | |
| D10 | 49 | 49 | 1 | | | 1 | <1 | | | | | |
| D11 | 45 | 54 | | | | <1 | <1 | | | | | |
| D12 | 50 | 45 | 2 | | | 2 | | | | 1 | | |
| D13 | 60 | 38 | 1 | | | <1 | <1 | | | | | |
| D14 | 47 | 44 | | | | 8 | <1 | | | | | |
| | | | | | | | | | | | | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| E1 | 84 | 2 | 12 | | | 2 | | | | | | |
| E2 | 40 | 42 | 18 | | | | | | | | | |
| E3 | 41 | 40 | 18 | 1 | | | | | | | | |
| E4 | 95 | | 5 | | | | | | | | | |
| E5 | 30 | 65 | 4 | 1 | | | | | | | | |
| E6 | 29 | 70 | 1 | 1 | | | | | | | | |
| E7 | | 98 | 1 | 1 | | | | | | | | |
| E8 | 55 | 45 | | | | | | | | | | |
| E9 | 1 | 97 | 1 | | | | | | 1 | | | |
| E10 | 2 | 92 | 1 | 4 | | | | | | | 1 | |
| E11 | 2 | 93 | 2 | | | | | | | | 3 | |
| E12 | 2 | 86 | 8 | 2 | | | | | | | 2 | |
| E13 | 12 | 35 | 40 | 4 | | | | 5 | | | 4 | |
| E14 | 10 | 45 | 25 | 1 | | 4 | 1 | 2 | | | 2 | |
| E15 | | 97 | 1 | 1 | | | | | | | 1 | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E16 | 3 | 94 | 2 | 1 | | | | | | | | |
| E17 | 52 | 43 | 1 | | | | | | | | 4 | |
| E18 | 8 | 60 | 10 | | | | | | | | 22 | |
| SN | CM | CG | OR | MF | PR | Fe | MC | QZ | CH | GL | SE | MS |
| E19 | 16 | 76 | 4 | 2 | | | | | | | 2 | |
| E20 | 1 | 74 | 1 | | | | | | | | 24 | |
| E21 | 55 | 44 | <1 | <1 | | | | | | | 1 | |
| E22 | | 92 | 6 | | | | | | | | 2 | |
| E23 | 98 | | 2 | <1 | | | | | | | | |
| E24 | 97 | 2 | 5 | | | | | | | | | |
| E25 | 62 | 30 | 7 | <1 | | | | | | | | |
| E26 | 59 | | | <1 | | | | 1 | | 39 | | |
| E27 | | 3 | 2 | 1 | | 1 | 1 | | | 92 | | |

# APPENDIX E

## GEOCHEMICAL ANALYSES

### Mobridge/Grand River Sections

| SAMPLE | Member/Zone | CONC. | NA2O % | MGO % | AL2O3 % | SIO2 % | P2O5 % |
|---|---|---|---|---|---|---|---|
| | (base) | Biot. | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| A36 | H. nicolleti (up) | cb | 1.27 | 1.42 | 12.9 | 68.9 | 0.13 |
| A35 | | | 1.43 | 1.16 | 11.9 | 71.5 | 0.13 |
| A34 | Limopsie-Gervillia | cb | 1.10 | 1.53 | 13.2 | 66.4 | 0.14 |
| A33 | H. nicolleti (low) | cb | 0.84 | 1.64 | 14.6 | 65.2 | 0.19 |
| A32 | | b | 1.00 | 1.60 | 14.3 | 64.4 | 0.16 |
| A31 | | cb | 0.92 | 1.99 | 16.2 | 61.0 | 0.15 |
| A30 | | | | | | | |
| A29 | | cb | 0.77 | 1.93 | 14.9 | 61.1 | 0.16 |
| A28 | | | | | | | |
| A27 | | | 0.74 | 1.61 | 15.7 | 63.1 | 0.10 |
| A26 | | | | | | | |
| A25 | | | 0.88 | 2.05 | 15.5 | 61.1 | 0.14 |
| A24 | | | | | | | |
| A23 | | | 0.99 | 1.92 | 15.3 | 60.4 | 0.16 |
| A22 | | | | | | | |
| A21 | | | 1.00 | 1.92 | 15.4 | 61.2 | 0.14 |
| A20 | | | | | | | |
| A19 | | | 1.07 | 2.05 | 15.2 | 57.9 | 0.14 |
| A18 | | cb | 1.29 | 1.99 | 15.1 | 60.3 | 0.14 |
| A17 | | b | 1.14 | 2.16 | 14.4 | 52.3 | 0.37 |
| A16 | | | | | | | |
| A15 | | | | | | | |
| A14 | | | 0.91 | 1.47 | 16.9 | 59.3 | 0.07 |
| A13 | B. clinolobatus | cb | 0.56 | 1.80 | 11.0 | 38.0 | 0.27 |
| A12 | | | | | | | |
| A11 | | | | | | | |
| A10 | B. grandis | b | 0.69 | 2.13 | 15.9 | 56.7 | 0.17 |
| A9 | B. grandis | b | 1.35 | 2.24 | 15.2 | 60.6 | 0.16 |
| A8 | | | | | | | |
| A7 | | | | | | | |
| A6 | B. eliasis | cb | 1.52 | 2.23 | 15.0 | 60.4 | 0.15 |
| A5 | B. eliasi | b | 1.41 | 2.20 | 14.8 | 61.8 | 0.15 |
| A4 | B. eliasi | | 2.01 | 2.84 | 18.3 | 56.2 | 0.17 |
| A3 | B.reesidei | | 1.29 | 2.04 | 14.4 | 61.9 | 0.13 |
| A2 | | | | | | | |
| A1 | B.reesidei | b | 1.04 | 2.14 | 14.9 | 60.1 | 0.12 |
| Z7 | B. cuneatus | | 0.60 | 1.99 | 15.1 | 63.2 | 0.09 |
| Z6 | B. cuneatus | | 0.53 | 1.72 | 13.2 | 64.2 | 0.14 |

**Mobridge/Grand River Section**

| SAMPLE | K2O % 0.01 | CAO % 0.01 | TIO2 % 0.001 | CR2O3 % 0.01 | MNO % 0.01 |
|---|---|---|---|---|---|
| A36 | 2.35 | 1.64 | 0.577 | <.01 | <.01 |
| A35 | 2.00 | 0.89 | 0.575 | <.01 | <.01 |
| A34 | 2.20 | 1.38 | 0.645 | <.01 | 0.01 |
| A33 | 2.34 | 1.03 | 0.680 | 0.01 | 0.01 |
| A32 | 2.36 | 1.50 | 0.676 | <.01 | 0.03 |
| A31 | 2.41 | 1.12 | 0.651 | <.01 | <.01 |
| A30 | | | | | |
| A29 | 2.47 | 1.46 | 0.661 | <.01 | 0.03 |
| A28 | | | | | |
| A27 | 2.49 | 0.53 | 0.685 | <.01 | <.01 |
| A26 | | | | | |
| A25 | 2.47 | 1.11 | 0.651 | <.01 | 0.03 |
| A24 | | | | | |
| A23 | 2.28 | 1.53 | 0.630 | <.01 | <.01 |
| A22 | | | | | |
| A21 | 2.41 | 1.44 | 0.638 | <.01 | 0.01 |
| A20 | | | | | |
| A19 | 2.15 | 3.19 | 0.595 | <.01 | 0.07 |
| A18 | 2.30 | 2.39 | 0.624 | <.01 | 0.02 |
| A17 | 2.59 | 6.34 | 0.596 | <.01 | 0.02 |
| A16 | | | | | |
| A15 | | | | | |
| A14 | 3.73 | 0.93 | 0.742 | <.01 | <.01 |
| A13 | 2.68 | 19.3 | 0.446 | <.01 | 0.36 |
| A12 | | | | | |
| A11 | | | | | |
| A10 | 3.82 | 2.40 | 0.665 | <.01 | 0.03 |
| A9 | 2.78 | 1.60 | 0.670 | <.01 | 0.03 |
| A8 | | | | | |
| A7 | | | | | |
| A6 | 2.54 | 2.28 | 0.628 | <.01 | 0.03 |
| A5 | 2.34 | 2.02 | 0.628 | <.01 | 0.02 |
| A4 | 0.96 | 2.95 | 0.454 | <.01 | 0.12 |
| A3 | 2.55 | 1.54 | 0.622 | <.01 | 0.01 |
| A2 | | | | | |
| A1 | 2.61 | 2.26 | 0.641 | <.01 | 0.06 |
| Z7 | 2.19 | 1.10 | 0.592 | <.01 | 0.02 |
| Z6 | 2.30 | 1.06 | 0.597 | <.01 | 0.02 |

**Mobridge/Grand River Section**

| SAMPLE | FE2O3 % 0.01 | RB PPM 10 | SR PPM 10 | Y PPM 10 | ZR PPM 10 |
|---|---|---|---|---|---|
| A36 | 4.71 | 77 | 278 | 32 | 236 |
| A35 | 3.97 | 67 | 231 | 23 | 287 |
| A34 | 4.71 | 84 | 222 | 33 | 221 |
| A33 | 5.90 | 108 | 207 | 27 | 187 |
| A32 | 5.43 | 97 | 213 | 36 | 193 |
| A31 | 6.20 | 96 | 187 | 25 | 151 |
| A30 | | | | | |
| A29 | 6.80 | 108 | 166 | 26 | 135 |
| A28 | | | | | |
| A27 | 4.94 | 114 | 131 | 21 | 141 |
| A26 | | | | | |
| A25 | 5.99 | 104 | 177 | 35 | 141 |
| A24 | | | | | |
| A23 | 6.52 | 88 | 212 | 23 | 145 |
| A22 | | | | | |
| A21 | 6.11 | 96 | 214 | 25 | 146 |
| A20 | | | | | |
| A19 | 6.26 | 103 | 242 | 36 | 141 |
| A18 | 6.14 | 100 | 201 | 21 | 144 |
| A17 | 6.17 | 111 | 334 | 40 | 159 |
| A16 | | | | | |
| A15 | | | | | |
| A14 | 4.87 | 110 | 187 | 29 | 157 |
| A13 | 5.34 | 63 | 284 | 31 | 112 |
| A12 | | | | | |
| A11 | | | | | |
| A10 | 6.41 | 110 | 120 | 25 | 149 |
| A9 | 5.99 | 112 | 214 | 30 | 177 |
| A8 | | | | | |
| A7 | | | | | |
| A6 | 6.06 | 113 | 225 | 34 | 186 |
| A5 | 5.56 | 95 | 229 | 30 | 172 |
| A4 | 5.44 | 41 | 336 | 35 | 180 |
| A3 | 5.92 | 123 | 261 | 32 | 176 |
| A2 | | | | | |
| A1 | 5.78 | 109 | 201 | 31 | 156 |
| Z7 | 5.13 | 95 | 147 | 24 | 151 |
| Z6 | 7.03 | 113 | 166 | 31 | 171 |

**Mobridge/Grand River Section**

| SAMPLE | NB PPM 10 | BA PPM 50 | LOI % 0.01 | SUM % 0.1 |
|---|---|---|---|---|
| A36 | 10 | 949 | 5.50 | 99.6 |
| A35 | 13 | 747 | 5.35 | 99.1 |
| A34 | 11 | 964 | 7.05 | 98.5 |
| A33 | 15 | 906 | 7.80 | 100.4 |
| A32 | 12 | 957 | 7.20 | 98.8 |
| A31 | 16 | 637 | 9.25 | 100.0 |
| A30 | | | | |
| A29 | 10 | 681 | 9.10 | 99.5 |
| A28 | | | | |
| A27 | 11 | 682 | 9.40 | 99.4 |
| A26 | | | | |
| A25 | 14 | 793 | 9.35 | 99.4 |
| A24 | | | | |
| A23 | 12 | 1230 | 9.55 | 99.5 |
| A22 | | | | |
| A21 | 12 | 679 | 9.45 | 99.8 |
| A20 | | | | |
| A19 | 14 | 845 | 9.50 | 98.3 |
| A18 | 11 | 920 | 8.70 | 99.2 |
| A17 | 20 | 742 | 10.1 | 96.3 |
| A16 | | | | |
| A15 | | | | |
| A14 | 12 | 1010 | 10.4 | 99.5 |
| A13 | 13 | 689 | 20.6 | 100.5 |
| A12 | | | | |
| A11 | | | | |
| A10 | 11 | 769 | 10.7 | 99.7 |
| A9 | 13 | 690 | 8.35 | 99.1 |
| A8 | | | | |
| A7 | | | | |
| A6 | 14 | 690 | 8.60 | 99.6 |
| A5 | 11 | 812 | 8.35 | 99.4 |
| A4 | 10 | 959 | 8.80 | 98.4 |
| A3 | 14 | 920 | 8.55 | 99.1 |
| A2 | | | | |
| A1 | 14 | 900 | 9.30 | 99.1 |
| Z7 | 12 | 815 | 9.15 | 99.3 |
| Z6 | 17 | 552 | 8.55 | 99.5 |

**Badlands National Park Sections**

| SAMPLE | Member/Zone | CONC. | NA2O % | MGO % | AL2O3 % | SIO2 % | P2O5 % |
|---|---|---|---|---|---|---|---|
| | (base) | Biot. | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| **Cedar Creek Locality, South Unit** | | | | | | | |
| B17 | B. clinolobatus Mounds | | 0.74 | 0.99 | 17.6 | 57.1 | 0.35 |
| B16 | B. clinolobatus Mounds | | 0.62 | 1.31 | 17.7 | 61.8 | 0.10 |
| B15 | B. clinolobatus | | 0.60 | 1.15 | 14.8 | 44.1 | 0.33 |
| B14 | B. clinolobatus | cb | 0.89 | 1.57 | 16.2 | 57.3 | 0.14 |
| B13 | B. reesidei/grandis | b | 0.41 | 1.22 | 15.1 | 48.5 | 0.93 |
| B12 | B. reesidei | | 0.63 | 1.82 | 13.7 | 59.2 | 0.13 |
| B11 | B. reesidei | b | 0.90 | 2.28 | 13.4 | 60.2 | 0.11 |
| B10 | B. reesidei | cb | 1.08 | 2.07 | 13.8 | 63.5 | 0.10 |
| B9 | B. reesidei | cb | 1.02 | 1.65 | 14.0 | 56.6 | 0.13 |
| B8 | B. reesidei | | 1.19 | 1.61 | 14.2 | 59.5 | 0.12 |
| B7 | B. cuneatus | | 1.16 | 1.99 | 15.2 | 60.8 | 0.12 |
| B6 | B. compressus | cb | 1.39 | 2.13 | 15.0 | 63.5 | 0.13 |
| B5 | B. compressus | b | 1.15 | 2.07 | 14.2 | 59.6 | 0.11 |
| B3 | B. compressus | b | 1.47 | 1.93 | 15.6 | 61.9 | 0.12 |
| B2 | | | | | | | |
| B1 | | | | | | | |
| **Sage Creek Area, North Unit** | | | | | | | |
| C15 | Fox Hills clinoform bed | | 0.85 | 1.30 | 11.7 | 52.6 | 0.17 |
| C14 | B. clinolobatus Mounds | | 1.24 | 2.51 | 14.2 | 60.2 | 0.17 |
| C13 | B. clinolobatus Mounds | | 1.52 | 1.75 | 13.6 | 63.7 | 0.16 |
| C12 | B. clinolobatus | c | 1.40 | 2.53 | 15.0 | 57.5 | 0.18 |
| C11 | B. clinolobatus | | 1.44 | 2.58 | 15.4 | 59.5 | 0.19 |
| C10 | | | | | | | |
| C9 | | | | | | | |
| C8 | | | | | | | |
| C7 | | | | | | | |
| C6 | | | | | | | |
| C5 | | | | | | | |
| C4 | B. compressus | cb | 1.06 | 2.84 | 14.9 | 57.0 | 0.16 |
| C3 | B. compressus | cb | 0.82 | 2.32 | 15.5 | 56.7 | 0.17 |
| C2 | | | | | | | |
| C1 | | | | | | | |

**Badlands National Park Sections**

| SAMPLE | K2O % | CAO % | TIO2 % | CR2O3 % | MNO % |
|---|---|---|---|---|---|
| | 0.01 | 0.01 | 0.001 | 0.01 | 0.01 |
| **Cedar Creek Locality, South Unit** | | | | | |
| B17 | 4.27 | 1.12 | 0.695 | <.01 | 0.03 |
| B16 | 4.11 | 0.70 | 0.701 | <.01 | <.01 |
| B15 | 2.82 | 1.39 | 0.433 | <.01 | 0.14 |
| B14 | 3.78 | 1.69 | 0.635 | <.01 | 0.02 |
| B13 | 4.32 | 5.55 | 0.642 | 0.05 | 0.01 |
| B12 | 2.96 | 3.63 | 0.584 | <.01 | 0.07 |
| B11 | 2.40 | 3.37 | 0.534 | <.01 | 0.03 |
| B10 | 2.29 | 2.42 | 0.521 | <.01 | <.01 |
| B9 | 2.77 | 5.18 | 0.594 | <.01 | 0.01 |
| B8 | 2.72 | 3.09 | 0.588 | <.01 | 0.01 |
| B7 | 2.87 | 1.40 | 0.572 | <.01 | 0.03 |
| B6 | 2.91 | 1.21 | 0.632 | <.01 | 0.02 |
| B5 | 2.67 | 3.00 | 0.594 | <.01 | 0.05 |
| B4 | | | | | |
| B3 | 2.51 | 1.56 | 0.581 | <.01 | 0.02 |
| B2 | | | | | |
| B1 | | | | | |
| **Sage Creek Area, North Unit** | | | | | |
| C15 | 3.13 | 12.0 | 0.504 | <.01 | 0.14 |
| C14 | 3.73 | 2.84 | 0.615 | <.01 | 0.05 |
| C13 | 3.73 | 1.86 | 0.595 | <.01 | 0.02 |
| C12 | 3.60 | 4.17 | 0.634 | <.01 | 0.07 |
| C11 | 3.77 | 1.76 | 0.676 | <.01 | 0.04 |
| C10 | | | | | |
| C9 | | | | | |
| C8 | | | | | |
| C7 | | | | | |
| C6 | | | | | |
| C5 | | | | | |
| C4 | 3.00 | 3.31 | 0.549 | <.01 | 0.14 |
| C3 | 3.23 | 2.83 | 0.591 | <.01 | 0.05 |
| C2 | | | | | |
| C1 | | | | | |

**Badlands National Park Sections**

| SAMPLE | FE2O3 %<br>0.01 | RB PPM<br>10 | SR PPM<br>10 | Y PPM<br>10 | ZR PPM<br>10 |
|---|---|---|---|---|---|
| **Cedar Creek Locality, South Unit** | | | | | |
| B17 | 8.62 | 134 | 1630 | 24 | 160 |
| B16 | 5.96 | 162 | 190 | 25 | 158 |
| B15 | 23.4 | 102 | 410 | 52 | 185 |
| B14 | 8.12 | 153 | 283 | 40 | 332 |
| B13 | 7.41 | 125 | 330 | 52 | 216 |
| B12 | 5.47 | 121 | 185 | 33 | 158 |
| B11 | 5.02 | 89 | 313 | 29 | 167 |
| B10 | 4.83 | 85 | 302 | 27 | 149 |
| B9 | 5.78 | 112 | 363 | 24 | 144 |
| B8 | 5.44 | 102 | 250 | 24 | 166 |
| B7 | 5.57 | 117 | 454 | 40 | 177 |
| B6 | 5.63 | 122 | 199 | 30 | 166 |
| B5 | 5.38 | 113 | 270 | 34 | 155 |
| B4 | | | | | |
| B3 | 5.51 | 99 | 227 | 31 | 160 |
| B2 | | | | | |
| B1 | | | | | |
| **Sage Creek Area, North Unit** | | | | | |
| C15 | 4.80 | 111 | 124 | 30 | 152 |
| C14 | 5.94 | 122 | 148 | 26 | 157 |
| C13 | 4.68 | 107 | 170 | 26 | 177 |
| C12 | 5.17 | 114 | 178 | 28 | 141 |
| C11 | 5.61 | 109 | 148 | 22 | 151 |
| C10 | | | | | |
| C9 | | | | | |
| C8 | | | | | |
| C7 | | | | | |
| C6 | | | | | |
| C6 | | | | | |
| C4 | 6.50 | 116 | 240 | 28 | 147 |
| C3 | 6.49 | 118 | 191 | 30 | 159 |
| C2 | | | | | |
| C1 | | | | | |

**Badlands National Park Sections**

| SAMPLE | NB PPM<br>10 | BA PPM<br>50 | LOI %<br>0.01 | SUM %<br>0.1 |
|---|---|---|---|---|
| **Cedar Creek Locality, South Unit** | | | | |
| B17 | <10 | 937 | 7.10 | 98.9 |
| B16 | 13 | 706 | 6.85 | 100.0 |
| B15 | 11 | 17200 | 9.10 | 100.3 |
| B14 | 12 | 1380 | 8.10 | 98.7 |
| B13 | 24 | 595 | 10.4 | 94.7 |
| B12 | 12 | 668 | 7.90 | 96.2 |
| B11 | 13 | 1470 | 8.35 | 96.8 |
| B10 | 11 | 531 | 7.45 | 98.2 |
| B9 | 10 | 572 | 8.85 | 96.7 |
| B8 | 10 | 597 | 7.65 | 96.3 |
| B7 | 14 | 7540 | 7.20 | 97.8 |
| B6 | 12 | 587 | 6.75 | 99.4 |
| B5 | 14 | 593 | 7.80 | 96.8 |
| B4 | | | | |
| B3 | 11 | 555 | 7.05 | 98.4 |
| B2 | | | | |
| B1 | | | | |
| **Sage Creek Area, North Unit** | | | | |
| C15 | 10 | 521 | 12.7 | 100.0 |
| C14 | 10 | 792 | 7.00 | 98.6 |
| C13 | 10 | 816 | 5.45 | 97.2 |
| C12 | 12 | 1060 | 8.35 | 98.8 |
| C11 | 12 | 794 | 7.20 | 98.3 |
| C10 | | | | |
| C9 | | | | |
| C8 | | | | |
| C7 | | | | |
| C6 | | | | |
| C5 | | | | |
| C4 | 13 | 1040 | 9.30 | 98.9 |
| C3 | 12 | 771 | 9.00 | 97.8 |
| C2 | | | | |
| C1 | | | | |

**Cheyenne River Valley Sections**

| SAMPLE | Member/Zone | CONC. | NA2O % | MGO % | AL2O3 % | SIO2 % | P2O5 % |
|---|---|---|---|---|---|---|---|
| | (base) | Biot. | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| **Cheyenne River/Tom Trask Ranch** | | | | | | | |
| D14 | Fox Hills trans. | cb | 1.22 | 2.60 | 13.9 | 61.4 | 0.23 |
| D13 | | | 1.23 | 2.79 | 14.4 | 61.5 | 0.22 |
| D12 | | cb | 1.07 | 2.84 | 13.0 | 55.6 | 0.20 |
| D11 | | | | | | | |
| D10 | | cb | 1.18 | 3.37 | 14.3 | 57.0 | 0.22 |
| D9 | H. traskii/B. clin. | cb | 1.06 | 2.81 | 13.1 | 55.6 | 0.20 |
| D8 | H. traskii/B. clin. | cb | 1.36 | 2.67 | 13.9 | 61.7 | 0.22 |
| D7 | B. clinolobatus | | 1.24 | 2.63 | 13.9 | 56.7 | 0.16 |
| D6 | B. clinolobatus | | 1.16 | 2.66 | 15.5 | 58.9 | 0.15 |
| D5 | B. clinolobatus | | 1.26 | 2.65 | 14.5 | 60.8 | 0.17 |
| D4 | B. grandis | | 1.13 | 2.55 | 14.7 | 57.0 | 0.15 |
| D3 | B. grandis | | 1.33 | 2.51 | 15.0 | 62.1 | 0.17 |
| D2 | B. eliasi (?) | cb | 0.76 | 2.27 | 15.1 | 54.3 | 0.21 |
| D1 | B. cuneatus | b | 0.65 | 2.02 | 16.6 | 58.3 | 0.13 |
| **Cherry Creek, SD** | | | | | | | |
| Z11 | B. cuneatus Virgin Creek (lower) | | 0.64 | 1.70 | 17.2 | 59.5 | 0.13 |

**Cheyenne River Valley Sections**

| SAMPLE | K2O % | CAO % | TIO2 % | CR2O3 % | MNO % |
|---|---|---|---|---|---|
| | 0.01 | 0.01 | 0.001 | 0.01 | 0.01 |
| **Cheyenne River/Tom Trask Ranch** | | | | | |
| D14 | 2.72 | 2.54 | 0.583 | <.01 | 0.03 |
| D13 | 2.90 | 1.94 | 0.613 | <.01 | 0.02 |
| D12 | 2.69 | 5.34 | 0.574 | <.01 | 0.05 |
| D11 | | | | | |
| D10 | 3.09 | 3.59 | 0.638 | <.01 | 0.05 |
| D9 | 2.90 | 6.33 | 0.581 | <.01 | 0.09 |
| D8 | 3.26 | 2.90 | 0.593 | <.01 | 0.03 |
| D7 | 3.19 | 4.14 | 0.587 | <.01 | 0.06 |
| D6 | 3.50 | 2.25 | 0.656 | <.01 | 0.03 |
| D5 | 3.00 | 2.43 | 0.645 | <.01 | 0.03 |
| D4 | 3.04 | 3.85 | 0.641 | <.01 | 0.04 |
| D3 | 3.00 | 1.70 | 0.641 | <.01 | 0.03 |
| D2 | 2.80 | 4.13 | 0.627 | <.01 | 0.05 |
| D1 | 2.90 | 1.22 | 0.683 | <.01 | <.01 |
| **Cherry Creek, SD** | | | | | |
| Z11 | 3.29 | 0.56 | 0.741 | <.01 | <.01 |

**Cheyenne River Valley Sections**

| SAMPLE | FE2O3 % | RB PPM | SR PPM | Y PPM | ZR PPM |
|---|---|---|---|---|---|
| | 0.01 | 10 | 10 | 10 | 10 |
| **Cheyenne River/Tom Trask Ranch** | | | | | |
| D14 | 5.45 | 93 | 191 | 29 | 164 |
| D13 | 5.63 | 97 | 190 | 30 | 168 |
| D12 | 5.08 | 90 | 303 | 33 | 155 |
| D11 | | | | | |
| D10 | 6.34 | 97 | 173 | 30 | 151 |
| D9 | 5.33 | 93 | 270 | 29 | 145 |
| D8 | 5.20 | 101 | 210 | 28 | 147 |
| D7 | 5.84 | 109 | 505 | 25 | 144 |
| D6 | 5.90 | 129 | 175 | 28 | 151 |
| D5 | 5.79 | 92 | 196 | 25 | 165 |
| D4 | 6.06 | 100 | 331 | 26 | 140 |
| D3 | 5.73 | 100 | 196 | 23 | 161 |
| D2 | 7.05 | 120 | 372 | 47 | 148 |
| D1 | 7.44 | 137 | 227 | 24 | 144 |
| **Cherry Creek, SD** | | | | | |
| Z11 | 5.93 | 138 | 298 | 23 | 149 |

**Cheyenne River Valley Sections**

| SAMPLE | NB PPM<br>10 | BA PPM<br>50 | LOI %<br>0.01 | SUM %<br>0.1 |
|---|---|---|---|---|
| **Cheyenne River/Tom Trask Ranch** | | | | |
| D14 | 12 | 1060 | 8.25 | 99.1 |
| D13 | 13 | 921 | 7.35 | 98.8 |
| D12 | <10 | 907 | 8.75 | 95.4 |
| D11 | | | | |
| D10 | 13 | 772 | 8.35 | 98.3 |
| D9 | <10 | 1360 | 9.80 | 98.0 |
| D8 | 11 | 989 | 6.55 | 98.6 |
| D7 | 10 | 1360 | 7.50 | 96.2 |
| D6 | 13 | 836 | 7.55 | 98.4 |
| D5 | 11 | 903 | 7.00 | 98.4 |
| D4 | 13 | 1150 | 7.85 | 97.2 |
| D3 | 11 | 1040 | 6.85 | 99.2 |
| D2 | 12 | 1040 | 9.65 | 97.2 |
| D1 | 12 | 929 | 9.40 | 99.5 |
| **Cherry Creek, SD** | | | | |
| Z11 | 14 | 959 | 9.55 | 99.4 |

**Black Hills - Western Flank/Mush Creek & Osage Oil Fields, Weston Co., WY**

| SAMPLE | Member/Zone | CONC. | NA2O % | MGO % | AL2O3 % | SIO2 % | P2O5 % |
|---|---|---|---|---|---|---|---|
| | (base) | Biot. | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| E27 | glauconitic Fox Hills | | 1.32 | 2.58 | 12.9 | 59.1 | 0.27 |
| E26 | Fox Hills trans. | | 0.93 | 1.56 | 8.55 | 42.0 | 0.20 |
| E25 | B. clinolobatus | cb | 1.23 | 1.93 | 14.5 | 62.9 | 0.15 |
| E24 | B. clinolobatus | cb | 1.11 | 1.86 | 15.2 | 61.4 | 0.17 |
| E23 | B. clinolobatus | | 1.30 | 1.47 | 14.5 | 63.3 | 0.16 |
| E22 | B. clinolobatus | cb | 1.84 | 2.25 | 13.6 | 61.6 | 0.18 |
| E21 | B. clinolobatus | cb | 1.45 | 2.52 | 14.5 | 62.4 | 0.15 |
| E20 | B. grandis | cb | 1.71 | 2.52 | 14.2 | 62.5 | 0.17 |
| E19 | B. grandis | cb | 1.26 | 2.31 | 14.2 | 60.8 | 0.15 |
| E18 | B. grandis | cb | 1.28 | 1.96 | 12.1 | 52.8 | 0.14 |
| E17 | B. grandis | | 0.94 | 1.65 | 10.8 | 51.5 | 0.12 |
| E16 | B. grandis | cb | 1.22 | 2.17 | 12.8 | 57.3 | 0.13 |
| E15 | B. grandis | cb | 1.71 | 2.33 | 14.1 | 61.6 | 0.14 |
| E14 | B. grandis | cb | 1.77 | 2.09 | 14.0 | 63.0 | 0.15 |
| E13 | | | | | | | |
| E12 | | | | | | | |
| E11 | B. eliasi | | 1.66 | 1.93 | 12.8 | 64.5 | 0.13 |
| E10 | B. eliasi | | 2.06 | 1.92 | 13.5 | 59.7 | 0.11 |
| E9 | B. eliasi | | 1.73 | 2.10 | 11.7 | 56.6 | 0.13 |
| E8 | | | | | | | |
| E7 | B. eliasi | c | 2.13 | 2.38 | 14.4 | 60.8 | 0.15 |
| E6 | B. eliasi | | 1.88 | 1.88 | 13.9 | 57.6 | 0.12 |
| E5 | B. eliasi | | 1.84 | 1.99 | 15.8 | 62.6 | 0.16 |
| E4 | B. jenseni/lobsters | cb | 0.84 | 1.46 | 15.9 | 59.5 | 0.12 |
| E3 | B. reesidei | | 0.77 | 1.65 | 17.7 | 59.6 | 0.16 |
| E2 | | | | | | | |
| E1 | B. reesidei | | 0.61 | 1.36 | 16.8 | 58.8 | 0.24 |

**Duplicate Analyses**

| SAMPLE | Member/Zone | NA2O % | MGO % | AL2O3 % | SIO2 % | P2O5 % |
|---|---|---|---|---|---|---|
| | (base) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| D A1 | | 1.05 | 2.13 | 14.8 | 59.7 | 0.12 |
| D A23 | | 0.98 | 1.91 | 15.2 | 60.2 | 0.15 |
| D B8 | | 1.18 | 1.63 | 14.2 | 59.5 | 0.12 |
| D C13 | | 1.54 | 1.74 | 13.6 | 63.6 | 0.16 |
| D D12 | | 1.06 | 2.86 | 13.0 | 55.9 | 0.21 |
| D E15 | | 1.71 | 2.34 | 14.2 | 62.0 | 0.15 |
| D Z7 | | 0.61 | 2.01 | 15.3 | 63.5 | 0.10 |

**Black Hills - Western Flank/Mush Creek & Osage Oil Fields, Weston Co., WY**

| SAMPLE | K2O %<br>0.01 | CAO %<br>0.01 | TIO2 %<br>0.001 | CR2O3 %<br>0.01 | MNO %<br>0.01 |
|---|---|---|---|---|---|
| E27 | 3.00 | 3.30 | 0.601 | <.01 | 0.03 |
| E26 | 2.23 | 19.6 | 0.417 | <.01 | 0.23 |
| E25 | 3.35 | 1.39 | 0.643 | <.01 | 0.03 |
| E24 | 3.31 | 1.08 | 0.677 | <.01 | 0.02 |
| E23 | 3.28 | 1.15 | 0.623 | <.01 | <.01 |
| E22 | 2.34 | 3.61 | 0.548 | <.01 | 0.02 |
| E21 | 2.50 | 1.80 | 0.591 | <.01 | 0.01 |
| E20 | 2.50 | 1.89 | 0.605 | <.01 | 0.02 |
| E19 | 2.51 | 2.49 | 0.613 | <.01 | 0.02 |
| E18 | 2.46 | 8.59 | 0.546 | <.01 | 0.05 |
| E17 | 2.15 | 9.64 | 0.471 | <.01 | 0.06 |
| E16 | 2.51 | 5.67 | 0.524 | <.01 | 0.06 |
| E15 | 2.50 | 2.57 | 0.591 | <.01 | 0.03 |
| E14 | 2.46 | 2.07 | 0.591 | <.01 | 0.03 |
| E13 | | | | | |
| E12 | | | | | |
| E11 | 1.96 | 4.27 | 0.475 | <.01 | <.01 |
| E10 | 2.31 | 4.41 | 0.541 | <.01 | 0.03 |
| E9 | 1.90 | 7.67 | 0.452 | <.01 | <.01 |
| E8 | | | | | |
| E7 | 3.12 | 2.26 | 0.601 | <.01 | 0.02 |
| E6 | 2.80 | 3.74 | 0.590 | <.01 | <.01 |
| E5 | 3.21 | 0.65 | 0.650 | <.01 | 0.01 |
| E4 | 3.40 | 0.75 | 0.638 | <.01 | 0.01 |
| E3 | 2.72 | 0.69 | 0.775 | <.01 | 0.02 |
| E2 | | | | | |
| E1 | 2.74 | 0.69 | 0.741 | <.01 | 0.01 |

**Duplicate Analyses**

| SAMPLE | K2O %<br>0.01 | CAO %<br>0.01 | TIO2 %<br>0.001 | CR2O3 %<br>0.01 | MNO %<br>0.01 |
|---|---|---|---|---|---|
| D A1 | 2.60 | 2.28 | 0.643 | <.01 | 0.06 |
| D A23 | 2.30 | 1.54 | 0.628 | <.01 | 0.01 |
| D B8 | 2.71 | 3.12 | 0.598 | <.01 | 0.01 |
| D C13 | 3.72 | 1.84 | 0.587 | <.01 | 0.02 |
| D D12 | 2.68 | 5.31 | 0.576 | <.01 | 0.05 |
| D E15 | 2.51 | 2.57 | 0.595 | <.01 | 0.03 |
| D Z7 | 2.18 | 1.10 | 0.593 | <.01 | 0.02 |

**Black Hills - Western Flank/Mush Creek & Osage Oil Fields, Weston Co., WY**

| SAMPLE | FE2O3 % 0.01 | RB PPM 10 | SR PPM 10 | Y PPM 10 | ZR PPM 10 |
|---|---|---|---|---|---|
| E27 | 7.92 | 96 | 399 | 52 | 213 |
| E26 | 5.70 | 51 | 193 | 45 | 166 |
| E25 | 5.30 | 120 | 238 | 27 | 180 |
| E24 | 6.22 | 113 | 373 | 23 | 148 |
| E23 | 5.12 | 101 | 533 | 18 | 156 |
| E22 | 4.74 | 98 | 443 | 36 | 180 |
| E21 | 5.14 | 96 | 298 | 23 | 177 |
| E20 | 5.00 | 84 | 375 | 25 | 186 |
| E19 | 5.57 | 106 | 310 | 31 | 164 |
| E18 | 5.00 | 104 | 496 | 31 | 134 |
| E17 | 4.82 | 95 | 389 | 28 | 153 |
| E16 | 5.50 | 114 | 318 | 31 | 165 |
| E15 | 5.22 | 94 | 293 | 26 | 165 |
| E14 | 5.15 | 102 | 310 | 29 | 183 |
| E13 | | | | | |
| E12 | | | | | |
| E11 | 3.50 | 75 | 326 | 31 | 197 |
| E10 | 4.68 | 91 | 564 | 30 | 177 |
| E9 | 3.89 | 88 | 311 | 31 | 147 |
| E8 | | | | | |
| E7 | 5.12 | 113 | 213 | 34 | 177 |
| E6 | 5.86 | 117 | 277 | 23 | 205 |
| E5 | 5.58 | 132 | 160 | 36 | 158 |
| E4 | 7.31 | 138 | 314 | 24 | 151 |
| E3 | 6.18 | 106 | 131 | 23 | 134 |
| E2 | | | | | |
| E1 | 7.34 | 122 | 146 | 20 | 147 |

**Duplicate Analyses**

| SAMPLE | FE2O3 % 0.01 | RB PPM 10 | SR PPM 10 | Y PPM 10 | ZR PPM 10 |
|---|---|---|---|---|---|
| D A1 | 5.75 | 114 | 207 | 28 | 155 |
| D A23 | 6.49 | 87 | 208 | 22 | 142 |
| D B8 | 5.40 | 90 | 245 | 23 | 161 |
| D C13 | 4.70 | 114 | 174 | 26 | 174 |
| D D12 | 5.04 | 90 | 302 | 33 | 157 |
| D E15 | 5.21 | 95 | 295 | 27 | 167 |
| D Z7 | 5.15 | 102 | 149 | 31 | 151 |

**Black Hills - Western Flank/Mush Creek & Osage Oil Fields, Weston Co., WY**

| SAMPLE | NB PPM<br>10 | BA PPM<br>50 | LOI %<br>0.01 | SUM %<br>0.1 |
|---|---|---|---|---|
| E27 | 16 | 585 | 7.90 | 99.1 |
| E26 | 10 | 615 | 19.0 | 100.5 |
| E25 | 10 | 780 | 6.90 | 98.5 |
| E24 | 12 | 857 | 8.20 | 99.4 |
| E23 | <10 | 915 | 7.45 | 98.6 |
| E22 | 15 | 1200 | 6.45 | 97.4 |
| E21 | <10 | 687 | 7.70 | 98.9 |
| E20 | 12 | 805 | 6.90 | 98.2 |
| E19 | 12 | 781 | 7.95 | 98.0 |
| E18 | 10 | 846 | 8.00 | 93.1 |
| E17 | 10 | 777 | 7.50 | 89.8 |
| E16 | 10 | 821 | 7.75 | 95.8 |
| E15 | 10 | 1080 | 7.55 | 98.5 |
| E14 | 13 | 918 | 6.85 | 98.3 |
| E13 | | | | |
| E12 | | | | |
| E11 | <10 | 764 | 6.40 | 97.8 |
| E10 | 12 | 712 | 6.35 | 95.8 |
| E9 | <10 | 803 | 6.75 | 93.1 |
| E8 | | | | |
| E7 | 13 | 635 | 6.90 | 98.0 |
| E6 | <10 | 619 | 7.70 | 96.2 |
| E5 | 13 | 645 | 6.75 | 99.4 |
| E4 | 13 | 764 | 9.80 | 99.9 |
| E3 | 11 | 965 | 9.35 | 99.8 |
| E2 | | | | |
| E1 | 12 | 969 | 10.5 | 100.0 |

**Duplicate Analyses**

| SAMPLE | NB PPM<br>10 | BA PPM<br>50 | LOI %<br>0.01 | SUM %<br>0.1 |
|---|---|---|---|---|
| D A1 | 14 | 906 | 9.65 | 98.9 |
| D A23 | <10 | 1210 | 9.80 | 99.4 |
| D B8 | 10 | 611 | 7.80 | 96.4 |
| D C13 | <10 | 813 | 5.65 | 97.3 |
| D D12 | 9 | 909 | 8.65 | 95.5 |
| D E15 | 11 | 1080 | 7.50 | 99.0 |
| D Z7 | 14 | 809 | 9.05 | 99.8 |

# APPENDIX F

## CORE SAMPLE CHARACTERISTICS

The list below includes representative specimens that were assighned AMNH fossil ID number, specimen description, date collected, and location collected (including AMNH locality number). All specimens were collected by Phil Stoffer and were added to the collections at the American Museum of Natural History on completion of this project. Additional untaged specimens were added to unlabled specimen collections for AMNH localities in the South Dakota and Eastern Wyoming area.

| ID# | SPECIMEN | LOCATION COLLECTED | | DATE |
|---|---|---|---|---|
| Pierre Shale Fossils | | | | |
| 45587 | *Baculites compressus* | Sage Creek Bridge, Badlands N. Unit | 3207 | 7/96 |
| 45586 | *Baculites compressus* | Sage Creek Bridge, Badlands N. Unit | 3207 | 7/96 |
| 45585 | *Baculites compressus* | Sage Creek Bridge, Badlands N. Unit | 3207 | 7/96 |
| 45601 | *Baculites compressus* | Sage Creek Bridge, Badlands N. Unit | 3207 | 7/96 |
| 45602 | *Baculites compressus* | Sage Creek Bridge, Badlands N. Unit | 3207 | 7/96 |
| 45619 | *Baculites cuneatus* | Cedar Creek, Badlands South Unit | 3212 | 7/96 |
| 45618 | *Baculites reesidei* | Cheyenne R. bluffs N. of Pedro, SD | 3184 | 7/96 |
| 45617 | *Baculites reesidei* | S. Fork of Sage Creek, BNP N. Unit | 3218 | 7/96 |
| 45613 | *Baculites reesidei* | Cheyenne R. bluffs N. of Pedro, SD | 3184 | 7/96 |
| 45588 | *Baculites eliasi* | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45589 | *Baculites eliasi* | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45590 | *Baculites eliasi* | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45591 | *Baculites eliasi* | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45614 | *Baculites grandis* | Sage Creek/White Butte, BNP N. Unit | 3219 | 7/96 |
| 45592 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45593 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45594 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45595 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45596 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45597 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45598 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45599 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45600 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45612 | *Baculites* grandis | Osage Oil Field, Weston County, WY | 3194 | 7/96 |
| 45581 | *Baculites clinolobatus* | Osage Oil Field, Weston Co., WY | 3194 | 7/96 |
| 45582 | *Baculites clinolobatus* | Osage Oil Field, Weston Co., WY | 3194 | 7/96 |
| 45583 | *Baculites clinolobatus* | Osage Oil Field, Weston Co., WY | 3194 | 7/96 |
| 45584a | *Baculites clinolobatus* | Osage Oil Field, Weston Co., WY | 3194 | 7/96 |
| 45584b | *Baculites clinolobatus* | Osage Oil Field, Weston Co., WY | 3194 | 7/96 |
| 45616 | *Baculites clinolobatus* | S. Fork Sage Creek, BNP N. Unit | 3218 | 7/96 |
| 45615 | *Baculites clinolobatus* | Sage Creek/White Butte, BNP N.Un. | 3219 | 7/96 |
| 45580 | *Baculites clinolobatus* (compressed) | S. Fork, Sage Creek | 3218 | 7/96 |
| 45579 | *Baculites clinolobatus* (compressed) | S. Fork, Sage Creek | 3218 | 7/96 |
| Fox Hills Fossils | | | | |
| 45609 | *Diplocraterian* traces | from Fox Hills, Grassy Tables area, BNP | | 7/97 |
| 45610 | *Nerites* traces | from Fox Hills, Roberts Prairie Dog Town, BNP | | 7/97 |
| 45611 | *Nerites* traces | from Fox Hills, Roberts Prairie Dog Town, BNP | | 7/97 |
| 45608 | *Nerites* traces | from Fox Hills, Roberts Prairie Dog Town, BNP | | 7/97 |

# REFERENCE LIST

Agnew, A. F. & P. C. Tychsen. 1965. *A guide to the stratigraphy of South Dakota.* South Dakota Geological Survey Bulletin 14.

Ainsworth, R. B. & S. A. J. Pattison. 1994. Where have all the lowstands gone? Evidence for attached lowstand systems tracts in the Western Interior of North America. *Geology* 22: 415-418.

American Association of Petroleum Geologist. 1983. Northern Rockies/Williston Basin Region. *Correlation of Stratigraphic Units of North America (COSUNA) Project,* 1 sheet.

American Geological Institute. 1995. *Portrait USA.* AGI Joint Education Initiative, CD-ROM.

Anderson , R. R. & B. J. Witzke. 1989. The terminal Cretaceous Manson impact structure in north central Iowa; a window into the Late Cretaceous geologic history of the eastern margin, Western Interior Seaway. *Geological Society of America, Abstracts with Programs* 21, no. 6, 310.

Arthur, M. A. & W. E. Dean. 1991. A holistic geochemical approach to cyclomania. examples from Cretaceous pelagic limestone sequences. In *Cycles and Events in Stratigraphy*, ed. G. Einsele, W. Ricken & A. Seilacher, 126-166. Berlin: Springer-Verlag.

Alt, D. D. & D. W. Hyndman. 1989. *Roadside Geology of Idaho.* Missoula, MT. Mountain Press.

Baadsgaard, H., J. F. Lerbekmo, J. R. Wijbrans, C. C. Swisher III, & M. Fanning. 1993. Multi-method radiometric age for a bentonite near the top of the *Baculites reesidei* Zone of southwestern Saskatchewan (Campanian-Maastrichtian stage boundary?). *Canadian Journal of Earth Sciences* 30:769-775.

Bally, A. W. 1986. Phanerozoic basins of North America. In *The Geology of North America - an Overview.* eds A. W. Bally & A. R. Palmer. The Geology of North America. v. A:397-446. Boulder, Colorado: Geological Society of America.

Barnes, O. R. & E. D. Goldberg. 1976. Methane production and consumption in anoxic marine sediments. *Geology* 4:297-300.

Barnett, P. R. 1961. *Spectrographic analysis for selected minor elements in Pierre Shale.* U.S. Geological Survey Professional Paper 391-B.

Barrera, E. 1994. Global environmental changes preceding the Cretaceous-Tertiary boundary. Early-Late Maastrichtian transition. *Geology* 22:877-880.

Barrera, E., S. M. Savin, E. Thomas, & C. E. Jones, 1997. Evidence for thermohaline-circulation reversals controlled by sea-level change in the latest Cretaceous. *Geology* 25:715-718.

Barron, E. J. & W. M. Washington. 1984. The role of geographic variables in explaining paleoclimates. results from the Cretaceous climate model sensitivity studies. *Journal of Geophysical Research* 89(D1):1267-1279.

Batt, R. J., 1987. *Pelagic biofacies of the Western Interior Greenhorn Sea (Cretaceous): evidence from ammonite and planktonic foraminifera.* University of Colorado (Boulder), Ph.D. dissertation, 778 p.

Berner, R. A. 1968. Calcium carbonate concretions formed by the decomposition of organic matter. *Science* 159:195-197.

Berner, R. A. & J. T. Westrich. 1975. Bioturbation and the early diagenesis of carbon and sulfur. *American Journal of Science* 285:193-206.

Bishop, G. A. 1975. *Geology, stratigraphy, and biostratigraphy of the north end of Cedar Creek anticline, Dawson County, Montana.* Montana Bureau of Mines and Geology, Special Publication no. 61.

Bishop, G. A. 1977. Pierre feces. a scatological study of the Dakoticancer assemblage, Pierre Shale (Upper Cretaceous) of South Dakota. *Journal of Sedimentary Petrology* 47:129-136.

_________. 1987. Positive taphomonic feedback in North American Tethyan Cretaceous decapod-worm associations. In *Shallow Tethys 2*, ed K. G. McKenzie, 319-329. Rotterdam: A. A. Balkema.

Burke, W. H., R. E. Denison, E. A. Hetherington, R. B. Kroepnick, H. F. Nelson, & J. B. Otto, 1982. Variation of $Sr^{87}/Sr^{86}$ throughout Phanerozoic time. *Geology* 10:516-519.

Bryant, B. 1993. The onset of the Laramide Orogeny. *Colorado School of Mines Quarterly* 93:17-19.

Bryant, J. D., D. S. Jones, & P. A. Mueller, 1995. Influence of freshwater flux on $^{87}Sr/^{86}Sr$ chronostratigraphy in marginal marine environments and dating of vertebrate and invertebrate fauna. *Journal of Paleontology* 69:1-6.

Carpenter, S. J. M. Erickson, K. C. Lohmann & M. R. Owen. 1988. Diagenesis of fossiliferous concretions from the Upper Cretaceous Fox Hills Formation, North Dakota. *Journal of Sedimentary Petrology* 58:706-723.

Chapelle, F. H. 1997. *The Hidden Sea: Groundwater, Springs, and Wells*. Tuscon, Arizona: Geoscience Press, Inc., 238 p.

Chaudhuri, S. & N. Clauer. 1986. Fluctuations of isotopic composition of strontium in seawater during the Phanerozoic Eon. *Chemical Geology (Isotope Geochemistry Section)* 59:293-303.

Cobban, W. A. 1958. Two new species of Baculites from the Western Interior Region. *Journal of Paleontology* 32:660--665.

________. 1962. Baculites from the Bearpaw Shale and equivalent rocks of the Western Interior. *Journal of Paleontology* 36:126-135.

________. 1993. Diversity and distribution of Late Cretaceous Ammonites, Western Interior, United States. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, 435-451, Special Paper no. 39. Calgary: Geological Association of Canada.

Cobban, W. A. & J. R. Gill. 1965. *Stratigraphy of the Pierre Shale, Valley City and Pembina Mountain areas, North Dakota*. U.S. Geological Survey Professional

Paper 0392-A.

Coleman, M. L. 1993. Microbial processes: controls on the shape and composition of carbonate concretions. *Marine Geology* 113:127-140.

Cook, H. J., 1922. *Pan-American Geologist* 37:421-424.

Coryell, H. N. and E. S. Salmon. 1934. A molluscan faunal from the Pierre Formation in eastern Montana. *American Museum Noviataes* 746:1-18.

Crandell, D. R. 1950. Revisions of Pierre Shale of central South Dakota. *AAPG Bulletin* 34:2337-2346.

Crandell, D. R. 1958. *Geology of the Pierre area, South Dakota.* U.S. Geological Survey Professional Paper 307.

Curtis, C. D. & M. L. Coleman. 1986. Controls on the precipitation of early diagenetic calcite, dolomite, and siderite concretions in complex depositional sequences. In *Roles of organic matter in sediment diagenesis*, ed Donald L. Gautier, 23-33, Special Publication no. 38. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists.

Dalbiez, F. 1959. Correlations et resolutions. In *Colloque sur le Cretace superieur francais*, Coloque Cretace, 857-867, no. 84-e. Dijon: Congress Societie Savantes Paris et Departmentes.

Daly, D. J. 1991. The stratigraphy and depositional environments of the Fox Hills Formation, Bowman County, North Dakota. *Saskatchewan Geological Society Special Publication*, 6:193-205.

Dean, W. E., M. A. Arthur & L. M. Pratt. 1988. Inorganic and organic geochemical cycles in petroleum source rocks of the Cretaceous Western Interior Seaway. U.S. Geological Survey. *Journal of Research* 11:10-13.

Denison, R. E., R. B. Koepnick, A Fletcher, D. A. Dahl, and M. C. Baker, 1993. Reevaluation of early Oligocene, Eocene, and Paleocene seawater strontium isotope ratios using outcrop samples from the U.S. Gulf Coat. *Paleoceanography* 8:101-126.

DePaolo, D. J. & B. L. Ingram, 1985. High-resolution stratigraphy with strontium isotopes. *Science*, 227:938-941.

DeWitt, E., J. A. Redden, D. Buscher & A. B. Wilson. 1989. *Geologic map of the Black Hills area, South Dakota and Wyoming*. U.S. Geological Survey, Miscellaneous Investigation Series Map I-1910; scale 1:250,000.

Dingle, H. 1983. Strategies of Agonistic behavior in crustacea. In *Studies in Adaptation and Behavior of Higher Crustacea*. ed S. Rebach. & D. W. Duncan. New York: Wiley Interscience.

Drake, C. L. 1986. History of studies of the Atlantic margin of the United States. In *The Atlantic Continental Margin*, ed R. E. Sheridan & J. A. Grow, 57-66, vol 1. Boulder, Colorado: Geological Society of America.

Dunham, J. 1961. *Geology of Uranium in Chadron area, Nebraska, South Dakota*. U.S. Geological Survey, Open File Report.

Dyman, T. S., W. A. Cobban, J. E. Fox, R. H. Hammond, D. J. Nicols, W. J. Perry, Jr., K. W. Porter, D. D. Rice, D. R. Setterholm, G. W. Shurr, R. G. Tysdal, J. C. Halley & E. B. Campen. 1994. Cretaceous rocks from southwestern Montana to southwestern Minnesota, northern Rocky Maintains, and Great Plains region. In *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, ed G. W. Shurr, G. A. Ludvigson, & R. H. Hammond, 5-26, Special Paper no. 287. Boulder, Colorado: Geological Society of America.

Eicher, D. L. & R. Diner. 1989. Origin of the Cretaceous Bridge Creek cycles in the Western Interior, United States. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74:127-146.

Einsele, G. 1991. Submarine mass flow deposits and turbidites. In *Cycles and Events in Stratigraphy*, ed G. Einsele, W. Ricken & A. Seilacher, 313-339. Springer-Verlag, Berlin.

Einsele, G. & W. Ricken. 1991. Limestone-marl alternations - an overview. In *Cycles and Events in Stratigraphy*, ed G. Einsele, W. Ricken & A. Seilacher, 23-47. Springer-Verlag, Berlin.

Elias, M. K. 1933. *Cephalopods of the Pierre Formation of Wallace County, Kansas, and adjacent areas*. University of Kansas Science Bulletin (Lawrence) 21:289-363.

Elder, W. R. 1993. New York Academy of Science. guest lecture abstract.

Emery, D. I A. Robinson, 1982. *Inorganic Geochemistry: Applications to Petroleum Geology*. Oxford: Blackwell Scientific Publ.

Ettensohn, F. R., M. L. Miller, S. B. Dillman, T. D. Elam, K. L. Geller, D. R. Swager, G. Markowitz, R. D. Woock, & L. S. Barron. 1988. Characterization and implications of the Devonian-Mississippian black shale sequence, eastern and central Kentucky, U. S. A. Pycnoclines, transgression, regression, and tectonism. *Canadian Society of Petroleum Geologists Memoir* 14(2):323-345.

Evans, J. & B. F. Shumard, 1854. Descriptions of new fossil species from the Cretaceous Formation of Sage Creek, Nebraska. *Philadelphia Academy of Natural Science Proceedings*, v. 7, p. 163-164.

Evans, James E. & Dennis O. Terry, Jr. 1993. The significance of incising and fluvial sedimentation in the Basal White River Group (Eocene-Oligocene), Badlands of South Dakota, U.S.A. *Sedimentary Geology* 90:137-152.

Feldman, R. M. 1972. *Stratigraphy and Paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota*. North Dakota Geolological Survey Bulletin 61.

Fischer, A. G. 1991. Orbital cyclicity in Mesozoic strata. In *Cycles and Events in Stratigraphy*, ed G. Einsele, W. Ricken & A. Seilacher, 48-62. Springer-Verlag, Berlin.

Fleming, P. B. & S. N. Nelson. 1991. Paleogeographic evolution of the Latest Cretaceous and Paleocene Wind River Basin. *The Mountain Geologist* 28:37-52.

Flores, R. M. & F. G. Ethridge. 1985. Evolution of inter-montane fluvial systems of Tertiary Powder River Basin, Montana and Wyoming. In *Cenozoic Paleogeography of the West-central States*. ed R. Flores, 107-126. SEPM, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium.

Friedman, G. M., J. E. Saunders, & D. C. Kopaska-Merkel. 1992. *Principles of Sedimentary Deposits. Stratigraphy and Sedimentology*. New York: MacMillan, New York.

Gautier, D. L. 1982. Siderite concretions. indicators of early diagenesis in the Gammon Shale (Cretaceous). *Journal of Sedimentary Petrology* 52:859-871.

Geraghty, M. D. & G. E. G. Westerman. 1994. Origin of Jurassic ammonite concretions assemblages at Alfeld, Germany: a biogenic alternative. *Palaont. Z.* 68:473-490.

Gill, J. R. & W. A. Cobban. 1965. *Stratigraphy of the Pierre Shale, Valley City and Pembina Mountain areas, North Dakota*. U.S. Geological Survey Professional Paper 392-A.

________. 1966. *The Red Bird Section of the Upper Cretaceous Pierre Shale in Wyoming*. U. S. Geological Survey Professional Paper 393-A.

________. 1973. *Stratigraphy and Geologic History of the Montana Group and Equivalent Rocks, Montana, Wyoming, North and South Dakota*. U. S. Geological Survey Professional Paper 776.

Gillespie, J. M. & J. E. Fox. 1991. Tectonically influenced sedimentation in the Lance Formation, eastern Wind River Basin, Wyoming. *The Mountain Geologist* 28:53-66.

Gries, J. P. 1942. *Economic Possibilities of the Pierre Shale*. South Dakota Geological Survey Report of Investigations no. 43.

Gries, R. 1983. North-south compression of Rocky Mountain foreland structure. In *Rocky Mountain Foreland Basins and Uplifts*, ed J. D. Lovell, 9-32. Denver, Colorado: Rocky Mountain Association of Geologists.

Gross, M. G. 1972. *Oceanography, a view of Earth*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Hall, J. & F. B. Meek. 1854. *Memoir of the Academy of Arts and Sciences* (Boston) (n. s.) 5:396.

Hallam, A. 1977. Anoxic events in the Cretaceous ocean. *Nature* 268:15-16.

Hancock, J. 1993. Transatlantic correlations in the Campanian-Maastrichtian stages by eustatic changes of sea level. In *High Resolution Stratigraphy*, ed E. A. Hailwood & R. B. Kidd, 241-256. Geological Society of London Special Publication 70.

Haq, B. U., J. Hardenbol & P. Vail. 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235:1156-1165.

Harris, A. G. & W. C. Sweet. 1989. Mechanical and chemical techniques for separating microfossils from rock, sediment and residue matrix. In *Paleotechniques*. eds. R. M. Feldman, R. E. Chapman & J. T. Hannibal, 70-86. The Paleontological Society Special Publication No. 40.

Hasiotis, S. T., T. M. Brown, & C. Abston. 1994. *Photoglossary of Marine and Continental Ichnofossils*. U.S. Geological Survey Digital Data Serives DDS-23, CD-ROM.

Hudson, J. D. & I. Friedman. 1976. Carbon and oxygen isotopes in concretions: Relationship to pore-water changes during diagenesis. In *Proceedings of the International Symposium on Water/Rock Interaction*, eds. J. Cadek & T. Paces, 331-339. Geological Survey Prague.

Hyatt, A., 1903. Pseudoceratites of the Cretaceous. *U.S. Geological Survey Monograph*, v. XLIV.

Imgram B. L. & D. Sloan, 1992. Strontium isotopic composition of estuarine sediments as paleosalinity-paleoclimate indicator. *Science* 255:68-72.

Jerzykiewicz, T. & A. R. Sweet. 1988. Sedimentological and palynological evidence of regional climatic changes in the Campanian to Paleocene sediments of the Rocky Mountain Foothills, Canada. *Sedimentary Geology* 59:29-76.

Jewell, P. W. 1993. Water-column stability, residence times, and anoxia in the Cretaceous seaway. *Geology* 21:579-582.

Kauffman, E. G. 1977. Geological and biological overview. Western Interior Cretaceous basin. *The Mountain Geologist* 14:75-99.

________. 1977. Illustrated guide to biostratigraphically important Cretaceous macro-fossils, Western Interior basin. *The Mountain Geologist* 14:225-274.

________. 1984. Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America. *Geological Association of Canada Special Paper* 27:273-3006.

________. 1990. High-resolution analysis of the Kiowa-Skull Creek, Greenhorn, and Niobrara cyclothems, Western Denver Basin, Central Colorado. *AAPG Bulletin* 78:1330.

________. 1990. High-resolution Cretaceous stratigraphy and sealevel history of the Canon City embayment, central Colorado. *AAPG Bulletin* 78:1330.

Kauffman, E. G., P. J. Harries, J. I. Kirkland & B. B. Sageman. 1990. Sequence stratigraphy and facies analysis of the Greenhorn Eustatic Cycle (late Albian-Middle Turonian), Western Interior Basin, Arizona to Minnesota. *AAPG Bulletin* 78:1330-1331.

Kauffman, E. G. & B. Howe. 1991. The origin and ecology of Tepee Buttes; extraordinary chemosymbiotic and normal marine biotas from methane springs on the Cretaceous seafloor of Colorado. *Geological Society of America, Abstracts with Programs* 23:167-168.

Kauffman, E. G. & B. B. Sageman. 1990. Biological sensing of benthic environments in dark shales and related oxygen-restricted facies. In *Cretaceous Resources, Events and Rhythms. Background and Plans for Research*, ed R. N. Ginsburg & B. Beaudoin, 121-138. Netherlands: Kluwer Academic Publishers.

Keefer, W. R. 1965. *Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene rocks in the Wind River Basin, Wyoming*. U. S. Geological Survey Professional Paper 495-A.

________. 1970. *Structural geology of the Wind River Basin, Wyoming*. U.S. Geological Survey Professional Paper 495-D.

Kennedy, W. J. & W. A. Cobban. 1993. Ammonites of the Saratoga Chalk (Upper Cretaceous), Arkansas, U.S.A. *Journal of Paleontology* 67:406-434.

Kennedy, W. J., R. O. Johnson & W. A. Cobban. 1995. Upper Cretaceous ammonite faunas of New Jersey. *Geological Association of New Jersey, Proceedings* 12:24-55.

Kennedy, W. J., W. A. Cobban &. J. R. Scott. 1992. Ammonite correlation of the uppermost Campanian of Western Europe, the U.S. Gulf Coat, Atlantic Seaboard and Western Interior, and the numerical age of the base of the Maastrichtian. *Geological Magazine* 129: 497-500.

Klitgord, K. D., D. R. Hutchinson, & H. Schouten. 1986. U.S. Atlantic continental margin; structural and tectonic framework. 19-56. In *The Atlantic Continental Margin*, ed R. E. Sheridan & J. A. Grow, 19-66, vol. 1. Boulder, Colorado: Geological Society of America.

King, D. T., Jr. & M. C. Skotnicki. 1994. Upper Cretaceous stratigraphy and sea-level history, Gulf Coastal Plain of central and eastern Alabama. In *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, ed G. W. Shurr, G. A. Ludvigson, & R. H. Hammond, 27-42, Special Paper no. 287. Boulder, Colorado: Geological Society of America.

Kerr, R. A. 1996. New way to read the record suggests abrupt extinction. *Science* 274:1303-1304.

Koepnick, R. B., R. E. Denison, & D. A. Dahl, 1988. The Cenozoic seawater $Sr^{87}/Sr^{86}$ curve; data review and implications for correlation of marine strata. *Paleoceanography* 3:743-756.

Kyser, T. K., W. G. E. Caldwell, S. G. Whitaker & A. J. Cadrin. 1993. Paleoenvironment and geochemistry of the northern portion of the Western Interior Seaway during Late Cretaceous time. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, 335-377, Special Paper no. 39. Calgary: Geological Association of Canada.

Laferriere, A. P. & D. E. Hattin. 1989. Use of rhythmic bedding patters for locating structural features, Niobrara Formation, United States Western Interior. *The American Association of Petroleum Geologists Bulletin* 73:630-640.

Landman, N. H.& K. M. Waage. 1993. Scaphitid ammonites of the Upper Cretaceous (Maastrichtian) Fox Hills Formation in South Dakota and

Wyoming. *Bulletin of the American Museum of Natural History* vol. 215.

Larson, N. L., S. D. Jorgensen, R. A. Farrar, P. L. Larson. 1997. *Ammonites and Other Cephalopods of the Pierre Shale; An Identification Guide*. Tuscon, Arizona: Geoscience Press, Inc.

Lewis, B. D. & W. R. Hotchkiss. 1961. *Thickness, percent sand, and configuration of shallow hydrologic units in the Powder River Basin, Montana and Wyoming*. U.S. Geological Survey, Miscellaneous Investigation Map I-1317.

Lisenbee, A. L. 1988. Tectonic history of the Black Hills uplift. *Wyoming Geological Association Guidebook* 39:45-52.

Litwin, R. J. & A. Traverse. 1989. Basic guidelines for palynomorph extraction and preparation from sedimentary rocks. In *Paleotechniques*, ed R. M. Feldmann, R., E. Chapman & J. T. Hannibal, 87-98. Paleontological Society Special Publication, vol. 4.

Love, J. D., A. C. Christiansen & L. W. McGrew. 1987. *Geologic map of the Newcastle 1 X 2 degree quadrangle, northeastern Wyoming and Western South Dakota*. Geological Survey of Wyoming, Map Series 25-I; scale 1:250,000.

Love, J. D., A. C. Christiansen, L. W. McGrew & J. K. King. 1990. *Geologic map of the Gillette 1 X 2 degree quadrangle, northeastern Wyoming and Western South Dakota*. Geological Survey of Wyoming Map Series 25-G; scale 1:250,000.

Love, J. D., A. C. Christiansen & A. J. Ver Ploeg. 1993. *Stratigraphic chart showing Phanerozoic nomenclature for the state of Wyoming*. Geological Survey of Wyoming, Map Series 41; one sheet.

Ludvigson, G. A., B. J. Witzke, L. A. Gonzalez, R. H. Hammond, & O. W. Plocher. 1994. Sedimentology and carbonate geochemistry of concretions from the Greenhorn Marine Cycle (Cenomaian-Turonian), eastern margin of the Western Interior Seaway. In *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, ed G. W. Shurr, G. A. Ludvigson, & R. H. Hammond, 45-173, Special Paper no. 287. Boulder, Colorado: Geological Society of America.

Lunar & Planetary Institute. 1994. *New developments regarding the K/T event and other catastrophes in Earth history*. LPI Contributions no. 825.

Mapel, W. J. & C. L. Pillmore. 1964, *Geology of the Upton Quadrangle, Crook and Weston counties, Wyoming*. U. S. Geological Survey Bulletin 1181-J.

Maples, C. G. & R. R. West, 1992. *Trace Fossils*. S. J. Culver, ed., The Paleontological Society, Short Courses in Paleontology, no. 5, 238 p.

McArthur, J. M., M. F. Thirlwall, A. S. Gale, W. J. Kennedy, J. A. Burnett, D. Mattey, & A. R. Lord. 1993. Strontium isotope stratigraphy for the Late Cretaceous. a new curve, based on the English Chalk. In *High Resolution Stratigraphy*, ed E. A. Hailwood & R. B. Kidd, 195-209. Geological Society of London Special Publication 70.

McArthur, J. M., W. J. Kennedy, M. Chen, M. F. Thirlwall, & A. S. Gale. 1994. Strontium isotope stratigraphy for Late Cretaceous time. Direct numerical calibration of the Sr isotope curve based on the US Western Interior. *Palaeogeography, Palaeoclimatology, Palaeoecology* 108:95-119.

McGookey, D. P., J. D. Haun, L. A. Hale, H. G. Goodell, D. G. McCubbin, R. J. Weimer, & G. R. Wulf. 1972. Cretaceous System. In *Geological Atlas of the Rocky Mountain Region*, 190-228. Denver, Colorado: Rocky Mountain Association of Geologists.

Meek, F. B. & F. V. Hayden. 1856. Descriptions of new species of gastropods and cephalopods from the Cretaceous formations of Nebraska Territory. *Proceedings of the Academy of Science of Philadelphia* 8:63-126.

________. 1861. Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils collected in Nebraska by the exploring expedition under the command of Captain W. F. Reynolds, U.S. Topographical Engineer, with some remarks on the rocks from which they were obtained. *Philadelphia Academy of Natural Sciences Proceedings* 415-477.

________. 1862. *Philadelphia Academy of Natural Sciences Proceedings* 13:419-424.

Mello, J. F. 1969. *Foraminifera and Stratigraphy of the Upper Part of the Pierre*

*Shale and Lower Part of the Fox Hills Sandstone (Cretaceous), North-Central South Dakota*. U. S. Geological Survey Professional Paper 611.

________. 1971. *Foraminiera from the Pierre Shale (Upper Cretaceous) at Red Bird, Wyoming*. U. S. Geological Survey Professional Paper 393-C.

Merin, I. S. & R. C. Lindholm. 1986. Evidence that the crystalline cores of uplifts adjacent to the Powder River Basin were breached during Paleocene time. *The Mountain Geologist* 23:128-131.

Merewether, E. A. 1990. Cretaceous formations in the southwestern part of the Powder River basin, northeastern Wyoming. *AAPG Bulletin* 74:1337.

Mieras, B. L., B. B. Sageman & E. G. Kauffman. 1993. Trace fossil distribution patterns in Cretaceous facies of the Western Interior Basin, North America. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, 585-619, Special Paper no. 39. Calgary: Geological Association of Canada.

Molenaar, C. M. & D. D. Rice. 1988. Cretaceous rocks of the Western Interior Basin. In *Sedimentary Cover - North American Craton: U.S.* ed L. L. Sloss, The Geology of North America. v. D2:77-82. Boulder, Colorado: Geological Society of America.

Morgon, R. E. & B. C. Petsch. 1945. *A Geological Survey in Dewey and Corson Counties, South Dakota*. South Dakota Geological Survey, Report of Investigations no. 49.

Morton, R. A. 1988. Nearshore responses to great storms. 7-20, Special Paper 229. Boulder, Colorado: Geological Society of America.

Nichols, T. C., Jr. D. S. Collins, M. Jones-Cecil & H. S. Swolfs. 1994. Faults and structure in the Pierre Shale, central South Dakota. In *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, ed G. W. Shurr, G. A. Ludvigson, & R. H. Hammond, 221-235, Special Paper no. 287. Boulder, Colorado: Geological Society of America.

Obradovich, J. D. 1993. A Cretaceous time scale. In *Cretaceous Evolution of the Western Interior Basin of North America*, ed. W. G. E. Caldwell & E. G.

Kauffman, 379-392, Special Paper no. 39. Calgary: Geological Association of Canada.

Obradovich, J. D. & W. A. Cobban. 1975. A Cretaceous time scale. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, 31-54. Special Paper no. 13. Calgary: Geological Association of Canada.

Olsson, R. K., T. G. Gibson, H. Hansen, & J. P. Owens. 1986. Geology of the northern Atlantic coastal plain. Long Island to Virginia. In *The Atlantic Continental Margin*, ed R. E. Sheridan & J. A. Grow, 87-105, vol. 1. Boulder, Colorado: Geological Society of America.

Owen, D. D. 1852. *Report of a Geological Survey of Wisconsin, Iowa, and Minnesota and Incidentally of a Portion of Nebraska Territory*. Philadelphia, Pa: Lippincott, Grambo & Co.

Palmer, M. R. & J. M. Edmond. 1989. The strontium isotope budget of the modern ocean. *Earth and Planetary Science Letters* 92:11-26.

Palmer, M. R. & J. M. Edmond. 1992. Controls over the strontium isotope composition of river water. *Geochimica et Cosmochimica Acta* 56:2099-2111.

Parrish, J. T. & D. L. Gautier. 1988. Upwelling in Cretaceous Western Interior Seaway; Sharon Springs Member, Pierre Shale. *AAPG Bulletin* 72:234-235.

Perman, R. C. 1988. *Stratigraphy and sedimentology of the Lewis Shale and the Fox Hills Formation in south-central Wyoming*. University of California, Berkeley, Ph.D. dissertation.

Pessagno, E. A., Jr. 1969. *Upper Cretaceous stratigraphy of the western Gulf Coast area of Mexico, Texas, and Arkansas*. Geological Society of America Memoir 111.

Pettijohn, W. A. 1965. *Eocene soil profile in the northern Great Plains*. Proceedings of the South Dakota Academy of Science XLIV:80-87.

________, 1966. *Eocene paleosol in the northern Great Plains*. U. S. Geological Survey Professional Paper 550C, p. 61-65.

________. 1975. *Sedimentary rocks, 3rd Ed.* New York: Harper & Row.

Poag, C. W. & P. C. Valentine. 1986. Mesozoic and Cenozoic stratigraphy of the United States Atlantic continental shelf and slope. In *The Atlantic Continental Margin*, ed R. E. Sheridan & J. A. Grow, 67-85, vol. 1. Boulder, Colorado: Geological Society of America.

Porter, K. W., E. B. Campen, W. A. Cobban, & W. B. Hansen. 1990. Stratigraphic sequences and unconformities in Cretaceous rocks of east-central Montana. *AAPG Bulletin* 8:1341.

Rader, L. F. & F. S. Grimaldi. 1961. *Chemical analyses for selected minor elements in Pierre Shale*. U.S. Geological Survey Professional Paper 391-A.

Raiswell, R. & N. J. M. White. 1978. Spatial aspects of concretionary growth in the Upper Lias of northeast England. *Sedimentary Geology* 20:291-300.

Raiswell, R. 1988. Evidence for surface reaction-controlled growth of carbonate concretions in shales. *Sedimentology* 35:571-575.

Raymond, W. H. & U. R. King. 1976. *Geologic map of the Badlands National Park and vicinity, west-central South Dakota.* U.S. Geological Survey, Miscellaneous Investigations Series Map I-934; scale 1:62,000.

Rebach, S. & D. W. Duncan. 1983. *Studies in adaptation and behavior of Higher Crustacea.* New York: Wiley Interscience.

Reiskind, J. 1975. Marine concretionary faunas of the uppermost Bearpaw Shale (Maestrichtian [sic]) in eastern Montana and southwestern Saskatchewan. In *Cretaceous System in the Western Interior of North America*, ed W. G. E. Caldwell, ed., 235-252, Special Paper no. 13. Calgary: Geological Association of Canada.

Retallack, G. J. 1983. Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota. *Field Trip Guidebook*, 24-28, Special Paper 193. Boulder, Colorado: Geological Society of America.

________. 1985. An excursion guide to fossil soils of the mid-Tertiary sequence in Badlands National Park, South Dakota. *South Dakota School of Mines &*

*Technology, Dakoterra* 2:277-302.

________. 1997. Cover photo description, *Geotimes*, Feb. 1997, p. 1.

Rhoads, D. C., I. G. Speden, & K. M. Waage. 1972. Trophic group analysis of Upper Cretaceous bivalve assemblages from South Dakota. *The American Association of Petroleum Geologists* 56:1100-1113.

Richen, W. & W. Eder. 1991. Diagenetic modification of calcareous beds - an overview. In *Cycles and Events in Stratigraphy*, ed G. Einsele, W. Richen & A. Seilacher, 430-449. Berlin: Springer-Verlag.

Robinson, C. S., W. J. Mapel & W. A. Cobban. 1959. Pierre Shale along western and northern flanks of Black Hills, Wyoming and Montana. *Bulletin of the American Association of Petroleum Geologists* 43:101-123.

Roehler, H. W. 1990. *Stratigraphy of the Mesaverde Group in the Central and Eastern Greater Green River Basin, Wyoming, Colorado, and Utah*. U. S. Geological Survey, Professional Paper 1508.

________. 1993. *Stratigraphy of the Upper Cretaceous Fox Hills Sandstone and adjacent parts of the Lewis Shale and Lance Formation, east flank of the Rock Springs Uplift, southwest Wyoming*. U. S. Geological Survey, Professional Paper 1532.

Roth, P. H. 1989. Ocean circulation and calcareous nannoplankton evolution during the Jurassic and Cretaceous. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74:111-126.

Sageman, B. B. 1989. The benthic boundary biofacies model. Hartland Shale Member, Greenhorn Formation (Cenomanian), Western Interior, North America. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74:87-110.

Sageman, B. B., P. B. Wignall & E. G. Kauffman. 1991. Biofacies models for oxygen-deficient facies in epicontinental seas. tool for paleoenvironmental analysis. In *Cycles and Events in Stratigraphy*, ed G. Einsele, W. Richen & A. Seilacher, 542-564. Berlin: Springer-Verlag.

Savrda, C. E. & D. J. Bottjer. 1989. Trace-fossil model for reconstruction oxygenation histories of ancient marine bottom waters; application to Upper Cretaceous Niobrara Formation, Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74:49-74.

Say, T., 1820. Observations on some species of zoophytes, shells, etc., principally fossil. *American Journal of Science, 1st Ser.* 2:34-45.

Schultz, L. G. 1964. *Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale.* U.S. Geological Survey Professional Paper 391-C.

________. 1965. *Mineralogy and stratigraphy of the lower part of the Pierre Shale, South Dakota and Nebraska.* U.S. Geological Survey Professional Paper 392-B.

________. 1978. *Mixed-layer clay in the Pierre Shale and equivalent rocks, northern Great Plains region. Geochemistry of the Pierre Shale and equivalent rocks of Late Cretaceous age.* U. S. Geological Survey, Professional Paper 1064-A.

Scott, G. R. & W. A. Cobban. 1986. *Geologic and biostratigraphic map of the Pierre Shale in the Colorado Springs-Pueblo area, Colorado.* U. S. Geological Survey, Miscellaneous Investigation map I-1627.

Scott, R. W. 1990. *Models and stratigraphy of mid-Cretaceous reef communities, Gulf of Mexico.* Tulsa, Oklahoma: Society of Economic Paleontogists and Mineralogists. No. 2, Concepts in Sedimentology and Paleontology.

Searight, W. V. 1937. *Lithologic stratigraphy of the Pierre Formation of the Missouri Valley in South Dakota.* South Dakota Geological Survey, Report of Investigations no. 27.

Sheridan, R. E. & J. A. Grow. 1986. U.S. continental margin; a typical Atlantic-type or passive continental margin. In *The Atlantic Continental Margin*, ed R. E. Sheridan & J. A. Grow, 1-8, vol. 1. Boulder, Colorado: Geological Society of America.

Shurr, G. S., R. H. Hammond, & R. F. Bretz. 1994. Cretaceous paleotectonism and post-depositional tectonism in south-central South Dakota. An example of epeirogenic tectonism in continental lithosphere. In *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, ed G. W. Shurr, G. A. Ludvigson, & R. H. Hammond, 237-255, Special Paper no. 287. Boulder, Colorado: Geological Society of America.

Shapurji, S. S. 1978. Depositional environments and correlation of the Mesaverde Formation, Wind River Basin, Wyoming. In *Resources of the Wind River Basin*, Wyoming Geological Association, 30th Annual Field Conference Guidebook, 167-180.

Sohl, N. F. 1967. *Upper Cretaceous gastropods from the Pierre Shale at Red Bird, Wyoming*. U.S. Geological Survey Professional Paper 393-B.

Spicer, R. A. & R. M. Corfield. 1992. A review of terrestrial and marine climates in the Cretaceous with implications for modelling "Greenhouse Earth." *Geological Magazine* 129:169-190.

Stanley, S. M. 1995. New horizons for paleontology, with two examples. The rise and fall of the Cretaceous Supertethys and the cause of the modern Ice Age. *Journal of Paleontology* 69:999-1007.

Steven, T. A., H. W. Smedes, H. J. Prostka, P. W. Lipman, & R. L. Christiansen. 1972. Upper Cretaceous and Cenozoic igneous rocks. In *Geological Atlas of the Rocky Mountain Region*, 229-232. Denver, Colorado: Rocky Mountain Association of Geologists.

Stoffer, P., P. Messina & J. A. Chamberlain, Jr. 1997. Buried slumps in the upper Pierre Shale/Fox Hills transition interval in Badlands National Park. Geological Society of America, Annual Meeting abstract.

________. 1996. Fossils from beaches in Gateway National Recreation Area: implications for the geologic history of the New York Bight. Geological Society of America, Annual Meeting abstract.

Stoffer, P., P. Messina & J. A. Chamberlain, Jr., 1997. Buried slumps in the Pierre Shale and Fox Hills Formation (Maastrichtian - Late Cretaceous) in Badlands National Park area. GSA Annual Meeting Abstract.

P. Stoffer & J. A. Chamberlain, Jr. 1996a. Unconformities in the upper Pierre

Shale/Fox Hills Interval (Campanian and Maastrichtian - Late Cretaceous) in Badlands National Park area: Implications for Tectonism and Eustacy in the Western Interior Seaway. Geological Society of America, Annual Meeting abstract.

________. 1996b. The upper Pierre Shale/lower Fox Hills interval (Late Cretaceous; Latest Campanian/Early Maastrichtian) in Badlands National Park Area compared with the type-areas of central South Dakota and Eastern Wyoming. Geological Society of America, Rocky Mountain Section Meeting abstract.

________. 1995a. Fossiliferous concretion-bearing horizons in the Upper Unnamed Member of the Pierre Shale (Maastrichtian, late Cretaceous) in Wyoming and South Dakota. implications for paeleocology and sequence stratigraphy. Geological Society of America, Rocky Mountain Section Meeting abstract.

________. 1995b. Significance of trace fossils to the formation of concretions. a comparison of late Cretaceous marine formations of New Jersey and the Western Interior of North America. Geological Society of America, Northeastern Section, Abstracts with Programs 27.

Sugarman, P. J., K. G. Miller, D. Bukry, & M. D. Feigneson. 1991. Uppermost Campanian-Maestrichtian strontium isotopic biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain. *GSA Bulletin* 107:19-37.

Terry, D. O. & J. E. Evans. 1994. Pedogenesis and paleoclimatic implications of the Chamberlain Pass Formation, Basal White River Group, Badlands of South Dakota. *Palaeogeography, Palaeoclimatology, Palaeoecology* 110:197-215.

Tilling, R. I. & D. Gottfried. 1969. ***Distribution of Thorium, Uranium, and Potassium in igneous rocks of the Boulder Batholith region, Montana, and its bearing on radiogenic heat production and heat flow.*** U. S. Geological Survey Professional Paper 614-E.

Toepelman, W. C. 1922. ***South Dakota Geological & Natural History Survey Bulletin*** 11:64.

Tourtelot, H. A. 1962. ***Preliminary investigation of the geologic setting and chemical composition of the Pierre Shale, Great Plains region.*** U. S. Geological Survey

Professional Paper 390.

Tourtelot, H. A. & Rye, R. O. 1969. Distribution of oxygen and carbon isotopes in fossils of Late Cretaceous age, Western Interior region of North America. *Geological Society of America Bulletin* 80:1903-1922.

Tucker, M. E. 1995. *Sedimentary Rocks in the Field, 2nd Ed.* New York: John Wiley & Sons.

U.S. Department of Interior, Forest Service. 1993. *Buffalo Gap National Grasslands* [western South Dakota, Badlands and Black Hills region map]. Scale 1:126,720.

________. 1993. *Thunder Basin National Grasslands* [eastern Wyoming on the western flank of the Black Hills and Powder River Basin region map]. Scale 1:126,720.

Vail, P. 1987. Seismic stratigraphic interpretation procedure. In, Bally, A. W., ed., *Atlas of seismic Stratigraphy.* Tulsa, OK. American Association of Petroleum Geologists, Studies in Geology 27:1-125.

Waage, K. M. 1968. The type Fox Hills Formation, Cretaceous (Maastrichtian), South Dakota, part 1. Stratigraphy and Paleoenvironments. *Peabody Museum Natural History Bulletin* no. 27.

________. 1964. Origin of repeated fossiliferous concretion layers in the Fox Hills Formation. *Kansas Geological Survey Bulletin,* no. 1969:541-563.

Wanless, H. R. 1923. untitled discussion. *American Philosophical Society Proceeding,* 62:194.

Ward, F. 1926. untitled discussion. *American Journal of Science, 5th Series* 2:350-352.

________. 1922. Geology of a portion of the Badlands. *South Dakota Geological and Natural History Survey Bulletin* 11:18-20.

Ward, P. D. 1990. The K/T extinctions in the marine realm. A. 1990 perspective. *Geological Society of America, Special Paper* 247:425-432.

Weimer, R. J. & C. B. Land. 1975. Maestrichtian deltaic and interdeltaic sedimentation in the Rocky Mountain region of the United States. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, 633-666. Special Paper no. 13. Calgary: Geological Association of Canada.

Weissert, H., J. McKenzie & P. Hochuli. 1979. Cyclic anoxic events in Early Cretaceous Tethys Ocean. *Geology* 7:147-151.

Williams, G. D. & R. Steick. 1975. Speculations on the Cretaceous palaeogeography of North America. In *Evolution of the Western Interior Basin*, ed W. G. E. Caldwell & E. G. Kauffman, Special Paper no. 13:1-19. Calgary: Geological Association of Canada.

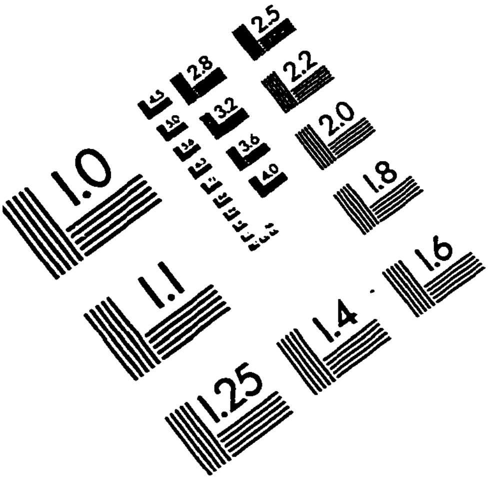
Wilson, M. A. & T. J. Palmer. 1989. Preparation of acetate peels. In *Paleotechniques*, ed R. M. Feldmann, R., E. Chapman & J. T. Hannibal. Paleontological Society Special Pubublication 4:142-145.

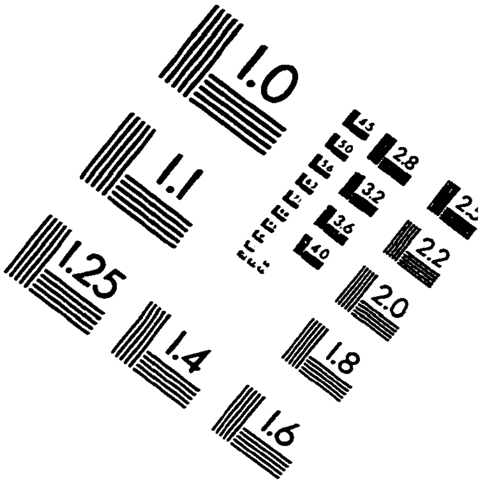
Winn, R. D., Jr., M. G. Bishop & P. S. Gardner. 1987. Shallow-water and sub-storm-base deposition of the Lewis Shale in Cretaceous Western Interior Seaway, south-central Wyoming. *American Association of Petroleum Geologists* 71:859-881.

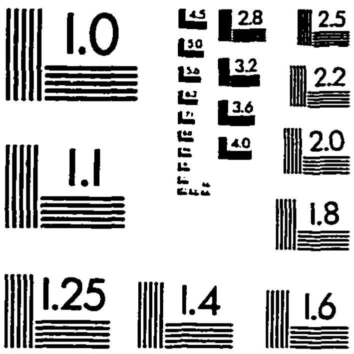
Wright, E. K. 1987. Stratification and paleocirculation of the Late Cretaceous Western Interior Seaway of North America. *Geological Society of America Bulletin* 99:480-490.

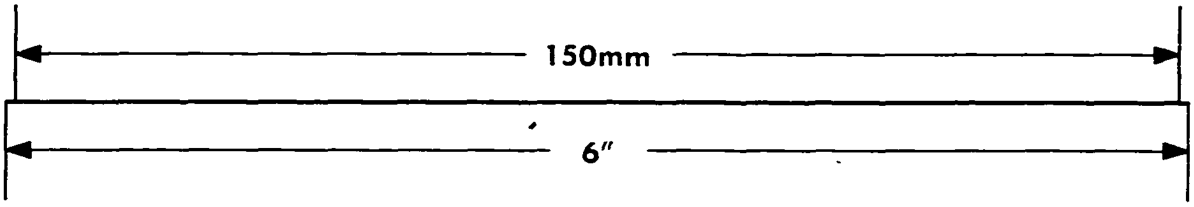
Wyoming Geological Association. 1978. Wyoming Stratigraphic Nomenclature Chart [revised in 1969]. *In* Resources of the Wind River Basin. Wyoming Geological Association Guidebook, 30th Annual Field Conference, no. 12.

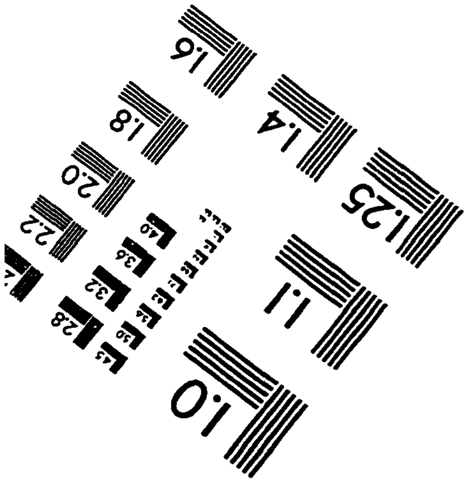
# IMAGE EVALUATION
# TEST TARGET (QA-3)

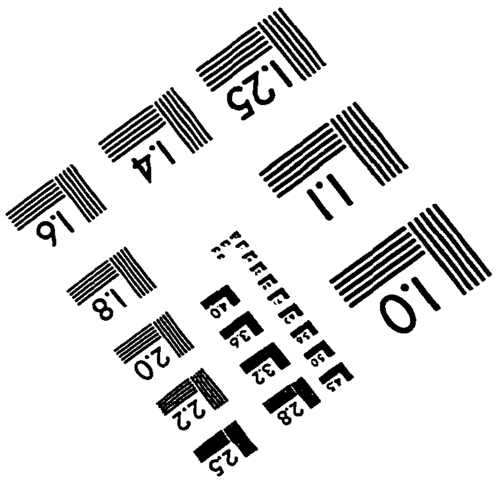












APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989