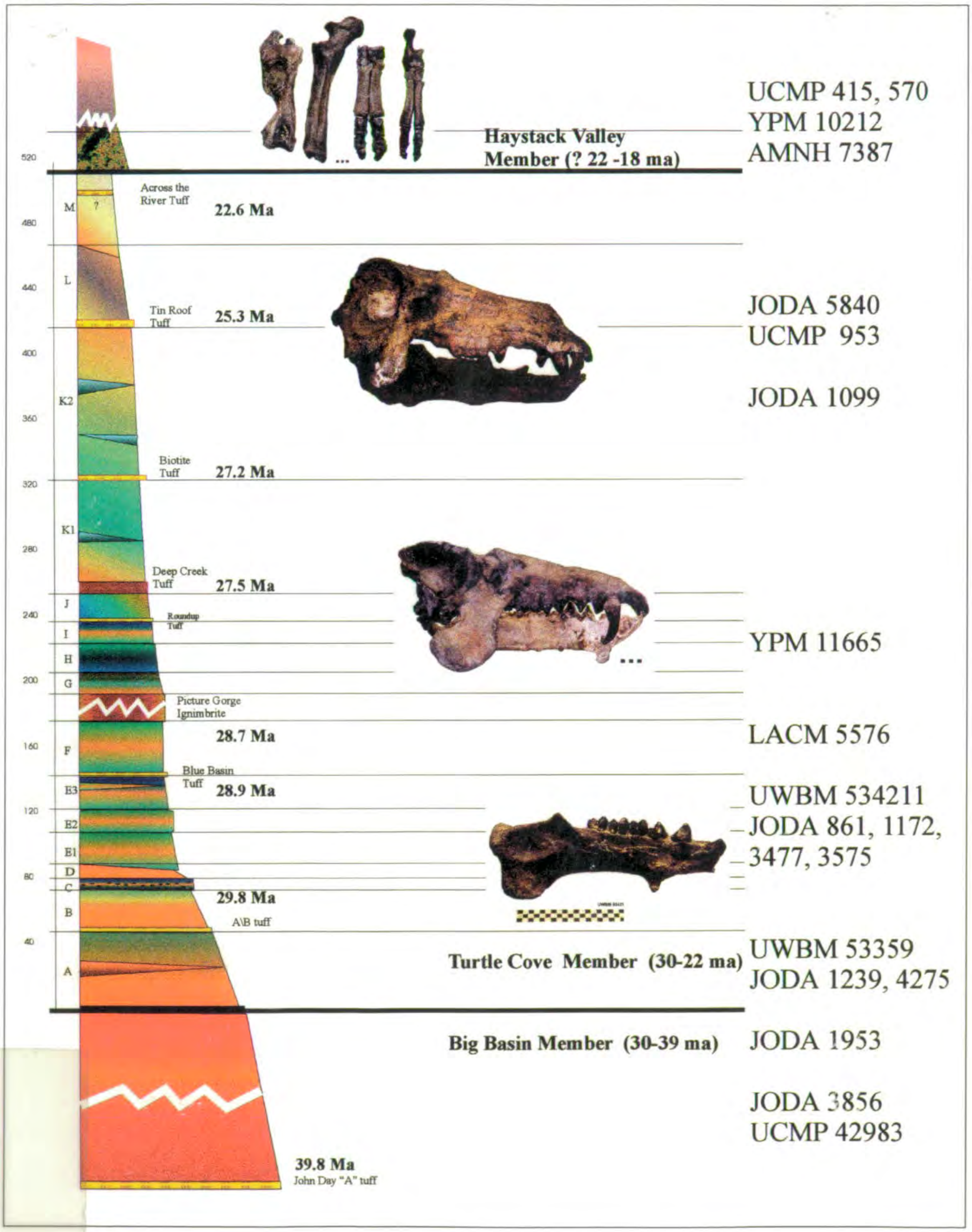
PARTNERS PRESERVING OUR PAST, PLANNING OUR FUTURE

Proceedings for the Fifth Conference on Fossil Resources

Editors:
James E. Martin, John W. Hogenson, and Rachel C. Benton



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National Park Service
USDA - Forest Service
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South Dakota School of Mines and Technology
North Dakota Geological Survey

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Cover Caption: Section of John Day Basin strata with the stratigraphic location of certain entelodont specimens, Foss and Fremd this volume, page 63.

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FOREWARD

The Fifth Conference on Fossil Resources - Partners Preserving Our Past, Planning Our Future is hosted by the National Park Service, the USDA - Forest Service, the Bureau of Land Management, the South Dakota School of Mines and Technology and the North Dakota Geological Survey. The conference stems from a tradition, which began in 1986 when the staff at Dinosaur National Monument hosted the first paleontological resources conference. Included among the conference objectives was a goal to educate National Park Service managers on the importance of protecting fossil resources on National Park Service lands. The fossil conferences have now expanded to include other land management and tribal agencies.

The conference themes for 1998 include: Paleontological Research and Resource Management, Fossil Curation, Preparation, and Conservation, Partnerships, Technology and Paleontology, Education and Outreach, and Paleontology and the Public Trust. The papers contained within this volume directly support many of the themes presented at the meetings and span a broad scope of topics. Many of these articles are the products of the increased promotion of paleontological resource protection and research on public lands over the past ten years.

Developing and organizing the Fifth Conference was a cooperative effort. We would like to thank the staffs of Agate Fossil Beds National Monument, Badlands National Park, Nebraska National Forest, Custer National Forest, the Bureau of Land Management - Wyoming Office, the North Dakota Geological Survey, the South Dakota School of Mines and Technology and Theodore Roosevelt National Park for their time and dedication to this project. Funding for the conference proceedings was obtained from grants from the following cooperating associations: the Badlands Natural History Association, the Conference of National Park Cooperating Associations, the Dinosaur Nature Association, the Rocky Mountain Nature Association and the Petrified Forest Museum Association. We would also like to thank the many professionals who carefully reviewed the papers contained within this volume. The editors wish to especially thank Rachel Schofield and Julie Smoragiewicz from the South Dakota School of Mines and Technology Office of University and Public Relations for their role in editing, formatting, and producing the volume.

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RESEARCH

ORDOVICIAN GRAPTOLITE BIOSTRATIGRAPHY IN THE VICINITY OF DELAWARE WATER GAP NATIONAL RECREATION AREA, NEW JERSEY AND PENNSYLVANIA

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ABSTRACT--Two decades of investigations in the Ordovician rocks of New Jersey and adjacent states have yielded considerable information about the graptolite facies. Although centered in the Delaware Water Gap National Recreation Area, state and private lands were also included within the investigations, which were coordinated by the New Jersey State Museum (designated repository of the collections).

The main body of the Martinsburg Formation correlates from the *Climacograptus bicornis* Zone up into the *Climacograptus spiniferus* Zone. Recent investigations have dealt with correlations of the outliers and allochthons southeast of the main body, notably the Jutland Klippe of Hunterdon County, New Jersey. Restudy of key exposures of the Jutland sequence, supplemented by new faunal collections, confirms previous correlations ranging from the *Adelograptus-Clonograptus* Zone up into the *Climacograptus bicornis* Zone, with no demonstrable overlap with the zonation of the Martinsburg Formation. The rocks are in original sequence, not overturned as some previous publications have suggested. The sequence is lithologically distinct and is recognized as a mappable unit.

INTRODUCTION

Throughout this century the Ordovician rocks near Jutland, Hunterdon County, New Jersey, have presented challenges to structural and paleontological investigations. Weller (1903) noted the presence of well preserved graptolites in fair abundance, in contrast with other rocks of the Ordovician System in New Jersey. Noting the unusually complicated structure, Weller's report foreshadowed other efforts to interpret the area, which mostly lies within Union Township. Various workers sought precise dates, structural interpretations, and a better understanding of the Taconic Orogeny, (Dodge, 1952; Markewicz, 1964; Kasabach, 1966; Perissoratis et al., 1979; Parris and Cruikshank, 1986; Lyttle and Epstein, 1987). Although the outcrop area is small, the Jutland sequence (also called the Jutland Klippe) has great potential for interpretation of Taconic area movements. This review of the biostratigraphic evidence of the graptolite facies is based both on new discoveries and refinement of information previously published. New faunal information from key exposures, some of them previously inaccessible, can now be presented. Some of our results were published in preliminary form (Parris et al., 1995, and in press). The completed information presented herein has confirmed and expanded our preliminary conclusions.

The ultimate objective of our studies is a comprehensive biostratigraphy that relates the allochthons and outliers to the Martinsburg Formation at Delaware Water Gap National Recreation Area (Fig. 1) where previous studies have established a range from the *Climacograptus bicornis* Zone to the *Climacograptus spiniferus* Zone (Parris and Cruikshank, 1992). One outlier has thus far been confidently correlated (Parris et al., 1993). The Port Murray Outlier correlates with the Bushkill Member of the Martinsburg Formation and the *Corynoides americanus* Zone. This report will deal with the Jutland Klippe, where new information from state and private tracts can now be placed on record.

MATERIALS AND METHODS

Only a few specimens from previous studies have been located in repositories. We have restudied all such materials available to us and have accepted the competent identifications of our predecessors for the most part. Editing of previously published faunal lists (including our own) has been done for the sake of consistency of presentation.

We also have prospected the Jutland sequence in search of more faunal material, including inspection of sites previously reported. The one major new site, herein described, was inspected in detail for the sake of a more detailed lithologic description of its fossiliferous sequence. Building upon the work of our predecessors, we have accordingly revised the map of the Jutland sequence outcrop (Fig. 2.) and have compiled a complete list of faunal specimens. Graptolite zones are those of Berry (1960, 1968) with modifications as presented by Finney (1982, 1986). A correlation chart based on that published by Ross et al. (1982) illustrates this usage (Fig. 3).

RESULTS

Paleontologic Data

The Clinton Block and Supply Site in Union Township (Fig. 2) is the major source of new information on the Jutland sequence. Four graptolite-bearing levels have been collected thus far in the younger portion of the section (Ojtb of Drake et al., 1996). Although significant deformation is present at the site, these collections apparently are in sequence, numbered herein as Collections 19-22. The strata strike generally N55°E and dip 24°SE with apparent consistency; collection 19 is the lowest, and collection 22 the highest. Collection 21 is from a metabentonite high in the quarry face. The other collections are from marine clastic units.

The strata recognizable at the Clinton Block and Supply Site can be traced to the north side of Interstate Highway 78 where an identical sequence is present at the former Mannon's Quarry (Fig. 2). This was the site primarily investigated by Perissoratis (1974) and thus provides additional clarification to work performed there.

We list here (Appendix 1) the faunal collections cited by Perissoratis et al. (1979) with minor changes in formal taxonomy and with commentary on sources and repositories. To that list are added the assemblages collected since that date, noting sources and repositories and continuing the numbering sequence. Zonation numbers are those of Berry (1960, 1968).

Localities 1-16 are those cited by Perissoratis et al. (1979) and shown on the map published by them. Localities 1-4 apparently also were those of Dodge (1952), although he numbered them differently. Locality 5 was first located by Weller (1903), and Locality 6 was Kummel's locality cited by Ruedemann (1947).

Locality 17 is along the Lehigh Valley Railroad tracks one kilometer east of Jutland. The graptolites were collected by Richard Volkert of the New Jersey Geological Survey and identified by Claire Carter of the United States Geological Survey (U.S.G.S. report on referred fossils, Shipment ERG-84-1M, 1984).

Locality 18 was published by Parris and Cruikshank (1986). Localities 19-22 all are from the Clinton Block and Supply Site, as noted above. More precise locality data are on file at the New Jersey State Museum.

Locality 1 of Perissoratis et al. (1979), which was also Locality 1 of Dodge (1952), is now very poorly exposed. In view of its importance as one of the oldest sites (Zones 2-4), and attributed to unit Ojta of Drake et al. (1996), we made an especially intensive effort to obtain material from there. The site, previously known as Hedgehaven Farm, is now on New Jersey State Land and designated as the Clinton Shotgun and Archery Training Area. It has now yielded additional specimens of graptolitic (generally dendroid) and conodont faunal material (NJSM 16566 and

FIGURE 1 - Martinsburg Formation and other Ordovician fine-grained clastic rock exposures in northwestern New Jersey. A, Main body of Martinsburg Formation. B, Port Murray Outlier, C, Asbury Outlier, D, Jutland Klippe (area shown in figure 2) and E, Peapack Klippe (after Parris et al., 1993). Star indicates most proximal position of Delaware Water Gap National Recreation Area.

NJSM 16131). Our identifications confirm previous age determinations for the site (Repetski et al., 1995). To date we have been unable to locate the repository of Dodge's (1952) original specimens, although there is no doubt that they were competently studied and very well illustrated.

Materials that were part of the basis of the age determination for Locality 6 are deposited at the New Jersey State Museum (NJSM 8132, 10914-10920). Specimens from Locality 17 are NJSM 12725. Specimens from Locality 18 were cited by number previously (Parris and Cruikshank, 1986). We have collected material from Locality 16 which has added *Pseudoclimacograptus scharenbergi* to that faunal list (NJSM 18771).

Numbers currently assigned to specimens from the Clinton Block and Supply Site are as follows: NJSM 16481-16490 from Locality 19; NJSM 16564 for Locality 20; NJSM 16565 for Locality 21. Specimens from Locality 22 are New Jersey Geological Survey specimens, currently unnumbered, but under study at the New Jersey State Museum.

Lithologic Data

Significant new quarry cuts at the Clinton Block and Supply Site yielded new lithologic information during 1997 and 1998 (Fig. 4). These excavations in map unit Ojtb directly correspond to levels of faunas 19-22.

FIGURE 2 - Approximate area of Jutland sequence rocks (Ordovician age) in Hunterdon County, New Jersey. Base maps are portions of High Bridge and Pittstown U.S.G.S. 7.5' topographic quadrangles. H, Hedgehaven Farm; C, Clinton Block and Supply Site; M, Mannon's Quarry.

GRAPTOLITE ZONE CORRELATIONS

(After Ross et al, 1982)

Correlations		Zones	Subzones
British	American		
Caradoc	Mohawkian	13. *Orthograptus amplexicaulus*	*Climacograptus spiniferus* *Orthograptus ruedemanni* *Corynoides americanus*
		12. *Climacograptus bicornis*	
Llandeilo	Whiterockian	11. *Nemograptus gracilis*	
Llanvirn		10. *Glyptograptus cf. G.teretiusculus*	
Arenig		9. *Paraglossograptus etheridgei*	
		8. *Isograptus*	
		7. *Didymograptus bifidus*	
	Ibexian	6. *Didymograptus protobifidus*	
		5. *Tetragraptus fruticosus* (3 and 4-branched)	
		4. *Tetragraptus fruticosus* (4-branched)	
		3. *Tetragraptus approximatus*	
Tremadoc		2. *Clonograptus*	

FIGURE 3 - Graptolite zone correlations, after Ross et al., (1982)

FIGURE 4 - View to southwest of quarry face at Clinton Block and Supply Site, Exposure includes base of gray thin-bedded shale at base on right, to top of thick-bedded red shale on left. Person is at contact of units. Dip of beds approximately 24°SE.

Jutland Sequence: Unit Ojtb of Drake et al. (1996)

Thin bedded medium-grained sandstone, brown, undetermined thickness exceeding 10 meters	Level of Fauna #22
Metabentonite interbedded with brown claystone and siltstone, 10 meters	Level of Fauna #21 Metabentonites in samples submitted to Janet Bertog (University of Cincinnati) for further correlation analysis.
Claystone, siltstone and fine-grained sandstone, brown and red interbedded, 20 meters	Level of Fauna #20 near base, in brown siltstone bed.
Thick-bedded claystone and siltstone, red, 10-12 meters	
Thin-bedded claystone and siltstone, gray, 10-12 meters	
Graywacke, brown, one meter	Level of Fauna #19
Claystone and siltstone, predominantly gray with interbedded limestones, gray. Undetermined thickness	

DISCUSSION

The question of whether the youngest horizons of the Jutland sequence overlap the oldest of the Martinsburg Formation nearby still cannot be answered with certainty. No graptolite species recorded from the Jutland Klippe have also been recorded from the Martinsburg Formation in New Jersey or adjacent areas. For example, correlations to the *Climacograptus bicornis* Zone in both areas have been based on possibly contemporaneous species, but not the same ones. The graptolite zone correlations for Faunas 1-16 (Appendix 1) are the attributions of previous authors and have not been critically reviewed by us, nor have we seen most of the specimens on which they were based. However, the question of overlapping ages basically concerns the *Climacograptus bicornis* Zone (Zone 12 of Berry, 1960) which may occur in both the Martinsburg Formation and the Jutland Klippe. Of the five Jutland faunas potentially correlated with that zone (localities 5, 8, 10, 14, 16), only the faunas from localities 8 and 10 seem likely to belong to it, based on the presence of *C. bicornis* itself. The others could as easily be from Zone 11, and it would appear that the few species recorded were not sufficiently diagnostic of age.

The oldest fauna from the Martinsburg Formation, as recorded by Parris and Cruikshank (1992), was that of their locality 22, which contained *Glyptograptus euglyphus* and some shelly species. *G. euglyphus* is known also from the *Corynoides americanus* Subzone of the *Orthograptus amplexicaulus* Zone and was part of the basis for correlation of the Port Murray Outlier (Parris et al., 1993), which also is low in the Martinsburg Formation. The Martinsburg Formation has produced none of the characteristically earlier taxa of the Jutland Klippe, such as *Nemagraptus* and *Didymograptus*, and it seems that little if any of the lowermost Martinsburg Formation correlates with even the youngest portion of the *Climacograptus bicornis* Zone.

The graptolite succession presented here aids in the structural interpretation of the site. The interpretation of an overturned succession by Perissoratis et al. (1979) is not supported by the evidence at the Clinton Block and Supply Site. Whereas, no previous faunal collections have been made from a continuous exposure from the Jutland sequence, the Clinton Block and Supply Site has produced four sequential older to younger faunal levels (collections 19-22) which are demonstrably older basal faunas to younger upper faunas. This relationship is apparently identical to that at the nearby Mannon's Quarry, thus the Jutland Sequence as a whole appears to be an upright sequence, not overturned. Further structural interpretation will be expected once other investigations are completed. In view of its lithologic distinction and mapability we endorse the recognition of the Jutland sequence as a lithologic unit (Drake et al., 1996), but remain skeptical about the interpretation of the structure as shown in previous publications.

ACKNOWLEDGMENTS

We thank the authorities at the New Jersey Geological Survey for their continued cooperation and encouragement, notably Richard Dalton, Donald Monteverde, and Richard Volkert. The extensive field studies of Frank Markewicz were the basis of much of our investigations. The help and permission granted by the Clinton Block and Supply Company was essential to our effort, as was access granted by the owners of the former Mannon's Quarry. As previously noted, tracts of land owned by the New Jersey Department of Environmental Protection and the New Jersey Department of Corrections were included within the study area and access was granted by those agencies. We especially thank Administrator Charlotte Blackwell and Assistant Administrator Karen Durastante for access to tracts on the Edna Mahan Correctional Center. Reviews by Drs. Jack B. Epstein, John E. Repetski, and John W. Hoganson contributed significant improvements.

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APPENDIX 1

Locality Number	Taxo	Graptolite Zone
1	*Adelograptus lapworthi* (Ruedemann)	2-4
	Adelograptus sp. cf. *A. pusillus* (Ruedemann)	
	Callograptus sp. cf. *C. salteri* (Hall)	
	Clonograptus sp.	
	Dictyonema sp. cf. *D. quadrangulare* (Hall)	
	Dictyonema sp. cf. *D. murrayi* Hall	
	Tetragraptus sp. cf. *T. quadribrachiatus* (Hall)	
2	*Adelograptus lapworthi* (Ruedemann)	2-4
	Tetragraptus sp. cf. *T. quadribrachiatus* (Hall)	
3	*Cryptograptus antennarius* (Hall)	probably 9
	Didymograptus sp. cf. *D. nicholsoni* (Lapworth)	
	Glossograptus sp. cf. *G. hystrix* Ruedemann	
4	*Cryptograptus antennarius* (Hall)	probably 9
	Dichograptidae	
5	*Climacograptus phyllophorus* Gurley	11-12
	Dicranograptus ramosus (Hall)	
	Nemagraptus sp.	
	Retiograptus geinitzianus (Hall)	
6	*Pseudoclimacograptus scharenbergi* (Lapworth)	11
	Diplograptus angustifolius (Hall)	
	Dicellograptus sp. cf. *D. divaricatus* (Hall)	
	Dicellograptus sextans (Hall)	
	Dicellograptus smithi Ruedemann	
	Dicranograptus sp.	
	Glyptograptus sp.	
	Pseudoclimacograptus scharenbergi cf. var. *stenostoma* (Bulman)	
7	*Pseudoclimacograptus scharenbergi* cf. var. *stenostoma* (Bulman)	11
	Climacograptus sp. cf. *C. riddelensis* Harris	
	Cryptograptus tricornis (Carruthers)	
	Glyptograptus sp.	
	Orthograptus sp.	
	Retiograptus sp.	
8	*Climacograptus bicornis* (Hall) ?	12
	Pseudoclimacograptus scharenbergi cf. var. *stenostoma* (Bulman)	
	Glyptograptus sp.	
9	*Amplexograptus arctus* (Elles and Wood)	probably 10
	Climacograptus sp. cf. *C. riddelensis* Harris	
	Diplograptus sp.	
	Glyptograptus sp.	
	Pseudoclimacograptus sp.	
10	*Climacograptus bicornis* (Hall)	probably 12
	Cryptograptus tricornis (Carruthers)	
	Glyptograptus sp.	
11	*Climacograptus riddelensis* Harris	10
	Cryptograptus tricornis (Carruthers)	
	Diplograptus decoratus Harris and Thomas	
	Glyptograptus sp. cf. *G. teretiusculus* (Hissinger)	
12 & 13	*Amplexograptus* sp.	probably 10
	Cryptograptus tricornis (Carruthers)	
	Diplograptus? sp.	
	Glyptograptus sp.	
	Hallograptus? sp.	
	Pseudoclimacograptus sp.	
14	*Climacograptus* sp.	11-12

APPENDIX 1 continued

Locality Number	**Taxo**	**Graptolite Zone**
15	*Didymograptus* sp. cf. *D. nicholsoni planus* Elles and Wood	4-8
16	*Dicellograptus* sp. *Pseudoclimacograptus scharenbergi* (Lapworth)	11-12
17	*Pseudoclimacograptus modestus* (Ruedemann) *Dicellograptus divaricatus salopiensis* Elles and Wood *Dicellograptus* sp. *Dicranograptus* sp. *Didymograptus sagitticaulis* Gurley *Climacograptus* sp. *Glyptograptus*? sp.	11
18	*Didymograptus sagitticaulis* Gurley *Didymograptus* sp. *Dicellograptus* sp. *Dicranograptus* sp. cf. *D. kirki* Ruedemann *Dicranograptus ramosus* (Hall) *Dicranograptus* sp. *Glossograptus ciliatus* Emmons *Climacograptus* sp. *Pseudoclimacograptus* sp.	11
19	*Isograptus forcipiformis* (Ruedemann) *Didymograptus* sp. (*extensus* Hall?) *Pseudotrigonograptus ensiformis* (Hall) *Tetragraptus* sp. (*bigsbyi* Hall or *serra* Brongniart) *Xiphograptus svalbardensis* (Archer and Fortey) *Isograptus victoriae maximus* (Harris) *Pseudisograptus* sp.	8
20	*Isograptus* sp. *Cryptograptus tricornis* (Carruthers) *Glossograptus* sp. (*holmi* Bulman?) *Climacograptus* sp.	9
21	*Glyptograptus teretiusculus* (Hissinger) Dichograptidae, genus indet. *Pseudoclimacograptus angulatus* Bulman *Cryptograptus tricornis* (Carruthers) ? *Reteograptus geinitzianus* Hall *Climacograptus* sp.	10
22	*Hallograptus*? *Dicellograptus*? *Nemagraptus*? *Glyptograptus*? *Climacograptus* sp. *Didymograptus* sp. *Glossograptus* sp. *Cryptograptus* sp. *Pseudoclimacograptus* sp.	11

NEW RECORDS OF TURONIAN MOSASAUROIDS FROM THE WESTERN UNITED STATES

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ABSTRACT--The early history of the highly successful marine mosasaurs was thought to be represented in fairly complete specimens from the northern end of the Adriatic Sea. Several previous hypotheses of relationships and evolutionary models were based upon that presumption. Recent discoveries in Israel and Texas show that diversity among basal forms is greater than previously suspected. Here, we document Turonian age fossils that demonstrate even greater diversity of basal mosasauroids and indicate there is much to be learned about the relationships, morphology, and distribution of these early forms. Although evidence of greater diversity is conclusive, the material is fragmentary and inappropriate for description of new taxa and phylogenetic revision. Isolated teeth from the early middle Turonian *Collignoniceras woollgari* Zone of the northern Black Hills region provide the earliest and most northerly evidence for an aigialosaur-grade mosasauroid in the Western Interior Seaway. Isolated teeth and a caudal vertebra from the base of the middle middle Turonian *Prionocyclus percarinatus* Zone include a similar basal mosasauroid and the oldest evidence of a "russellosaurine" mosasaur from South Dakota. Teeth from the early late Turonian *Prionocyclus wyomingensis* Zone record a "russellosaurine" mosasaur and an unusual basal mosasauroid. Vertebrae from the latest Turonian of the southern Black Hills suggest two types of "russellosaurines" were present, one of which may be a tylosaurine.

The oldest mosasauroids from Texas have not been directly associated with ammonites, and their ages may be bracketed from early Turonian to late middle Turonian. There are no less than three different morphologies of basal mosasauroids and one "russellosaurine" mosasaur present in this fauna. All but one basal form from this fauna ranges into the upper *C. woollgari* or lower *P. hyatti* Zone, where another type of "russellosaurine" appears. Total evidence suggests that at least four basal mosasauroid morphologies are present in middle Turonian sediments of the western United States, and that the first radiation among mosasaurs occurred within "Russellosaurinae."

INTRODUCTION

Whereas the Coniacian through Maastrichtian fossil record of mosasauroids comprises thousands of well preserved specimens, the early history of the clade is rather sketchily represented. North American Turonian records include those of Martin and Stewart (1977) from the middle Turonian *Collignoniceras woollgari* and *Prionocyclus hyatti* zones of the Carlile Shale, Kansas; and Bell (1995) from the middle Turonian *C. woollgari* Zone (but see comments below) of the Boquillas Formation in Big Bend National Park, Texas. Both of these report very fragmentary remains. Well represented remains were briefly noted by Bell and Polcyn (1995) and Polcyn and Bell (1996) from the middle Turonian *C. woollgari* or *P. hyatti* Zone of the Arcadia Park Formation at Dallas, Texas. These specimens are currently being described. Outside of this continent, fairly well preserved late Turonian mosasaur skulls with vertebrae were described by Antunes (1964) from Angola and Paramo (1994) from Colombia.

Reports of still older Cenomanian mosasaurs have all been dispelled. Hector (1878) correlated New Zealand beds containing mosasaurs with Cenomanian rocks in England, but Welles and Gregg (1971:101-106) gave a complete synopsis of the reassignment of these beds to the Maastrichtian Stage. Cenomanian records of mosasaurs from North America (Stenzel, 1944:443; Thurmond, 1969:78) were actually found to be remains of teleosts (Stewart and Bell, 1994). Woodward (1905) briefly mentioned a few mosasaur vertebrae from the terminal Cenomanian part of the English Chalk (BMNH R3357, three vertebrae in one piece of chalk), but they are now thought to be of middle to late Turonian age on the basis of microfaunal analysis (Lingham-Soliar, 1994:268).

Basal mosasauroids from Slovenia and Croatia (Kornhuber, 1893, 1901; Kramberger, 1892) were previously referred to the Family Aigialosauridae (paraphyletic, see Bell, 1997b:321) on the basis of several plesiomorphic features. Their ages are poorly resolved and are bracketed from Cenomanian to early Turonian (Langer, 1961). A new taxon of basal (aigialosaur-grade) mosasauroid from the early Cenomanian of Israel will soon be described (Polcyn et al., in press). All these taxa possessed somewhat shortened limbs with normal lizard-like digits that were presumably functional in the terrestrial environment.

Initial discoveries of aigialosaur-grade mosasauroids in central and west Texas led us to adopt a more aggressive program to try to better understand their range and diversity in the Western Interior Seaway. Due to their relatively small size, disarticulated elements of basal mosasauroids are most difficult to locate using normal prospecting methods, and their rarity renders the process even more ineffectual. We chose instead to sample carbonate beds or lag deposits that contained obvious concentrations of vertebrate fragments and lay within the late Cenomanian and Turonian age interval. Most of the carbonate beds meeting these requirements are calcarenites comprised mostly of prisms of inoceramid molluscan shells, foraminiferan tests, or both. In some instances, vertebrate fragments were the dominant grain type. Calcarenite flags were dissolved in a solution of 10% acetic acid. Bulk samples of sandy or marly lags were dissaggregated by soaking in an aqueous solution of trisodium phosphate. All samples were graded into +6 mm, 6-1.5 mm, and 1.5-0.5 mm fractions. The smaller-sized fractions were picked under a binocular microscope.

Current records of aigialosaur-grade mosasauroids are from the northern Adriatic area, Israel, and Texas. Here, we report the first such mosasauroids from the Western Interior Cretaceous Seaway and the most northerly occurrences of more derived Turonian mosasauroids in that Seaway.

Abbreviations--**BBNP**, Big Bend National Park; **DMNH**, Dallas Museum of Natural History; **KUVP**, Kansas University Museum of Natural History; **SDSM**, South Dakota School of Mines, Museum of Geology; **TMM**, Texas Memorial Museum, Vertebrate Paleontology Laboratory.

GEOGRAPHIC SETTING

Turonian mosasauroid and coniasaur materials discussed in this report were recovered from five areas (Fig. 1). The most northerly areas include various outcrops around Belle Fourche Reservoir (Fig. 1-1) in Meade County, South Dakota, and west of the town of Edgemont (Fig. 1-2), Fall River County, South Dakota, and near the town of Upton, Weston County, Wyoming (Fig. 1-3). All these sites flank the Black Hills Uplift and were well within the Western Interior Cretaceous Seaway during Late Cretaceous time. Exact locality information is on file at the Museum of Geology at the South Dakota School of Mines and Technology.

South of Dallas, Texas, there is a locality (Fig. 1-4) known to local collectors as the "1382 Locality" near the town of Cedar Hill, which has produced several important mosasauroids and some coniasaur materials. During the Late Cretaceous, this area lay within the western portion of the Tethys Seaway. An area in west Texas (Fig. 1-5) centers around two sites within Big Bend National Park and several other minor sites approximately 40 kilometers northwest of the Park on the eastern and northeastern flanks of a well known geologic feature called "The Solitario" (Fig. 1-6). These areas lay near the juncture of the Tethys Seaway and the Western Interior Cretaceous Seaway during Turonian time. Exact locali-

FIGURE 1 - Locality map of sites discussed in this report. 1, Belle Fourche Reservoir (Orman Lake) area, Meade Co., South Dakota. 2, Angostura Reservoir Area, Fall River Co., South Dakota. 3, Upton, Weston Co., Wyoming. 4, Cedar Hill, south of Dallas, Tarrant Co., Texas. 5, eastern portion of Big Bend National Park, Brewster Co., Texas. 6, eastern flanks of "The Solitario," Brewster Co., Texas.

ty information for the Texas sites is on file with the Vertebrate Paleontology Laboratory of the University of Texas at Austin.

GEOLOGY AND BIOSTRATIGRAPHIC CORRELATION

The oldest mosasauroid materials from the Black Hills region were recovered from a small lag lens and an oyster-packed calcarenite bed at the very top of the Greenhorn Formation on Belle Fourche Reservoir (BFR). Highly abraded, fragmented, and polished vertebrate bones and teeth found in both sediment types suggest an unconformable contact between the Greenhorn limestones and marls below and the black silty shales of the Pool Creek Member of the Carlile Shale above (Fig. 2). Arguably, these higher energy bedforms may represent the basal reworked material above an unconformity and should therefore be placed within the Carlile Shale. However, these bedforms may only reflect a temporary shoaling episode and, because the dominant rock types at this level are calcarenites or calcareous shales, we here place them at the top of the Greenhorn. Two ammonites found in the oyster/calcarenite bed are identified as *Collignoniceras woollgari*, indicating the same nominal biostratigraphic zone (Cobban, 1993, Fig. 2) and an early middle Turonian age.

The next youngest mosasauroid remains were recovered from a thin (3-15 cm) unit of locally shelly calcarenite that lies approximately 5 meters below the top of the Pool Creek Member of the Carlile Shale (Fig. 3) west of Edgemont, South Dakota. Ammonites recovered from this same bed include *Prionocyclus percarinatus*, *Collignoniceras praecox*, *C. vermillionense*, and *Scaphites patulus* (Martin et al., 1996:70), all of which indicate the *P. percarinatus* Zone of middle middle Turonian age. Additionally, the unit should be in the lowest part of that ammonite zone, as the highest *C. woollgari* are found about 1 meter below. Mosasaur jaw fragments and teeth were also found in a lower sandstone/conglomerate unit approximately 2-3 meters above the base of the Turner Sandy Member of the Carlile Shale. These occur with numerous shark and teleost teeth and bones, as well as rounded and sub-rounded phosphate and quartzite pebbles. Locally, this bed is referred to as the "Shark Tooth Conglomerate," and has its best development in a small area about eight kilometers west of Edgemont. Good examples of *Scaphites warreni* found in the same bed indicate that nominal subzone within the lower part of the *Prionocyclus wyomingensis* Zone and therefore an early late Turonian age (Hancock et al., 1993). Two other mosasaur jaw fragments found near Upton, Wyoming, are from the same lower sandstone unit of the Turner Member.

Three unassociated mosasaur vertebrae were found eroding from soft shales within the upper few meters of the Sage Breaks Member of the Carlile Shale. No ammonites were found in association with these specimens, but the stratigraphic level lies just below the unconformable Niobrara Formation contact and in this region is generally correlated to the latest part of the Turonian Stage by virtue of the presence of *Scaphites corvensis* (Cobban, 1951:2190). Dyman et al. (1994:18) noted that the upper part of the Sage Breaks Member is of middle Coniacian age in the Black Hills region. However, differential erosion has removed a large portion of the upper part of the unit on the southern end of the Black Hills, possibly including all of the Coniacian.

To this point, Turonian squamates from the Big Bend region of west Texas are all derived from near the base of the middle one-third of the Ernst Member of the Boquillas Formation (Bell, 1995, Fig.1). At this level, sediment types change from dominantly hard skeletal limestones and light-colored laminated marls to more clastic calcareous shales and calcarenites. This unit occupies an interval 38-47 meters above the base of the member. Shales are medium gray when fresh and yellow-buff when weathered. Calcarenites consist dominantly of skeletal grains of foraminiferans and/or inoceramid prisms. The calcarenites also contain high percentages of vertebrate fragments and coprolites. Bell (1995) gave the stratigraphic positions of mosasaur fragments found at the Hot Springs Locality as 38, 42, and 42.4 meters above the base of the member. Two ammonites were found at the highest level (4.4 meters above the base of the shale/calcarenite interval) and were identified as *Collignoniceras woollgari*. Both are nearly 2 cm in diameter, a size at which *C. woolgari* and *Prionocyclus hyatti* can easily be confused. It is more likely that those ammonites are actually *P. hyatti* because of the recovery of a good specimen of *Coilopoceras springeri* from 4.3 meters above the base of this shale/calcarenite interval at the Ernst Tinaja Locality only 11.5 km north of the Hot Springs. *C. springeri* is the nominal taxon of a subzone occupying the upper part of the *P. hyatti* Zone of late middle Turonian age. A distinctive stratigraphic marker which can be traced between these two localities consists of a bed of vertebrate fossil hash in calcarenite lying directly on a thin tan-colored bentonite, which in turn lies on a 15-18 cm hard, burrowed limestone. This set consists of the last bed of the hard skeletal limestones with laminated marl interbeds below and the first beds of the shale and calcarenite sequence above. Mosasauroids from Ernst Tinaja included in this report were found in the basal vertebrate hash bed and also in the same bed as the specimen of *Coilopoceras springeri*. The shale/calcarenite interval can be relocated on the eastern flanks of "The Solitario," 80 km to the northwest. Here the unit is thicker, 22 meters as opposed to 10 meters, and more clastic than in the eastern part of Big Bend National Park. In this area, calcarenites 3.1 and 15.7 meters above the base of the shale/calcarenite unit have produced fragmentary remains of coniasaurs and mosasauroids. *P. hyatti* was found 13 meters above the base, *P. hyatti* and *C. springeri* at 15 meters, and *Romaniceras mexicanum* and *P. hyatti* at 16.5 meters.

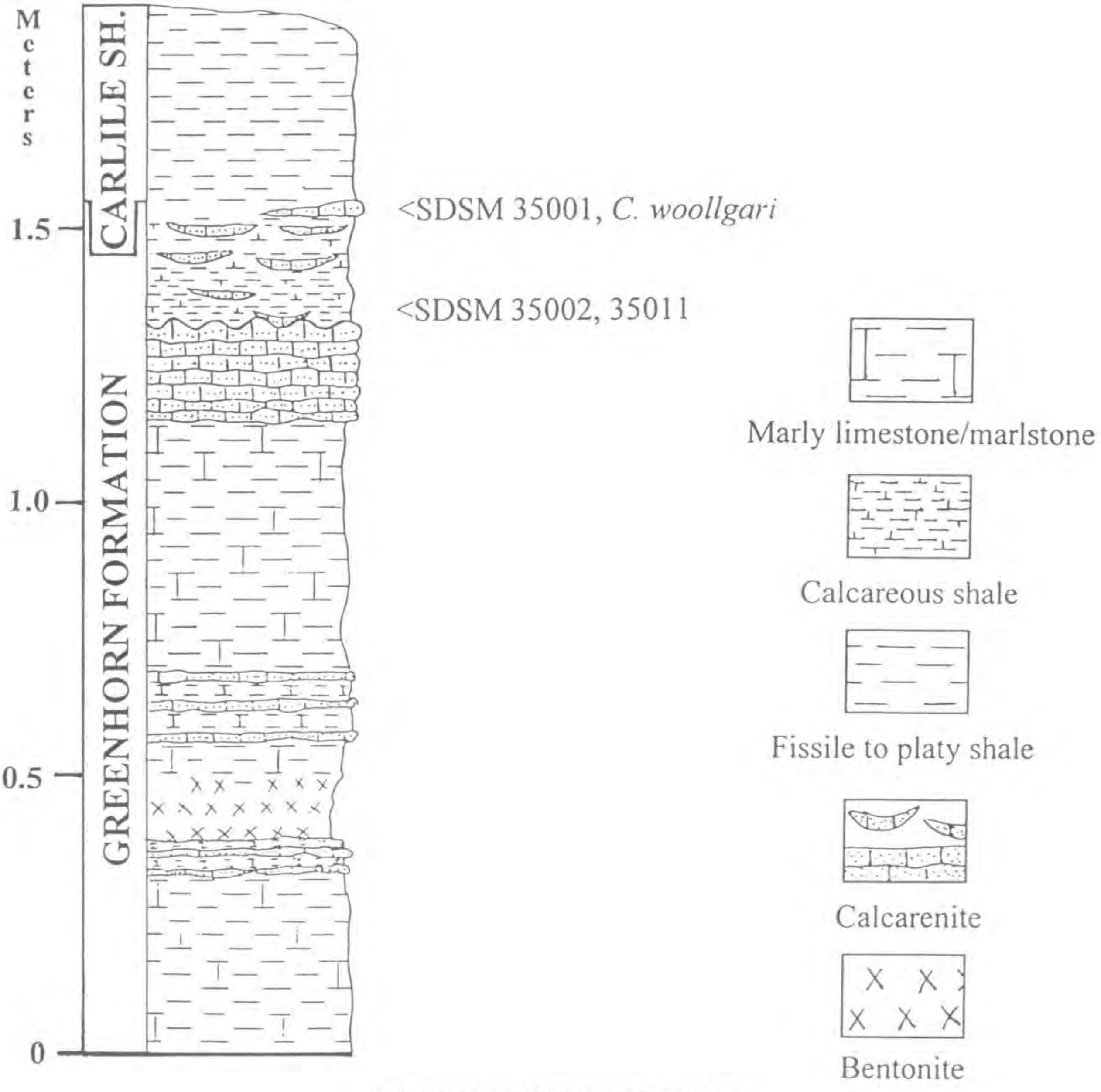
No ammonites have been found associated with the lowest mosasauroid occurrences. Speculation on their possible age may be risky, but a condensed zone in the Boquillas Fm. at Gold Hill in northern Jeff Davis County (Hook, 1983) contains both *C. woollgari regulare* and *P. hyatti*. The latter ammonite and *Coilopoceras* also occur in the beds immediately overlying the condensed interval. In the Chispa Summit Fm. at Chispa Summit (Kennedy et al., 1989), there is a zone of hiatus concretions that contain *C. woollgari regulare*. The next ammonites found above this level include *P. hyatti*, *C. springeri* and *R. mexicanum*. We have been unable to find this condensed interval in the Big Bend region and suspect that it may be represented by a hardground preserved in the hard, burrowed limestone immediately underneath the shale/calcarenite interval. If true this would make all these squamates late middle Turonian age.

The "1382 Locality" south of Dallas lies within the Arcadia Park Formation of the Eagle Ford Group. The "Kamp Ranch Limestone member" is present within the outcrop and contains *C. woollgari regulare* and *Scaphites larvaeformis* (Kennedy, 1988:13 and fig. 4). Two individual specimens of aigialosaur-grade mosasauroids were found about a meter above the limestone, as well as some shed teeth and isolated vertebrae recovered during screen washing. The ten meters of shale overlying the limestone have not produced any identifiable ammonites, but above that *P. hyatti* and *C. springeri* are fairly common.

MORPHOLOGICAL DIVERSITY OF MOSASAUROIDS

Due to the fragmentary nature and incompletely resolved relationships among the earliest mosasauroids (Bell, 1997b), it is difficult to place these specimens within a set of systematic relationships. Recent analyses (Polcyn et al., in press) have produced significant questions regarding the monophyly of derived mosasaurids (Mosasauridae as defined by Bell, 1993). A basal mosasauroid from the "1382 Locality" near Dallas shares several characters with the mosasaurine clade of derived mosasauroids and lacks many characters of derived "russellosaurine" mosasauroids (Bell, 1997b:323,324), yet also maintains relatively elongate limbs like other basal mosasauroids from the Adriatic and Middle East. Should subsequent phylogenetic analysis (presently in progress) support the aigialosaur-grade mosasauroid from Dallas as a basal member of Mosasaurinae, then, clearly, paraphyly of aigialosaurs would be upheld (Bell, 1997b). Additionally, derived mosasaurs complete with all their modifications for obligate marine life would become a polyphyletic group. The fact that the basal mosasauroid from Dallas occurs at the same

FIGURE 2 - Stratigraphic section of the upper Greenhorn Formation and lower Pool Creek Member of the Carlile Shale in NE 1/4, Sec. 3, T9N, R3E at Belle Fourche Reservoir, Meade Co., South Dakota, indicating positions from which ammonites and basal mosasauroid teeth were obtained. Zone of x's indicate the highest prominent bentonite in the Greenhorn Formation in this area.



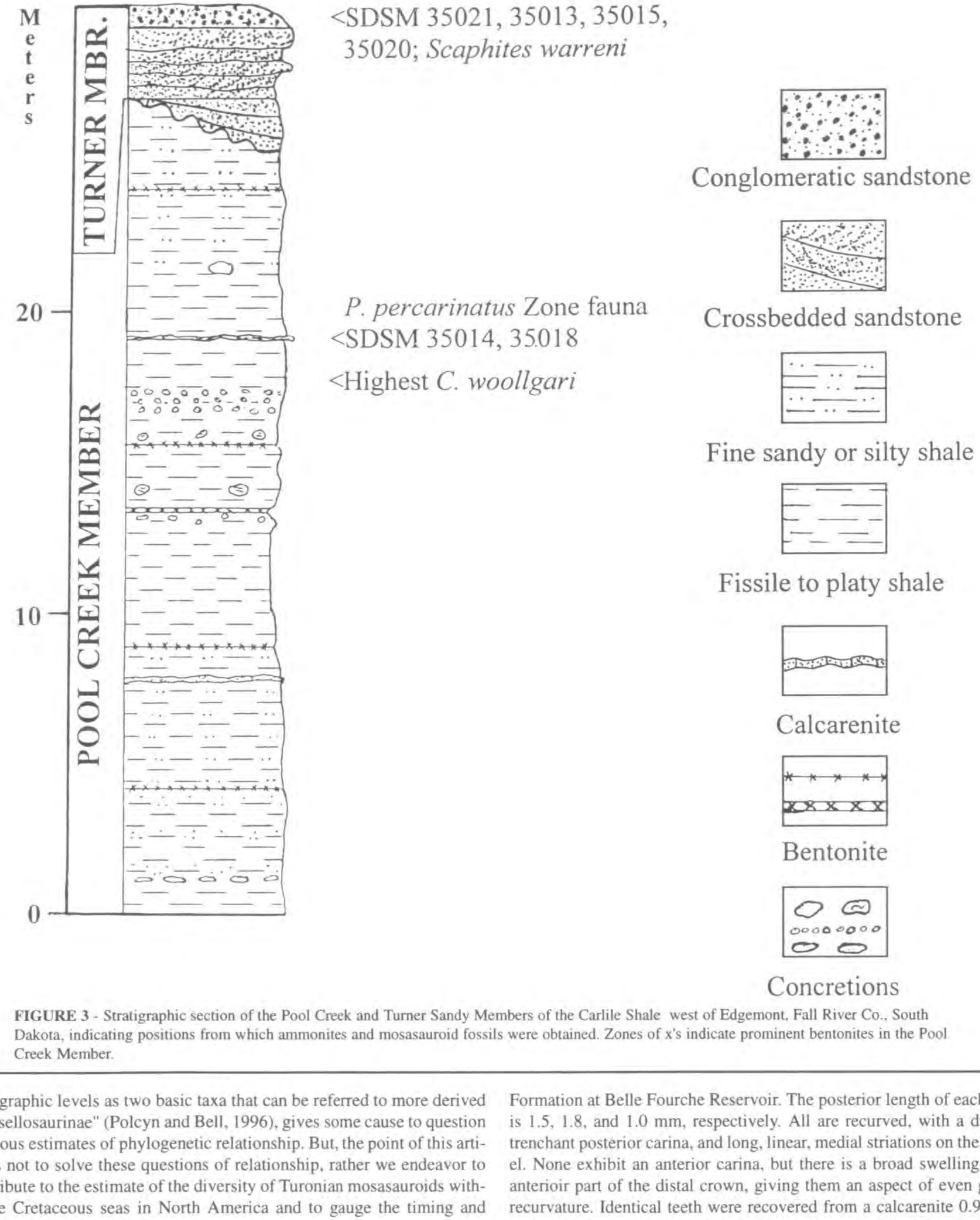


FIGURE 3 - Stratigraphic section of the Pool Creek and Turner Sandy Members of the Carlile Shale west of Edgemont, Fall River Co., South Dakota, indicating positions from which ammonites and mosasauroid fossils were obtained. Zones of x's indicate prominent bentonites in the Pool Creek Member.

stratigraphic levels as two basic taxa that can be referred to more derived "Russellosaurinae" (Polcyn and Bell, 1996), gives some cause to question previous estimates of phylogenetic relationship. But, the point of this article is not to solve these questions of relationship, rather we endeavor to contribute to the estimate of the diversity of Turonian mosasauroids within the Cretaceous seas in North America and to gauge the timing and extent of their immigration.

BASAL (AIGIALOSAUR-GRADE) MOSASAUROIDS

Basal mosasauroids are represented by shed teeth, vertebrae, and one humerus, as well as two partial skeletons. The oldest materials consistent with basal mosasauroid morphology consist of three shed teeth, SDSM 35001(Fig. 4-C), 35002, and 35011 from the top of the Greenhorn Formation at Belle Fourche Reservoir. The posterior length of each tooth is 1.5, 1.8, and 1.0 mm, respectively. All are recurved, with a distinct, trenchant posterior carina, and long, linear, medial striations on the enamel. None exhibit an anterior carina, but there is a broad swelling in the anterioir part of the distal crown, giving them an aspect of even greater recurvature. Identical teeth were recovered from a calcarenite 0.9 meter above the base of the shale/calcarenite interval near "The Solitario." Three of these, TMM 43359-1, 43359-2, and 43359-3, are illustrated (Fig. 5-G) herein. Additionally, six comparable shed teeth are from the basal vertebrate hash bed at Ernst Tinaja (TMM 43056-5), and another six are from the same bed at the Hot Springs (TMM 43352-5).

A different type of tooth morphology is represented in one of the partial skeletons (TMM 43209-1) from the "1382 Locality." Several teeth attached to portions of maxillary fragments of this specimen are strongly recurved, not medially striated, and bear only a posterior trenchant carina (Fig. 5-A). The anterodistal portion of the crown is even more strongly inflated than in the preceding tooth type and that inflation also extends more proximally. This area bears several small irregular striae that originate along the anterodistal crest and trail a short distance toward the crown base on both medial and lateral sides. Posterior teeth (Fig. 5-B) are so strongly inflated that the anterodistal surfaces of the crown face directly away from the dental margin of the maxilla and the tips point posteriorly at almost 90 degrees. The posterior lengths of these teeth range from 1.4 to 3.7 mm. A tooth with this morphology, TMM 43056-6, (Fig. 5-D) was recovered from about 10 cm below the level of the *Coilopoceras springeri* specimen from Ernst Tinaja in BBNP.

The two types of teeth described above are undoubtedly from different taxa. How different is a more difficult question. The medial striations of the first type are very similar to those seen in every "russellosaurine" mosasaur, whereas the strong inflation and irregular striae are found in some mosasaurine taxa. However, mosasaurine taxa possessing these characters (Globidensini) are not considered to be basal representatives within that lineage (Bell, 1997b). Additionally, presence of medial tooth striations is not necessarily a synapomorphy for a clade including "russellosaurines" because of problems in determining character polarity. It is not out of the realm of possibility that these teeth belong to basal representatives of two distinctly divergent clades, but basing such an hypothesis on tooth characters alone is very risky.

Finally, a third tooth morphology is present within our basal mosasauroid sample. We have recovered two unusual teeth (SDSM 35012, 35013) from an anthill built directly on top of the sandstone/conglomerate unit near the base of the Turner Member near Edgemont, South Dakota (Fig. 5-E). These are morphologically close to teeth of TMM 43209-1, except that they are even more anteriorly inflated and the anterior striations are much stronger and more numerous. SDSM 35013 (Fig. 5-E, right) is so anteriorly inflated as to be strongly anteroposteriorly elongated. They could be easily confused with teeth of *Coniasaurus* or even some pycnodont fishes, except for the strong trenchant posterior carina.

Small vertebrae constitute a significant portion of the basal mosasauroid sample. One (TMM 43352-6, Fig. 6) is obviously distinct from all others because of the extreme dorsoventral compression of the centrum. This compression is not a result of sedimentary compaction, because the vertebra was acidized from a coarse, grain-supported calcarenite along with many other vertebrate fragments which show no sign of compaction. It is presumed to be a middle to posterior trunk or an anterior caudal vertebra because the portion of synapophysis preserved on the right side is not tall and does not project dorsolaterally as do those of anterior trunk vertebrae. The base of the centrum is very flattened and even bears a shallow anterior furrow, which rules out the possibility of it being a cervical vertebra. The posterior condyle shows the ventral flattening by being more strongly arched across its dorsal edge. There is no indication of hemal arches. The small portion of the anterior cotyle preserved suggests some degree of anterior inclination of the central articulation, but the degree cannot be reliably established. The cotyle is also very deeply inset into the body of the centrum. Measurements of the centrum are as follows: lateral interarticular length - 5.2 mm, posterior condylar width - 4.7 mm, posterior condylar height - 2.0 mm. The bone surface is smooth and finished, indicating an adult ontogenetic stage. This specimen is completely unlike any other aigialosaur-grade mosasauroid, including those from the Mediterranean region. The only mosasauroid to which it bears any resemblance is *Halisaurus*, but that taxon is substantially more derived than TMM 43352-6.

The two individuals from the "1382 Locality" preserve virtually a complete set of cervical, trunk and caudal vertebrae. These will soon be described in another publication; therefore, we will only briefly describe them here for the purposes of comparison to others we have recovered. The cervicals bear a sharp, narrow anteroposterior ventral ridge, and the posterior articulations form an inverted, slightly subrounded triangle. Posterior articulations on trunk vertebrae (Fig. 7) are more equally rounded and inclined only about 10 degrees anteriorly. Measurements of a mid-trunk vertebrae are: ventral interarticular length - 16.5 mm, posterior condylar width - 8.7 mm, posterior condylar height - 6.7 mm. The sacral area is easily identified by a sudden change in centrum length. Except for the first three pygals, all caudal vertebrae bear completely fused hemal arches. These are the only such vertebrae in our sample. All others recovered have different characters or combinations of characters.

A left atlas neural arch, TMM 43352-15 (Fig. 11-D), also from the basal calcarenite/vertebrate hash bed at the Hot Springs, is probably from an aigialosaur-grade mosasauroid. It is 6.1 mm in its greatest anteroposterior direction and the lateral surface of the bone is finished, suggesting full maturity. The thin anterodorsal process is the only broken portion. Dorsomedially, a short fold descends onto the articular surface. There is a small short synapophysis on the posterior edge of the element and no thin descending lamina or "skirt" on the ventral edge. The element is similar to that of *Opetiosaurus buccichi*, but definitely unlike that of the Dallas specimen (TMM 43209-1) or the Trieste specimen (Carroll and deBraga, 1992).

One vertebra of a basal mosasauroid, TMM 43056-7, acidized from the basal vertebrate hash/calcarenite bed (32 meters above the base of the member) at Ernst Tinaja can be identified as a cervical (Fig. 8). It does not preserve the neural arch or spine, but most of the centrum and synapophyses are present. It is similar to *Opetiosaurus buccichi* and the Trieste specimen (Carroll and deBraga, 1992) in having a moderately compressed centrum. Its measurements are: ventral interarticular length - 10.5 mm, posterior condylar width - 5.0 mm, posterior condylar height - incomplete but > 3.1 mm. In general, it appears to be relatively long compared to its width, certainly longer proportionally than cervicals of *Opetiosaurus buccichi* or the Trieste specimen. It is unlike the latter also in having an ovoid hypopophyseal facet instead of subtriangular, and a sharp ventral keel anterior to that. The synapophyses are level with the base of the centrum. Two fragments consisting of the right and left prezygopophyses were found in the concentrate, but could not be reattached. They are relatively long and large. The bone surface is not completely finished, indicating the individual to which it belonged might not have been fully mature. An anterior trunk vertebra, TMM 43352-10, and mid- to posterior trunk vertebra, TMM 43352-11 were recovered from the basal calcarenite/vertebrate hash bed at the Hot Springs Locality. Measurements on both are approximate due to the rough treatment suffered during deposition and recovery by acidizing. The anterior trunk vertebral measurements are: dorsal interarticular length - ~13 mm, anterior cotylar height - ~6 mm, anterior cotylar width - 7.5 mm. TMM 43352-11 (Fig. 9) measures: dorsal interarticular length - ~10 mm, anterior cotylar height - ~7 mm, anterior cotylar width - ~9 mm. Both have subtle indications of low, broad, ventrolateral cornices running the length of the centrum. Inclination of the articular surfaces measures very close to 20 degrees, double that of the two individuals from the Dallas area. The bone surfaces are finished. Slight dorsoventral compression is a character these vertebrae share with the Trieste specimen and "russellosaurines."

Our sample contains several caudal vertebrae, all of which share two characters: vascular (immature) bone surfaces and unfused hemal arches. One anterior caudal (TMM 43056-4) from 1.2 meters below the *Coilopoceras springeri* level at Ernst Tinaja is very well preserved except for its neural arch and spine (Fig. 10). Its measurements are: ventral interarticular length - 4.1 mm, posterior condylar height - 3.2 mm, posterior condylar width - 4.0 mm. A portion of a transverse process is preserved for a distance of 4 mm on the left side. This process is significantly more narrow than those preserved on *Opetiosaurus buccichi*. Ventrally are two distinct circular facets for articulation of the hemal arches. These are preceded by a pair of low rounded ridges and shallow medial groove which become less distinct anteriorly. These same ventral features are preserved on a single damaged anterior caudal from the basal calcarenite/vertebrate hash bed at Ernst Tinaja. A posterior caudal, TMM 43209-2, (Fig. 11-C) was recovered during screen washing for pieces of one of the Dallas individuals (TMM 43209-1). Its surface texture and hemal articulations immediately distinguish it from TMM 43209-1. Its ventral interarticular

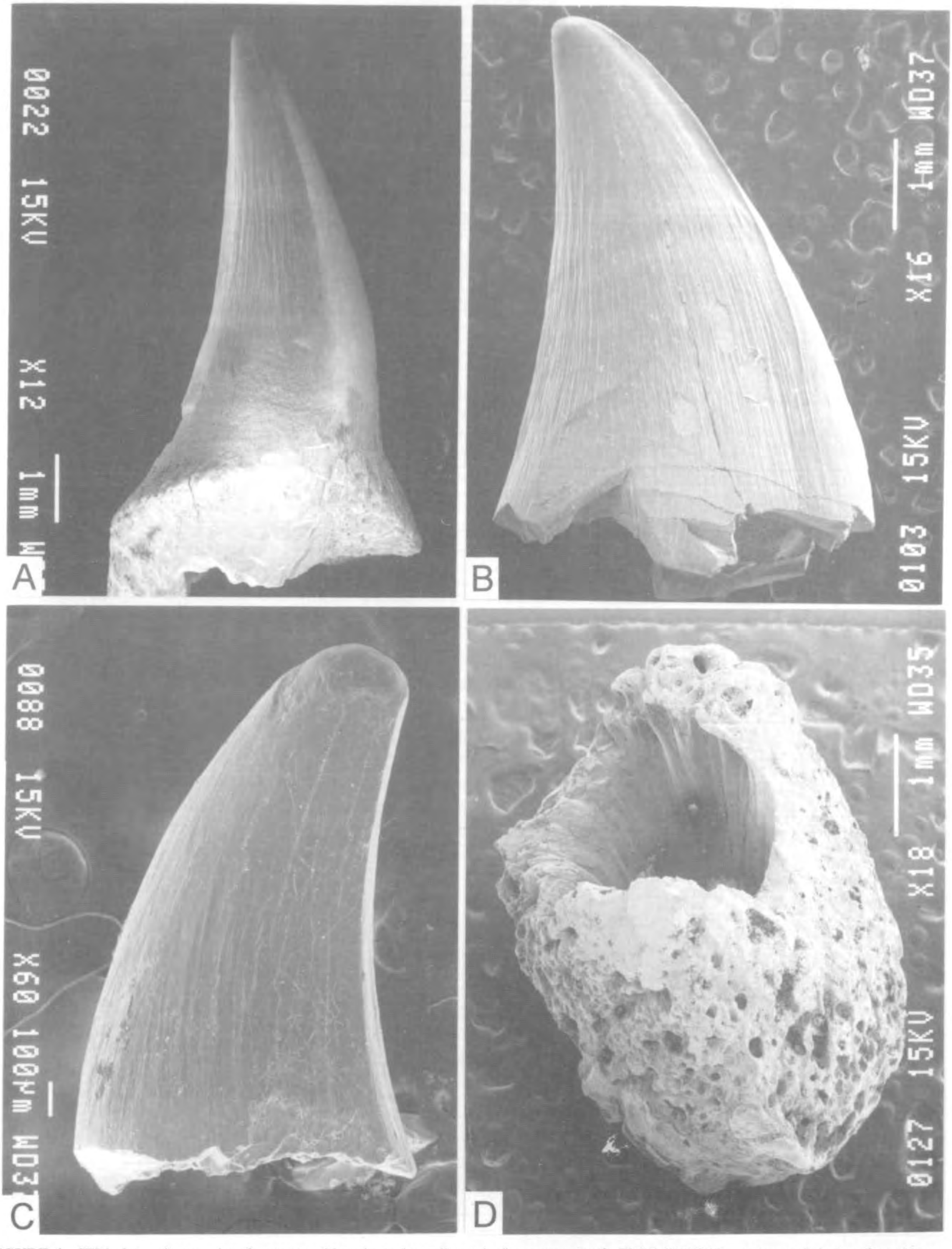


FIGURE 4 - SEM photomicrographs of mosasauroid teeth. A, "russellosaurine" mosasaur tooth, TMM 43056-12, posteromedial view, from 32 m above base of Ernst Member, Boquillas Fm., Ernst Tinaja, BBNP. B, "russellosaurine" mosasaur tooth, SDSM 35018, posteromedial view, from shelly calcarenite bed approximately 5 m below top of Pool Creek Member, Carlile Shale, SDSM locality V9413. C, basal (aigialosaur-grade) mosasauroid, SDSM 35001, posteromedial view, from highest Greenhorn Fm., Belle Fourche Reservoir. D, mosasaur tooth root, TMM 43352-17, basal view into pulp cavity, 38 m above base of Ernst Member, Boquillas Fm., Hot Springs, BBNP. Use only bar scales for dimensions.

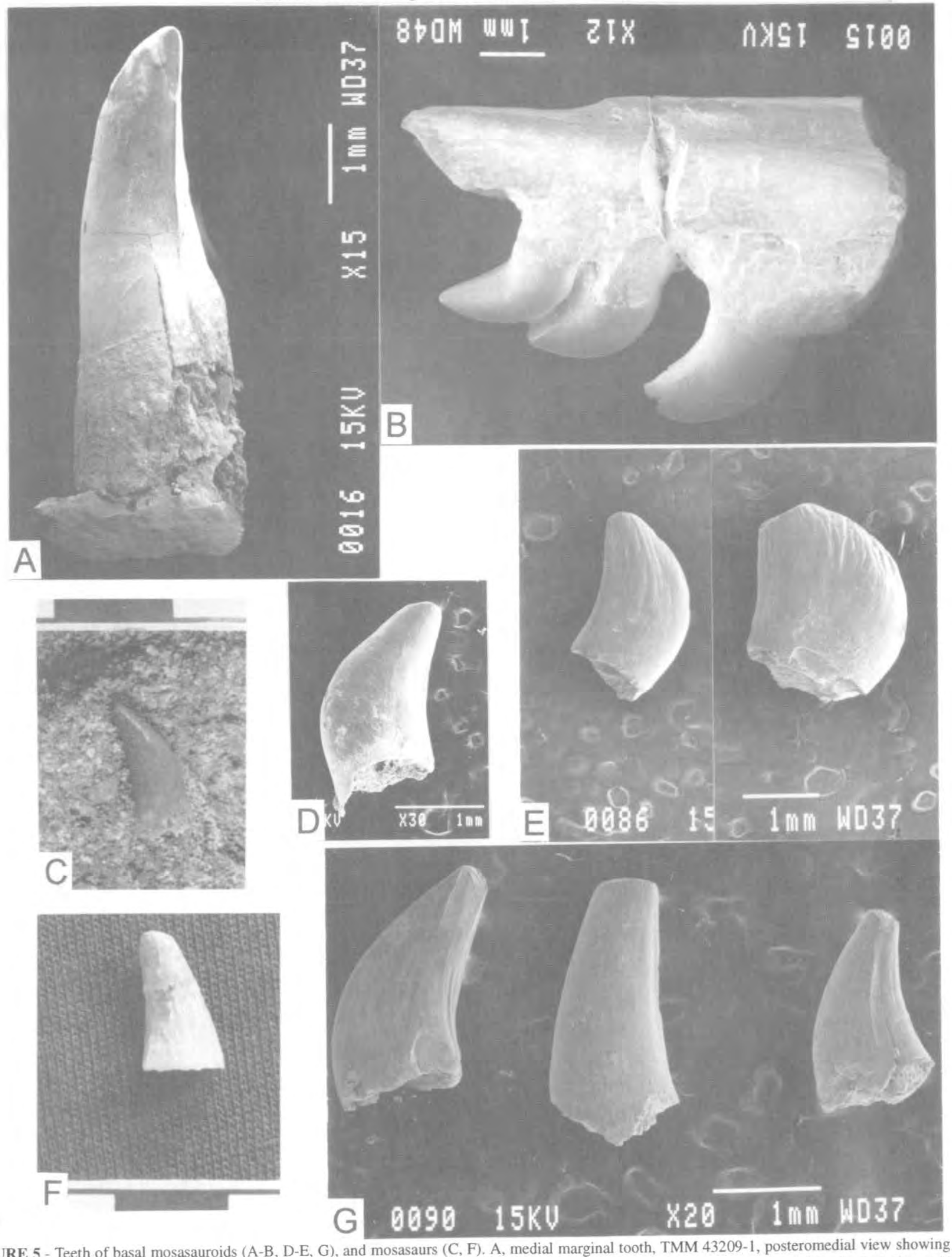


FIGURE 5 - Teeth of basal mosasauroids (A-B, D-E, G), and mosasaurs (C, F). A, medial marginal tooth, TMM 43209-1, posteromedial view showing strong carina and irregularly granular/vermiculate ornamentation of surface, from 1 m above "Kamp Ranch Limestone member," Arcadia Park Fm. at "1382 Locality" near Dallas. B, posterior right maxilla, TMM 43209-1, lateral view, showing strong recurvature and anterodistal inflation of teeth. C, mosasaur tooth, SDSM 35019, lateral view, from "Shark Tooth Conglomerate" bed near base of Turner Sandy Member, Carlile Shale, SDSM locality V897 near Edgemont. D, basal mosasauroid tooth, TMM 43056-6, lateral view, from 34 m above base of Ernst Member, Boquillas Fm. at Ernst Tinaja, BBNP, probably same taxon as A, B above. E, two basal mosasauroid teeth, SDSM 35012, left, and SDSM 35013, right, lateral views showing strong inflation, trenchant posterior carina, and coarse vertical ribbing, probably from same bed and locality as C above. F, "russellosaurine" mosasaur tooth, SDSM 35020, posteromedial view, same bed and locality as C above. G, three basal mosasauroid teeth, left is TMM 43359-1 medial view, middle is TMM 43359-2 in lateral view, right is TMM 43359-3 in posterior view, from 32 m above base of Ernst Member, Boquillas Fm., on eastern flanks of "The Solitario." Note trenchant carina on TMM 43359-3 and distinct posteromedial striations on TMM 43359-1. Use only bar scales for A-B, D-E, G; black bar on C, F is 10 mm.

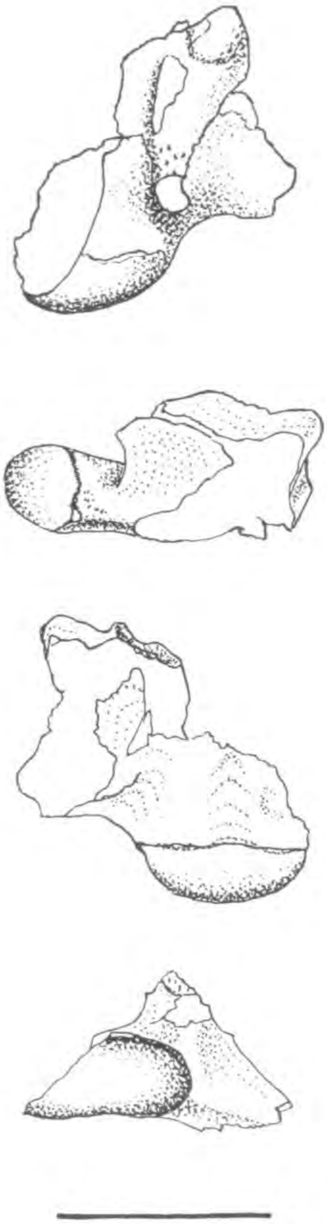


FIGURE 6 - Basal mosasauroid posterior trunk or pygal vertebra, TMM 43352-6, dorsal, right lateral, ventral, and posterior views in descending order, from 38 m above base of Ernst Member, Boquillas Fm. at Hot Springs, BBNP. Bar scale is 5 mm.

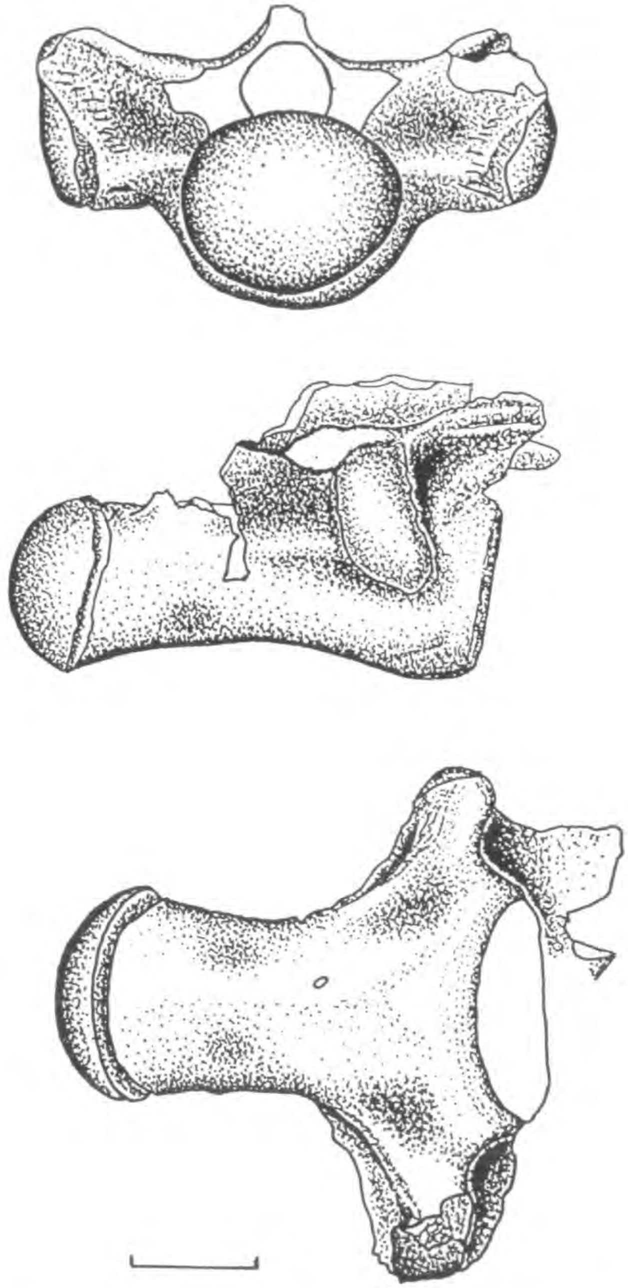


FIGURE 7 - Basal mosasauroid anterior trunk vertebra, TMM 43209-1, posterior, right lateral, and ventral views in descending order, from 1 m above "Kamp Ranch Limestone member," Arcadia Park Fm. at "1382 Locality" near Dallas. Bar scale is 5 mm.

length is 1.9 mm and posterior condylar height is 2.0 mm. A virtually identical posterior caudal, TMM 43352-12 (Fig. 11-A), is from the basal calcarenite/vertebrate hash bed at the Hot Springs Locality. Its ventral interarticular length is 2.3 mm and its posterior condylar height is 2.2 mm. Another virtually identical posterior caudal, SDSM 35014 (Fig. 11-B), was recovered from acidized concentrate of the shelly calcarenite about 5 meters below the top of the Pool Creek Member of the Carlile Shale west of Edgemont, South Dakota. It is only slightly smaller than the other two, having a ventral interarticular length of 1.8 mm and a posterior condylar height of 1.6 mm.

Among most modern terrestrial squamates, fusion of the hemal arches to the centra takes place ontogenetically, yet among derived mosasauroids this has never been shown to occur. Within mosasaurines, even the ontogenetically youngest specimens have fused hemals as do more mature individuals, but within "russellosaurines" no individuals, including the largest, have articulating hemal arches. All of the Adriatic basal mosasauroids that exist in collections have articulating hemals. If some less derived taxa had already lost ontogenetic fusion of the hemals, that character condition would be a potential synapomorphy for a lineage including the Adriatic basal mosasauroids and more derived "russellosaurine" mosasauroids. In this regard, all of the caudal vertebrae with articulating hemals could be referred to that lineage. However, every one of the caudal vertebrae with articulating hemals reported herein are apparently from immature individuals and we are unable to assess the condition in later stages of growth. We must defer to a later time when we may have sufficient information from more mature individuals in order to test this hypothesis of phylogenetic relationships.

A proximal portion of a right humerus and a distal portion of a right humerus, TMM 43352-13 (Fig. 11-E, F) were recovered from the same sample fraction of acidized concentrate from the basal calcarenite/vertebrate hash bed at the Hot Springs Locality. It is quite probable that these were originally parts of the same bone, but the intervening fragment could not be found. It is then impossible to determine an exact length, but the elongate aigialosaur-grade proportions are unmistakable. The epiphyseal ends are not preserved which further compromises reliable measurements and prevents assessment of characters on the articulations. The distal end appears to be slightly broader than the proximal end. There is a long narrow ectepicondylar groove raking at a slight angle across the anterodistal corner on the dorsal surface. Carroll and deBraga (1992:79) stated that there is no clear indication of an ectepicondylar foramen in aigialosaurs. In *Opetiosaurus buccichi* and the Trieste specimens, their conclusion is mainly due to exposure of the ventral side of the humeri only, but *Aigialosaurus dalmaticus* definitely possesses a long slender groove which distally becomes a very narrow foramen. This is also the case in the distal humerus of one of the associated skeletons from near Dallas (TMM 43209-1). Estimated length of TMM 43352-13 is 14 mm based on continuation of the curvature at the broken ends, the proximal width is 4.1 mm, and the distal width is 4.6 mm. The ratio of length (if correct) to distal width is very close to 3:1 as in *A. dalmaticus* and *O. buccichi*, but it is only 35% of the size of those taxa. This small size is probably a result of its relatively young ontogenic stage, as indicated by lack of fused calcified epiphyses. It is even smaller compared to TMM 43209-1.

DERIVED (MOSASAUR-GRADE) MOSASAUROIDS

Material representing more derived mosasauroids consists predominantly of unassociated elements and teeth. A specimen from a few centimeters above the "Kamp Ranch Limestone member" near the "1382 Locality" consists of a complete skull and will soon be described in a separate publication. Those from the calcarenite/vertebrate hash bed 38 meters above the base of the Ernst Member at the Hot Springs Locality in BBNP include a right prootic, a right splenial, a right atlas neural arch, three caudal vertebrae, and several shed teeth.

The prootic, TMM 43352-1, was briefly mentioned previously but not described (Bell, 1995:35). As with many of the specimens acidized from samples of this bed, the element has suffered some abrasion and the original outline is not preserved. However, several attributes of the interior and posteromedial surface are well defined. A portion of the anteromedial surface has been broken away to reveal unusually long extensions of the ampullae of the anterior vertical and horizontal semicircular canals (Fig. 12-F). The latter is enlarged completely from its juncture with the anterior vertical semicircular canal to the facet that abuts the opisthotic. This is significantly different from the small canals that can be seen in the otic capsules of *Clidastes*, *Tylosaurus* or *Platecarpus* (Russell, 1967:35-37). A well-preserved small pit with several foramina marks the position of the macula within the utricle. The seventh cranial nerve, or facial nerve, enters the bone medially below the utricle and exits posteriorly from within a prominent, long, narrow groove in the posterior edge of the element (Fig. 12-E). Another unusual feature is a rough, circular pit laterally adjacent to the position of the prootic portion of the groove for the fenestra ovalis. In life, the pit may have accepted a sutural peg from the opisthotic. The element cannot be referred to any currently known mosasaur taxon.

A partial right splenial, TMM 43352-14 (Fig. 12-G), was reassembled from several fragments picked from acidized concentrate and a large portion still adhering to a calcarenite block. It is from the basal calcarenite/vertebrate hash bed at the Hot Springs Locality. Although a bit ragged, it does preserve the medial foramen, the posterior part of the medial wing, and the posterior articular surface for the angular. The medial wing rises at a relatively low angle anteriorly similar to the condition seen in a complete plioplatecarpine skull from just above the "Kamp Ranch Limestone member" near the "1382 Locality." The angular articular surface is an inverted triangle and has a relatively short vertical extent. The complete plioplatecarpine skull has a somewhat expanded ventrolateral edge, giving a more oval shape to the articulation and a higher posterior profile. These two specimens are probably very similar in age, but the splenial from the Hot Springs has a more conservative appearance. The splenial is probably from an early "russellosaurine" or an early plioplatecarpine.

Three jaw fragments without teeth are from the lower sand unit of the Turner Sandy Member of the Carlile Shale. One, SDSM 35015 (Fig. 12-D), was found in a conglomeratic lag about 2 meters above the base of the member (Fig. 3) west of Edgemont, Fall River County, South Dakota. Two tooth bases and portions of two tooth sockets are preserved on this fragment. It also exhibits one posteromedial resorbtion pit. The edge opposite the tooth row is also incomplete. The two other jaw fragments (SDSM 35016, 35017) are from near Upton, Weston County, Wyoming. Each preserves only a single tooth base, but the larger one has a resorption pit. It is impossible to determine the relationships of these fragments to other mosasaurs, except that their size indicates they are significantly more derived than aigialosaur-grade mosasauroids.

Relatively large mosasaur-grade teeth have been found at several localities. The oldest from the Black Hills region, SDSM 35018 (Fig. 4-B) was found in acidized concentrate from the shelly calcarenite bed approximately 5 meters below the top of the Pool Creek Member of the Carlile Shale west of Edgemont, South Dakota. It is conical, slightly recurved and bears distinct carinae on the anterior and posterior faces. There are numerous fine striations on the enamel surface especially distinct on the posteromedial face. It is certainly referable to "Russellosaurinae." Several rather abraded teeth were recovered along with one of the jaw fragments noted just above. Two are shown in Figure 5-C (SDSM 35019) and Figure 5-F (SDSM 35020). As many as 20 mosasaur teeth have been found in the "Shark Tooth Conglomerate" at SDSM locality V897, but many are so abraded that characters of the surfaces cannot be determined. SDSM 35020 does have enough enamel left to preserve fine posteromedial striations, indicating it should be referred to "Russellosaurinae." Several russellosaurine teeth, TMM 43352-16, were recovered from the basal calcarenite/vertebrate hash bed at the Hot Springs Locality and one, TMM 43056-12 (Fig. 4-A), from the same horizon at the Ernst Tinaja Locality. More were found in calcarenite samples from near the base of the shale/calcarenite interval (TMM 43359-4) and 14.3 meters above that (TMM 43342-1) on the flanks of "The Solitario." Others (TMM 43209-3) were found while screen washing for fragments of one of the "1382 Locality" skeletons. A tooth base without a crown, TMM 43352-17, from the basal calcarenite/vertebrate hash bed at the Hot Springs is sufficiently large and well ossified to indicate its derived mosasauroid affinities. The opening of the pulp cavity has been enhanced by abrasion and exposes the very base of the dentinal core, which exhibits marked infolding of the walls of the cavity (Fig. 4-D). The condition is very similar to that within varanoid lizards. This is the only known mosasaur specimen which demonstrates this feature and is the first evidence of this potential synapomorphy which might imply close common ancestry between varanoids and mosasaouroids.

Bell (1995:36) reported two mosasaur caudal vertebrae (TMM 43352-2, 43352-3) from the shale/calcarenite interval at the Hot Springs in BBNP. The presence of an articulating hemal arch in one suggested it could be referable to "Russellosaurinae." Here we report another relatively well preserved caudal with hemal articulations, TMM 43352-18, from the basal calcarenite/vertebrate hash bed at the same locality. The centrum is uniformly round in anterior and posterior views (Fig. 12-A). The hemal articulations are prominent in extending ventrolaterally beyond the curvature of the cylindrical centrum (Fig. 12-B). There are small bases of very reduced transverse processes (Fig. 12-C), indicating the vertebra was positioned just anterior to the midpoint of the tail in life. The centrum appears somewhat long (relative to its diameter) for that position. Measurements for the centrum are: ventral interarticular length - 19 mm, anterior cotylar height - 15 mm, anterior cotylar width - 16 mm. This vertebra is also referable to "Russellosaurinae."

Three vertebrae are from the upper few meters of the Sage Breaks Member of the Carlile Shale west of Edgemont. Two, SDSM 35021 (Fig. 11-G, H), and SDSM 35022, (not figured) are from the mid- to posterior trunk and were found *in situ*. They are somewhat large for Turonian mosasaurs; SDSM 35021 has an interarticular length of 61 mm, SDSM

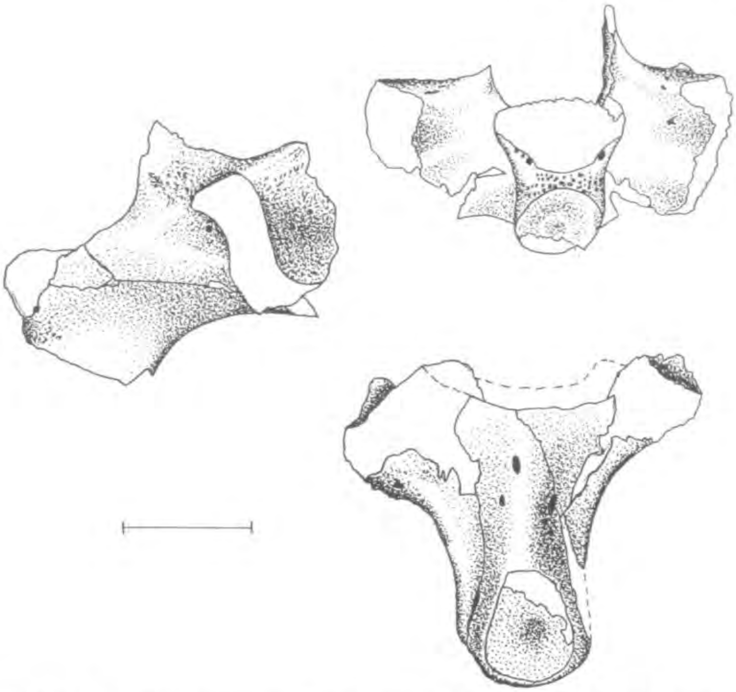


FIGURE 8 - Basal mosasauroid cervical vertebra, TMM 43056-7, in right lateral, posterior, and ventral views proceeding clockwise from left, from 32 m above base of Ernst Member, Boquillas Fm., at Ernst Tinaja, BBNP. Bar scale is 5 mm.

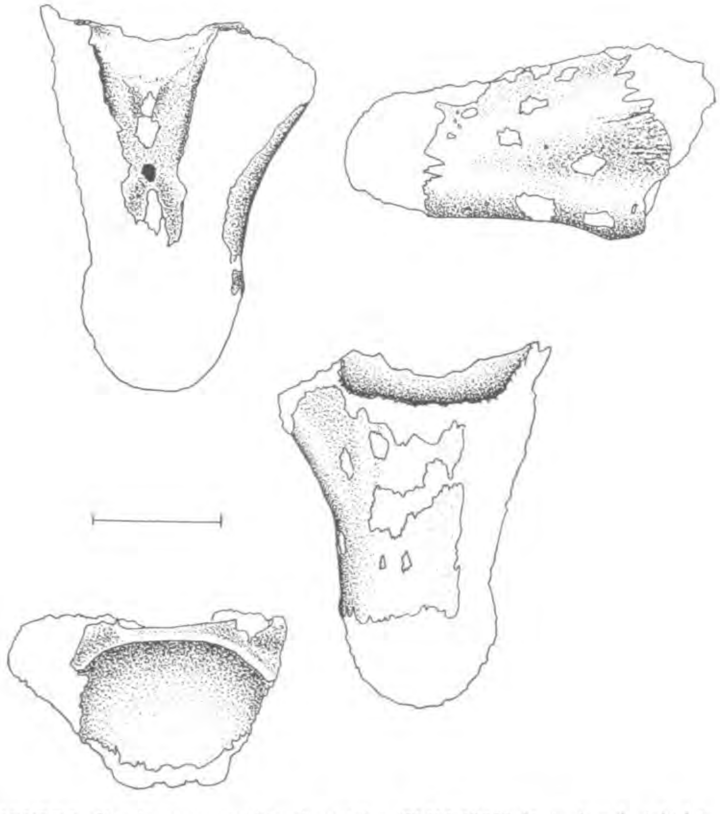


FIGURE 9 - Basal mosasauroid trunk vertebra, TMM 43352-11, in dorsal, right lateral, ventral, and anterior views proceeding clockwise from upper left, from 38 m above base of Ernst Member, Boquillas Fm., Hot Springs, BBNP. Bar scale is 5 mm.

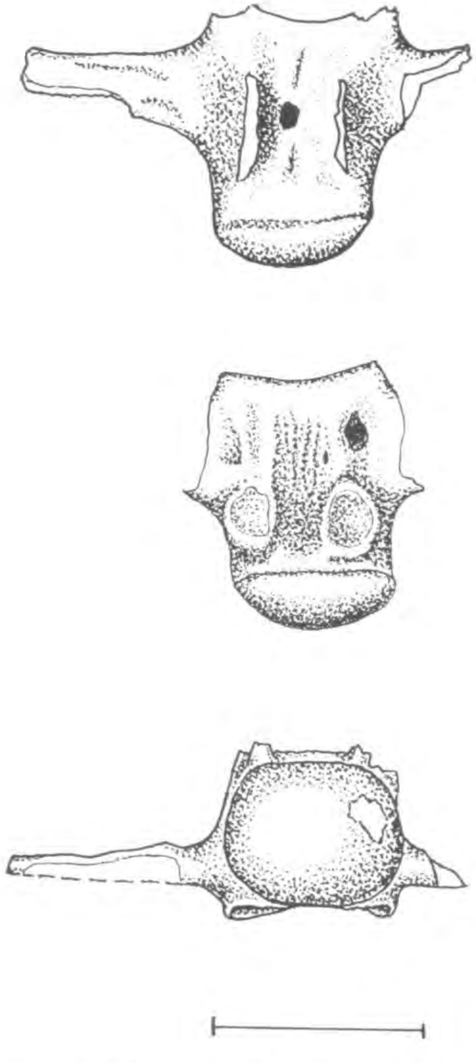


FIGURE 10 - Basal mosasauroid anterior caudal vertebra, TMM 43056-4, dorsal, ventral, and posterior views in descending order, from 33 m above base of Ernst Member, Boquillas Fm., at Ernst Tinaja, BBNP. Note ventral articulations for hemal arches. Bar scale is 5 mm.

35022 has an interarticular length of 107 mm. A vertebra (KUVP 6176) from the late middle Turonian Blue Hill Shale Member of the Carlile Shale reported by Martin and Stewart (1977) and tentatively described as having "affinities with the *Clidastes* group," is 65 mm long or about the same size as SDSM 35021. The two Sage Breaks trunk vertebrae are compacted dorsoventrally. Unfortunately, there is little information that can be extracted from them, because they have also suffered damage from gypsum growth while weathering near the surface. The third vertebra (SDSM 35023) was found as float and is a fragmentary posterior caudal with an interarticular length of 23 mm. There is an indication of an articular facet for a hemal arch on its left ventrolateral margin, but physical damage has destroyed the definite evidence for such. The large size of SDSM 35022 suggests relationships with large tylosaurine mosasaurs and a possible hemal articulation on SDSM 35023 reinforces the possibility of the presence of a "russellosaurine" mosasaur.

CONCLUSIONS

At least one type of aigialosaur-grade mosasauroid had immigrated into the Black Hills region by the time Greenhorn deposition ceased there. Ammonite evidence places this within, but well below the top of, the *Collignoniceras woollgari* Zone of early middle Turonian age. The radiometric age of this occurrence, interpolated from data presented by Obradovich (1993, fig. 2) is 92 Ma. Perhaps between one quarter and one half million years later, at the time of the beginning of the *Prionocyclus percarinatus* Zone, at least one type of derived "russellosaurine" mosasaur was present in the area. This derived form was temporally and spatially sympatric with at least one type of basal mosasauroid. Current evidence indicates this diversity persisted into the early late Turonian. Significant numbers of "russellosaurine" teeth in coarsely clastic deposits of that age may suggest increased population numbers or perhaps a preference for nearshore habitats. Presence of a very large vertebra near the top of the Carlile Shale implies that tylosaurines may have evolved or moved into the region by the close of Turonian time.

In the western Tethyan region and near the southern end of the Western Interior Cretaceous Seaway in Texas, there is evidence that the mosasauroid fauna was more diverse and probably held greater population numbers. Unfortunately, the biostratigraphic correlation and inferred radiometric age of the rocks containing that fauna are not well constrained. The fauna is certainly no younger than the *Coilopoceras springeri* Subzone of the *Prionocyclus hyatti* Zone, which has been radiometrically dated at 90.51 +/- 0.45 million years (Obradovitch, 1993). However, the fauna may be older, perhaps even as old as early Turonian. At least three types of basal mosasauroids are present in the fauna. Each type exhibits at least one character shared with each of the three main clades of derived mosasauroids: Halisauromorpha, "Russellosaurinae," and Mosasaurinae. This is an interesting circumstance, but should not be taken as reliable evidence that ancestors of all the derived mosasaur clades are present within the fauna. There is much homoplasy evident within the evolutionary history of mosasaurs and these basal representatives are much too incomplete to make such a leap of faith. In addition, this same fauna may include two types of relatively conservative "russellosaurines," one of which is derived along the plioplatecarpine lineage. Again lack of biostratigraphic indicators causes equivocation in the inferred temporal sympatry of these two morphologically distinct mosasaurs.

However, if the two "russellosaurines" are temporally sympatric, it would imply that diversification began within that clade no later than the middle Turonian. Additional evidence supporting this hypothesis is that no verifiable evidence of the presence of mosasaurine mosasaurs can be found in the Turonian record. Martin and Stewart (1977) implied their vertebrae might be related to *Clidastes*, but did not come to a definite conclusion. Stewart and Bell (1994) found that Texas material referred to *Clidastes* from the Cenomanian of northeast Texas (Stenzel, 1944) was actually remains of a teleost. Another specimen, referred to *Mosasaurus* by Adkins (1923), and reported to have been found near the Austin Chalk-Eagle Ford Fm. contact, was found in Sweden and is being prepared. It is distinctly a basal plioplatecarpine mosasaur. The record of *Mosasaurus iembeensis* from the late Turonian of Angola has proven to be a tylosaurine (Lingham-Soliar, 1992:182; Bell, 1993b) and it occurs with a plioplatecarpine, *Angolosaurus bocagei* (Antunes, 1964). In addition, the only known Turonian mosasaur from South America, *Yaguarasaurus colombianus*, is a plioplatecarpine. At present, the best data available suggest that the first mosasaur radiation occurred within "Russellosaurinae" during the middle to late Turonian Stage of the Cretaceous Period.

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ADMINISTRATIVE RESPONSIBILITIES

Localities around Belle Fourche Reservoir in Meade County, South Dakota are on lands administered by the U.S. Department of the Interior - Bureau of Reclamation. Those west of the town of Edgemont, Fall River County, South Dakota lie on Buffalo Gap National Grassland administered by the U.S. Department of Agriculture - U.S. Forest Service. The Upton, Weston County, Wyoming locality lies on a portion of the Thunder Basin National Grassland, also administered by the U.S.D.A. - U.S.F.S. Through various memoranda of understanding and challenge costshare agreements with these agencies, the Museum of Geology of the South Dakota School of Mines and Technology has the responsibility to collect and curate fossil specimens, and maintain collection records derived from each resource area.

Big Bend National Park is administrated by the U.S. Department of the Interior - U.S. Park Service and collections derived therefrom are curated, maintained, and archived by permit to the Vertebrate Paleontology Laboratory (Texas Memorial Museum) of the University of Texas at Austin. Collections were made in Big Bend National Park under Resource Activity Permits 91-BIBE-1(P) and 93-BIBE-045. The primary author has placed some of the fossil materials from the "1382 Locality" in the collections at TMM, and wishes to thank Chuck Finsley and Tony Fiorillo of the Dallas Museum of Natural History for loans of other material from that locality.

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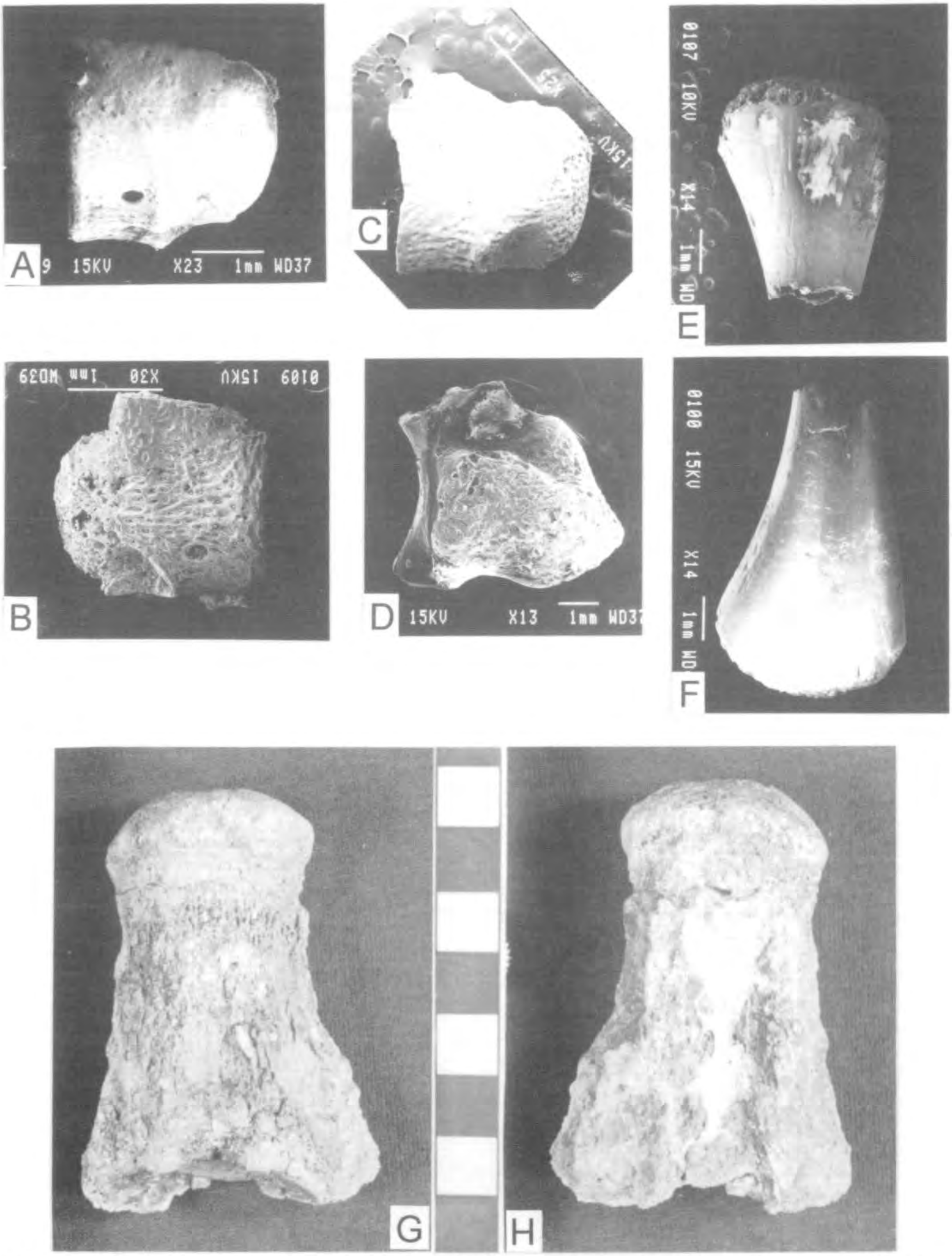

FIGURE 11 - SEM photomicrographs of basal mosasauroids A-F, and mosasaur (G-H). A, basal mosasauroid posterior caudal vertebra, TMM 43352-12, left lateral view, from 38 m above base of Ernst Member, Boquillas Fm., at Hot Springs, BBNP. Articulation for hemal arch present in lower right. B, basal mosasauroid posterior caudal vertebra, SDSM 35014, right lateral view, from shelly calcarenite bed approximately 5 m below top of Pool Creek Member, Carlile Shale near Edgemont. Articulation for hemal arch present in lower left. C, basal mosasauroid posterior caudal vertebra, TMM 43209-2, left lateral view, from 1 m above "Kamp Ranch Limestone member," Arcadia Park Fm. at "1382 Locality" near Dallas. Articulation for hemal arch present in lower right. D, basal mosasauroid left atlas neural arch, TMM 43352-15, medial view with anterior to right, from 38 m above base of Ernst Member, Boquillas Fm., at Hot Springs, BBNP. E, basal mosasauroid proximal right humerus, TMM 43352-13, dorsal view, from same bed and locality as D above. F, same specimens as E above, distal right humerus in dorsal view. Ectepicondylar groove is seen as bright streak in lower right corner of element. G, mosasaur trunk vertebra, SDSM 35021, in ventral view with posterior up, 2 m below top of Sage Breaks Member, Carlile Shale at SDSM locality V936 west of Edgemont. H, same specimen as G above, dorsal view. Use only bar scales for dimensions in A-F. Bar scale in G and H is in increments of 1 cm.

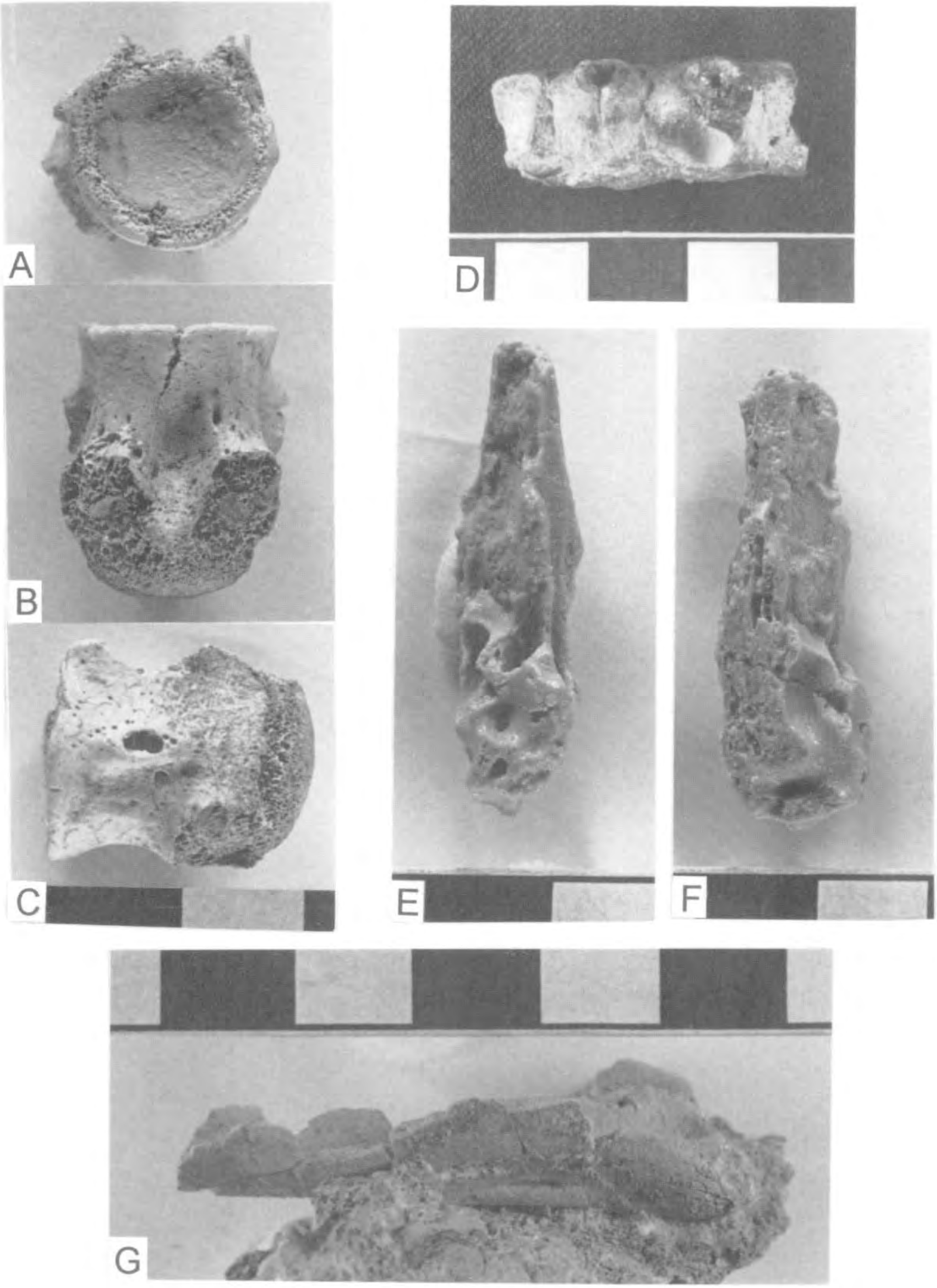

FIGURE 12 - Mosasaur skeletal elements. A, "russellosaurine" mosasaur caudal vertebra, TMM43352-18, anterior view, from 38 m above base of Ernst Member, Boquillas Fm., at Hot Springs, BBNP. B, same specimen as in A above, ventral view. C, same specimen as in A above, left lateral view. Note hemal articulations visible in B and C. D, mosasaur jaw fragment, SDSM 35015, medial view, from from "Shark Tooth Conglomerate" bed near base of Turner Sandy Member, Carlile Shale, SDSM locality V897 near Edgemont, Fall River Co., South Dakota. Resorption pit is visible on base of right tooth. E, mosasaur right prootic, TMM 43352-1, posterior view, from 38 m above base of Ernst Member, Boquillas Fm., at Hot Springs, BBNP. F, same specimen as in E above, medial view. Note large, curved ampullar regions of semicircular canals that converge in lower right. G, mosasaur right splenial, TMM 43352-14, medial view, from 38 m above base of Ernst Member, Boquillas Fm., at Hot Springs, BBNP. All bar scales are in increments of 1 cm.

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FOSSIL REPTILES FROM THE LATE CRETACEOUS GREENHORN FORMATION (LATE CENOMANIAN-MIDDLE TURONIAN) OF THE BLACK HILLS REGION, SOUTH DAKOTA

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ABSTRACT--A variety of sampling techniques has yielded a moderately diverse marine reptile fauna from the early late Cenomanian-early middle Turonian Greenhorn Formation in western South Dakota. Ages are based on ammonites found at various stratigraphic levels within the formation. Here we report the first North American occurrence of the large pliosaur, *Polyptychodon interruptus*; a new unnamed pliosauroid; and the oldest polycotylid from the Black Hills region. First records for the Greenhorn include a pterodactyloid wing metacarpal and a chelonioid costal. We note the presence of the aquatic lizard, *Coniasaurus crassidens*, at the base of the formation and just below the Cenomanian-Turonian boundary. Teeth of plesiomorphic (aigialosaur-grade) mosasauroids were recovered at the very top of the formation. This is the first indication of basal mosasauroids in the Western Interior Cretaceous Seaway and most northerly Turonian occurrence documented in North America.

Sedimentological data suggest that highest abundances and diversity of marine reptiles are correlated with the basal transgressive phase of the Greenhorn. A reduced- diversity component of the earlier fauna recurs during a shallowing event just prior to the C-T boundary, but none of those taxa have been observed to occur later. Presence of a neonatal chelonioid and mosasauroids that are relatively unadapted to open marine conditions suggest a very shallow, nearshore environment at the close of Greenhorn deposition.

INTRODUCTION

The Greenhorn Formation was deposited in the middle of a north-south trending epeiric seaway in the late Cretaceous Period between the stable craton on the east and the cordilleran mobile belt on the west (MacDonald and Byers, 1988). The formation is characterized by thin, widespread, burrow mottled limestones, calcarenites, intercalated calcareous shale and bentonites (Weimer, 1978). Exposures of the Greenhorn Formation crop out extensively in Colorado, Kansas, Wyoming, Nebraska, South Dakota, and northern New Mexico. Greenhorn carbonates are thought to have been deposited far from the nearest shorelines in relatively deep, mostly quiet water environments where pelagic sedimentation prevailed. However, there is considerable debate about water depth during Greenhorn deposition. Kauffman (1969) and Hattin (1975), on the basis of geological structures and microinvertebrates, suggest environments of deposition of mid- to outer shelf depths (100-200 m maximum) except during regression when the depth was shallower. Eicher (1967) suggested, based on reconstructed slope measurements and microinvertebrates, that water depth of the sea at maximum transgression was 2000 - 3000 ft. (915 m).

The Black Hills region is the site of a facies change in the Greenhorn between carbonate rich facies to the south and east and clay rich facies to the west (Hattin, 1975; MacDonald and Byers, 1988). The Greenhorn Formation in western South Dakota is dominantly marl to calcareous shale with abundant limestone concretions, thin to moderately thick limestone beds, and bentonites. West of this area the unit grades into noncalcareous shales of the Marias River, Frontier, and Mancos formations. There is a difference in the formation between the northern and southern Black Hills which may be due to the diachronous deposition of the Greenhorn in the basin or possibly an unconformity. Cobban (1951) described the formation in the northern Black Hills using four informal lithologic units. The formation reaches its maximum known thickness of 110 m in Crook County, Wyoming. The maximum measured thickness of the formation in the southern Black Hills at Angustora Reservoir is 63 m. The "X" bentonite appears to be missing in the northern Black Hills; whereas, it is present at the base of the formation in the southern Black Hills. There may also be an unconformity at the top of the formation in the northern hills, indicated by a vertebrate lag bed and abrupt change from light colored limestones and marls to dark shales. The top of the formation is difficult to identify in the southern Black Hills due to a gradational interval of 18 m of highly clastic carbonates below typical black noncalcareous shales of the Pool Creek Member of the Carlile Shale.

The Greenhorn Formation of western South Dakota shares many of the same ammonite zones as the type section in southern Colorado near Pueblo. The basal bed of the formation in the northern Black Hills is in the *Dunveganoceras pondi* Zone that is early late Cenomanian in age. The uppermost beds, in the northern Black Hills, are in the *Collignoniceras woollgari* Zone that is of early middle Turonian age (Obradovich, 1993). The base of the formation is older in the southern Black Hills where the ammonite *Plesiacanthoceras wyomingense* has been found in the basal part of the Orman Lake Member, indicating a late middle Cenomanian age. Based on this ammonite zonation, the age of the Greenhorn in western South Dakota is considered to be late middle Cenomanian to early middle Turonian.

The vertebrate fauna, especially the teleosts and elasmobranchs, of the Greenhorn Formation in the Black Hills region is similar to the fauna present in the equivalent-aged Eagle Ford Group and Boquillas Formation of Texas, and the Greenhorn Formation in Kansas. However, the marine reptile fauna in the Black Hills region is more diverse than other regions of equivalent-aged rocks. The purpose of this article is to document the apparent diversity of the reptile fauna and consider its paleoecological implications.

Abbreviations: **USNM,** United States National Museum, **SDSM,** South Dakota School of Mines, **FHSM,** Fort Hays, Sternberg Museum, **KUMNH,** Kansas University Museum of Natural History.

FOSSIL RECOVERY METHODS

Recovery methods for microvertebrates consisted of quarrying calcarenites and breaking the slabs up into sizes that could be placed in 1 or 2 gallon ziploc bags for easy transport. The samples were dissagregated in a 10% solution of acetic acid, and then rinsed in water to remove calcium acetate from the concentrated material. After drying, the fine-grained fraction was removed using 0.3 mm sieves. The fraction larger than 0.3 mm were picked by hand using a binocular microscope. Macrovertebrates were collected using standard paleontological field techniques.

GREENHORN FORMATION LOCALITIES

Specimens were collected from several localities from around the eastern portion of the Black Hills Uplift in western South Dakota (Fig. 1). Precise locality information is on file with the Museum of Geology, South Dakota School of Mines and Technology, Rapid City. Localities around Belle Fourche Reservoir and Angustora Reservoir are located on U.S. Department of Interior- Bureau of Reclamation lands. Localities west of Edgemont, South Dakota, are located on U. S. Department of Agriculture- U. S. Forest Service holdings in the Buffalo Gap National Grasslands. The Haas plesiosaur(s)(AMM 98.1.1) were collected in 1934 from near Fruitdale, South Dakota, south of Belle Fourche Reservoir on private land. A plesiosaur, SDSM 35009, was collected from a right of way for a county road near Fairburn, South Dakota.

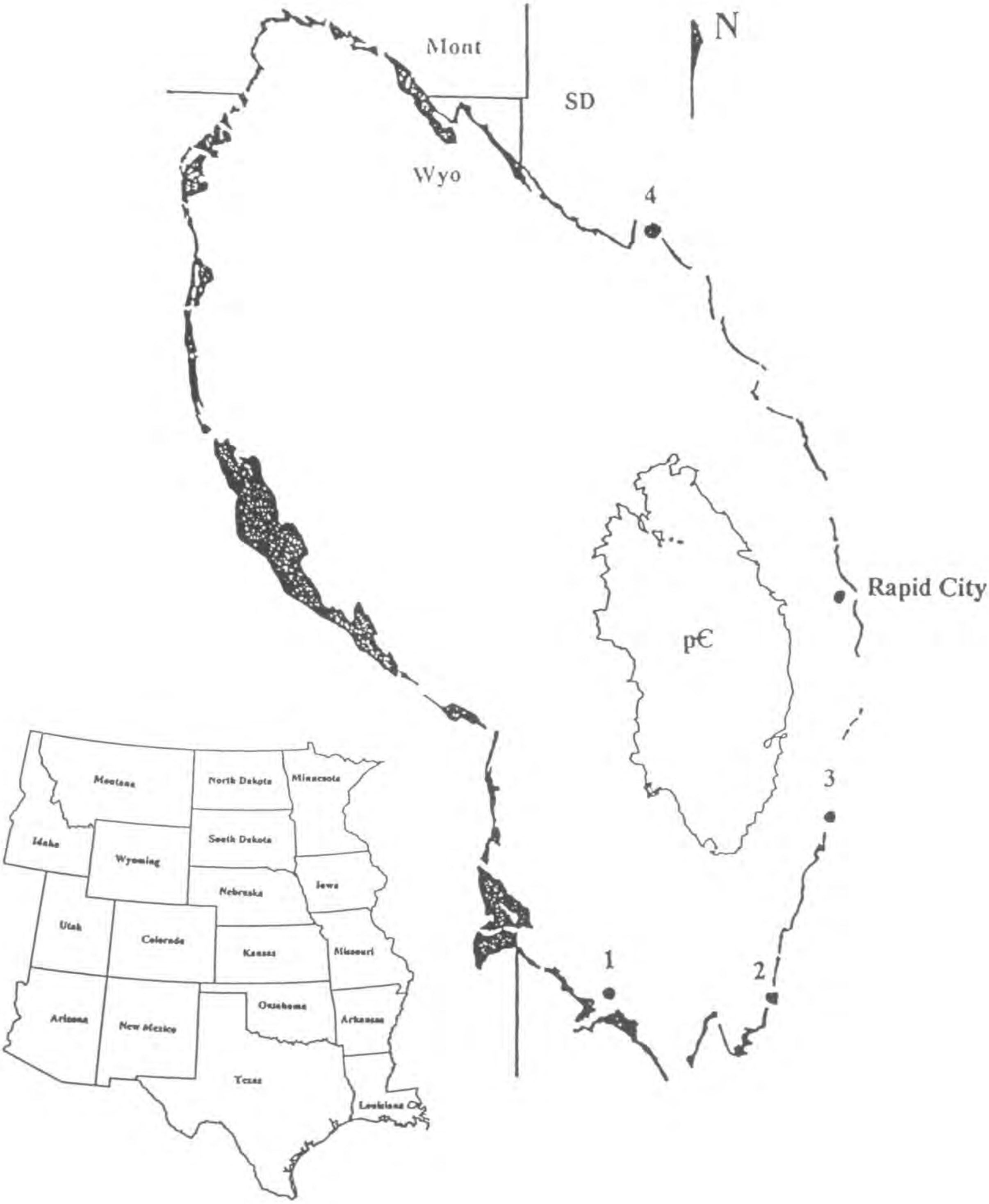


FIGURE 1 - Greenhorn Formation outcrops around the Precambrian core of the Black Hills Uplift. Numbers denote collection areas: 1 - Edgemont, Fall River County, South Dakota; 2 - Angustora Reservoir, Fall River County, South Dakota; 3 - Fairburn, Custer County, South Dakota; 4 - Belle Fourche Reservoir (Orman Lake), Butte County, South Dakota. Inset- Boxed area for regional reference to the location of the Black Hills Uplift.

PREVIOUS COLLECTIONS OF MARINE REPTILES FROM THE GREENHORN FORMATION

Previous research on vertebrates from the Greenhorn age equivalent rock units have focused on the classic exposures of the Greenhorn Formation in Kansas and the Eagle Ford Group of Texas. The only vertebrates that have been studied in any detail are the elasmobranchs (Meyer, 1974; Welton & Farrish 1992; Williamson et al., 1993). Previous research on reptiles focused on plesiosaurs. The Cretaceous North American plesiosaurs are divided into three families: Elasmosauridae, Pliosauridae, and Polycotylidae, and representatives of each of these families have been found in the Greenhorn Formation or equivalent-aged formations of the Western Interior Seaway. The large pliosaur *Brachauchenius lucasi* (USNM 4989, 2361) was found in the Greenhorn Formation in Kansas and the Bouldin Member of the Lake Waco Formation of Texas (Williston, 1903, 1907). Another pliosaur that has been referred to *Brachauchenius lucasi* is FHSM VP321 from upper Greenhorn of Kansas (Carpenter, 1996a, b). Welles and Slaughter (1963) reported the first occurrence of *Polyptychodon* in North America and described *P. hudsoni* from the Arcadia Park Member of the Eagle Ford Shale (Storrs, 1981).

Polycotylids make their first appearance in the Western Interior Seaway during Greenhorn deposition. Cragin (1888, 1891) described *Trinacromerum bentonianum* from the Fencepost Limestone bed at the top of the Kansas Greenhorn. *Trinacromerum willistoni* (KUMNH 5070) was described by E.S. Riggs from the Hartland Shale Member of the Kansas Greenhorn (Riggs, 1944). *Trinacromerum anonymum* was described by Williston based on a specimen that was collected from the Benton Cretaceous of Osborne County, Kansas, in 1873 by the Yale Peabody Museum (Williston, 1908). The paratype of *Trinacromerum anonymum* is from the lower Turonian Jetmore Member of the Greenhorn Formation in the Kansas section (Carpenter, 1996a, b). *Ceraunosaurus brownorum* was described from the Lake Waco Formation of the Eagle Ford Group in Texas (Thurmond, 1968; Storrs, 1981; Carpenter, 1996a). *Trinacromerum kirki* is from the lower middle Turonian Assinibone Member of the Favel Formation of Manitoba, Canada (Russell, 1935).

Only two taxa of elasmosaurs have been previously described in the Greenhorn or its equivalents in the Western Interior Seaway. *Elasmosaurus morgani* (= *Libonectes*) was described from the uppermost Eagle Ford Shale (Welles, 1949; Carpenter, 1996a, 1997). *Alzadasaurus riggsi* is from the Benton Cretaceous near Alzada, Montana (Welles, 1952; Carpenter, 1996a; Riggs, 1939).

Desmatochelys lowi has previously been described from the Benton Cretaceous of Nebraska and the Mancos shale of northern Arizona. This taxon has also been described from the Carlile Formation of eastern South Dakota and the Campanian of Vancouver Island (Williston, 1894; Zangerl and Sloan, 1960; Nicholls, 1992; Irby et al., 1994; Elliott et al., 1997). The only other previously described turtle of similiar age is *Protostega eaglefordensis* from the Eagle Ford Shale of Texas (Zangerl, 1953).

Coniasaurus crassidens is the only squamate described from the Greenhorn in the Western Interior Seaway (Bell, 1993). This lizard has been described from the Eagle Ford Group of Texas, Boquillas Formation of west Texas, Greenhorn Formation of South Dakota, and the Lower Chalk Group of southeast England (Bell et al., 1982; Bell and Polcyn, 1996; Martin et al.,1996; Caldwell and Cooper, in press).

SYSTEMATIC PALEONTOLOGY

TESTUDINES Linnaeus 1758

CHELONIOIDEA Baur 1893

Genus and Species indeterminate

(Fig. 4 A, B)

Referred material - SDSM 35010, one costal fragment.

Stratigraphic position - shell/vertebrate lag bed; at the Greenhorn/Carlile formational contact; Belle Fourche Reservoir, Butte County, South Dakota (Fig. 2).

Age - early middle Turonian, *Collignoniceras woollgari* Zone.

The only specimen that can be identified as turtle is a proximal fragment of a very small costal. The nature of the nutrient foramina and the presence of the circulatory grooves on this specimen would seem to indicate that this specimen is neonatal. Its thinness and strongly interdigitate sutural edges are typical of marine chelonioids. This is the first reported occurrence of a turtle in the Greenhorn Formation in South Dakota. The bed where the costal was recovered also contains many closely packed oysters, as well as subrounded and polished phosphate grains and teeth fragments, indicating a high-energy environment close to shoreline.

PLESIOSAURIA Blainville 1835

Indeterminate taxon

Referred specimen - SDSM 35008 two fragments of a plesiosaurian pectoral or pelvic girdle.

Stratigraphic position - basal calcarenites, Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota (Fig. 3).

Age - early late Cenomanian, *Dunveganoceras pondi* Zone.

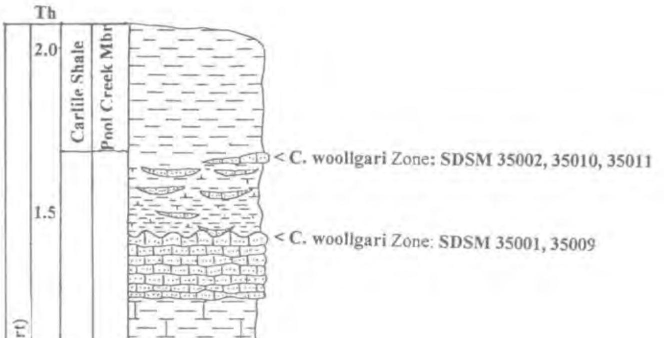
The fragmentary nature of these specimens makes it impossible to make an assignment below the order level.

Unnamed taxon

(Fig. 4 C, D; Fig. 5)

Referred specimens - AMM 98.1.1 skull with nearly complete front paddle, femur, and vertebrae. SDSM 35007 sixteen vertebrae, one femur and some miscellaneous bone fragments.

Stratigraphic position - AMM 98.1.1:basal Orman Lake Member, Greenhorn Formation, Fruitdale, Butte County, South Dakota; SDSM 35007:basal Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota (Fig. 2).



< C. woollgari Zone: SDSM 35002, 35010, 35011

< C. woollgari Zone: SDSM 35001, 35009

FIGURE 2 - Representative stratigraphic section for the uppermost Fourth member of the Greenhorn Formation in the northern Black Hills. Measured at Belle Fourche (Orman Lake) Reservoir, Butte Co., SD. Marine reptiles included in this report are indicated on the right. Th - indicates thickness in meters.

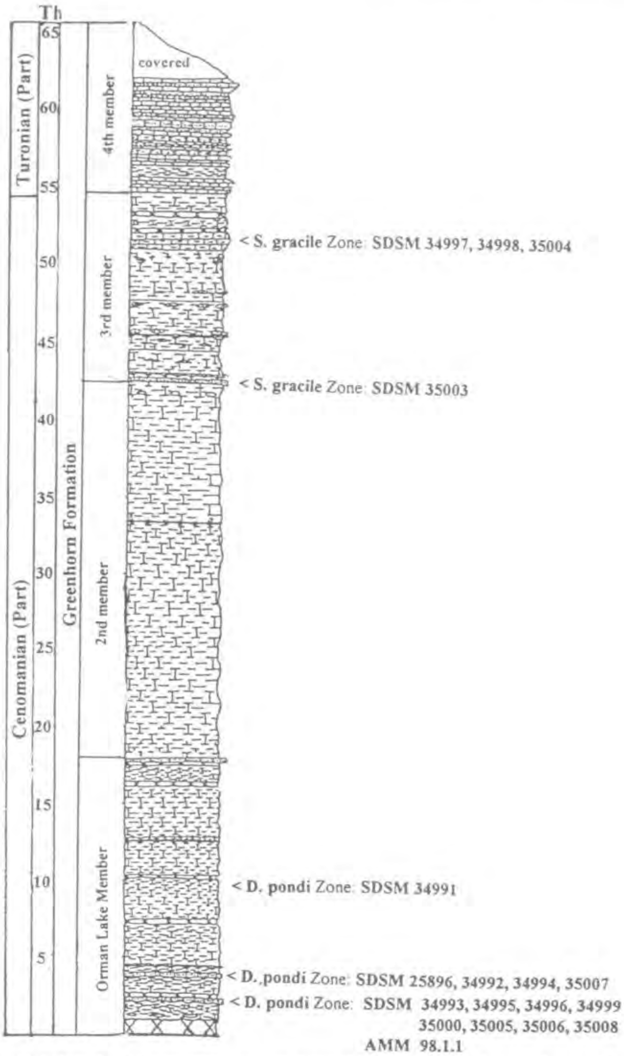


FIGURE 3 - Representative stratigraphic section for the southern end of the Black Hills. Measured at Angustora Reservoir, Fall River Co., SD. Position of Cenomanian-Turonian boundary is extrapolated from Elder's (1987) Hot Springs, Fall River Co., SD locality. Position and projected positions of marine reptiles included in this report are indicated on the right side of the column. Th- indicates thickness in meters.

Age - AMM 98.1.1 and SDSM 35007, early late Cenomanian, *Dunveganoceras pondi* Zone.

AMM 98.1.1 was collected from the basal Orman Lake Member, Greenhorn Formation, in 1934 by Mr. Charles C. Haas. This specimen is an unusual plesiosaur in that it appears to possess characters of both Polycotylidae and Pliosauridae. AMM 98.1.1 has a long snout and uniformly sized slender teeth like polycotylids. However, the palate is fully roofed without an anterior interpterygoid vacuity. The propodials are relatively long and slender and the radius and ulna are longer than wide, all of which are characters of pliosaurs. Its exact systematic position is yet to be determined. The specimen is in the process of being described by B. A. Schumacher and G.L. Bell, Jr.

Another set of ten vertebrae cataloged with this specimen belong to a different pliosaurid, possibly *Polyptychodon* or *Brachauchenius*. Correspondence from C. Haas indicated the latter specimen was from the same stratigraphic level only a mile from the first specimen. Length/width ratios of these vertebrae are significantly greater than those associated with the skull and paddle.

SDSM 35007 is probably from the Orman Lake Member, Greenhorn Formation, from around Belle Fourche Reservoir. There was no stratigraphic information with this specimen when it was donated to the Museum of Geology. The vertebrae and propodial proportions are similiar to those of the Haas plesiosaur. The femur has a proximal width of 103 mm and a total length of 308 mm. The vertebrae are too badly crushed to measure accurately. Based on the similiarities of the propodial and the vertebrae we believe this specimen can be referred to the same taxon as AMM 98.1.1.

PLIOSAURIDAE Seeley 1874
Polyptychodon interruptus Owen 1840
(Fig. 6 A, B)

Referred specimens - SDSM 34991, nearly complete mandible with posterior half of skull; SDSM 35004, one tooth 3/4 of the crown present; SDSM 35005, one tooth fragment; SDSM 35006, fragments of a mandible questionably assigned to *P. interruptus*.
Stratigraphic position - SDSM 34991: 80 cm below fourth bentonite seam from the base of unit; Orman Lake Member, Greenhorn Formation, Angustora Reservoir, Fall River County, South Dakota. SDSM 35004: calcarenite bed near middle of the third member; Greenhorn Formation, Edgemont, Fall River County, South Dakota. SDSM 35005:basal calcarenite of the Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota. SDSM 35006:basal Orman Lake Member, Greenhorn Formation, Fairburn, Custer County, South Dakota (Fig. 3).
Age - SDSM 34991:early late Cenomanian; *Dunveganoceras pondi* Zone; SDSM 35004:late Cenomanian; *Sciponoceras gracile* Zone; SDSM 35005:early late Cenomanian; *Dunveganoceras pondi* Zone; SDSM 35006 : early late Cenomanian.

SDSM 34991 has twenty-five teeth in each ramus, which are coarsely striated with unbranched striations from the tip of the crown to the base of the enamel. The reconstructed length of the mandible of SDSM 34991 is 145 cm. L.B. Tarlo (1960) in his review of upper Jurassic pliosaurs showed that tooth characters could be used in identification. Welles and Slaughter (1963) described *Polyptychodon hudsoni* as the first occurrence of the genus *Polyptychodon* in North America. The teeth of *Polyptychodon hudsoni* are coarsely striated like Owen's (1840) type material of *P. interruptus*; however, the main striations branch near the tip unlike *P. interruptus*. This branching is also found in the type of *Brachauchenius lucasi* (Williston, 1903, 1907) and a specimen referred to that taxon, FHSM VP321. *Polyptychodon hudsoni* and *Brachauchenius lucasi* are younger than SDSM 34991. SDSM 34991 is of late Cenomanian age and *B. lucasi* and *P. hudsoni* are of early to early middle Turonian age. Comparison of the teeth of SDSM 34991 with the type specimen of *Polyptychodon interruptus* show that both are without branching of main striations near the tip. In England, *P. interruptus* occurs in the Upper Greensand and Lower chalk (Owen, 1851, 1861, 1864) which is of lower and middle Cenomanian age (Mortimore, 1986). We refer SDSM 34991 to *Polyptychodon interruptus* because the teeth do not have branching stria. This specimen is currently being described by the authors.

POLYCOTYLIDAE Cope 1869
Indeterminate taxon
(Fig. 6 C)

Referred specimen - SDSM 35009, one tooth.
Stratigraphic position - oyster/vertebrate lag bed 6" below Greenhorn/ Carlile formational contact, Belle Fourche Reservoir, Butte County, South Dakota (Fig. 2).
Age - early middle Turonian, *Collignoniceras woollgari* Zone.

SDSM 35009 is a nearly complete tooth that is missing the tip of the crown. This tooth has fine striations running near the tip of the crown then terminating. The tooth is recurved and slender, and is similiar to teeth of *Trinacromerum bentonianum*, a polycotylid from the top of the Greenhorn Formation in Kansas. No other diagnostic material was found with this specimen. We refer SDSM 35009 to Polycotylidae because of the similiarity of this tooth to *T. bentonianum*.

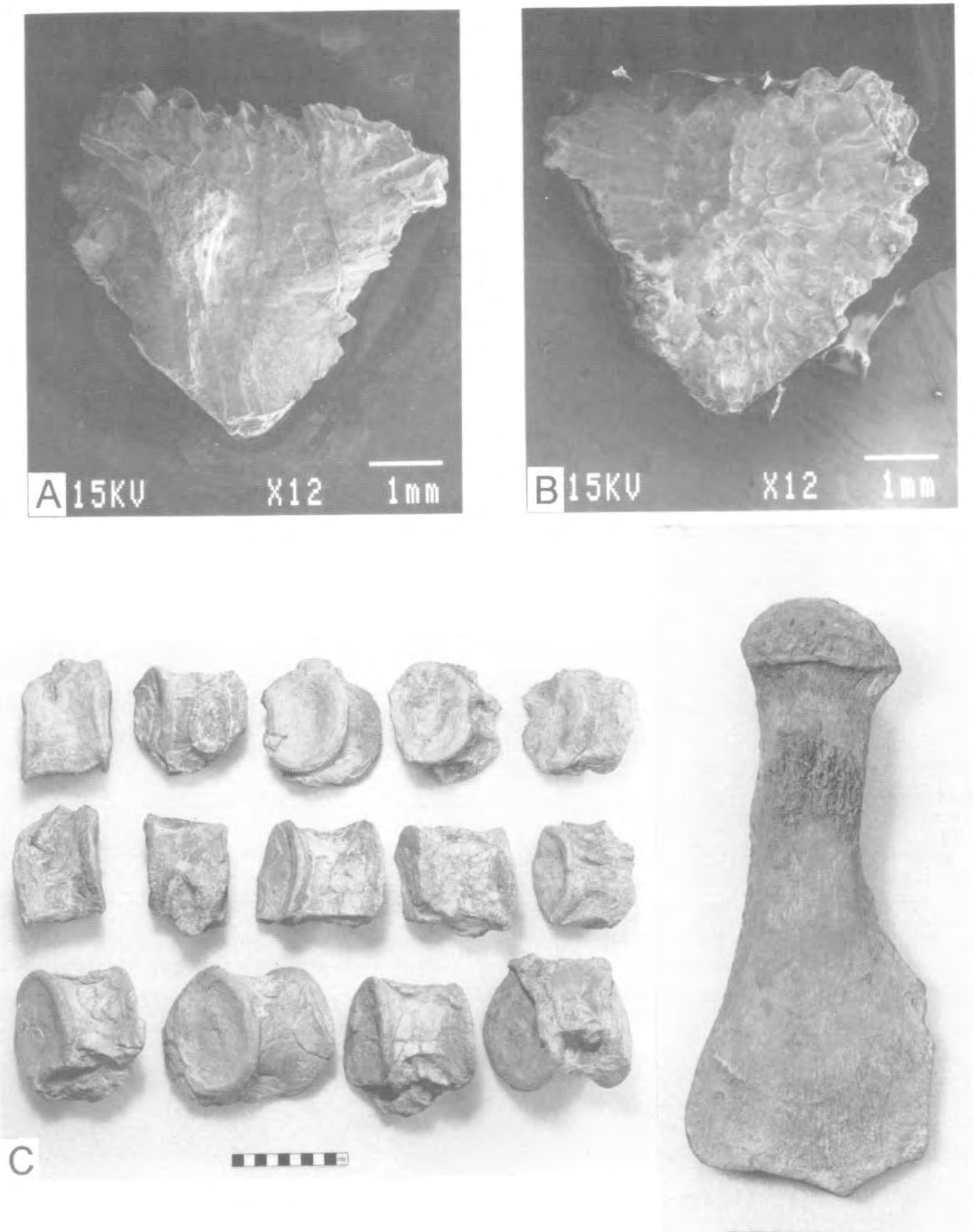


FIGURE 4 - A, Unidentified chelonioid costal, SDSM 35010: Ventral view. Scale bar = 1 mm; B, Unidentified chelonioid costal, SDSM 35010: Dorsal view. Scale bar = 1 mm; C, Unnamed pliosauroid miscellaneous vertebrae, SDSM 35007. Scale bar = 10 cm; D, Unnamed pliosauroid left femur, SDSM 35007. Dorsal view. Scale bar = 10 cm.

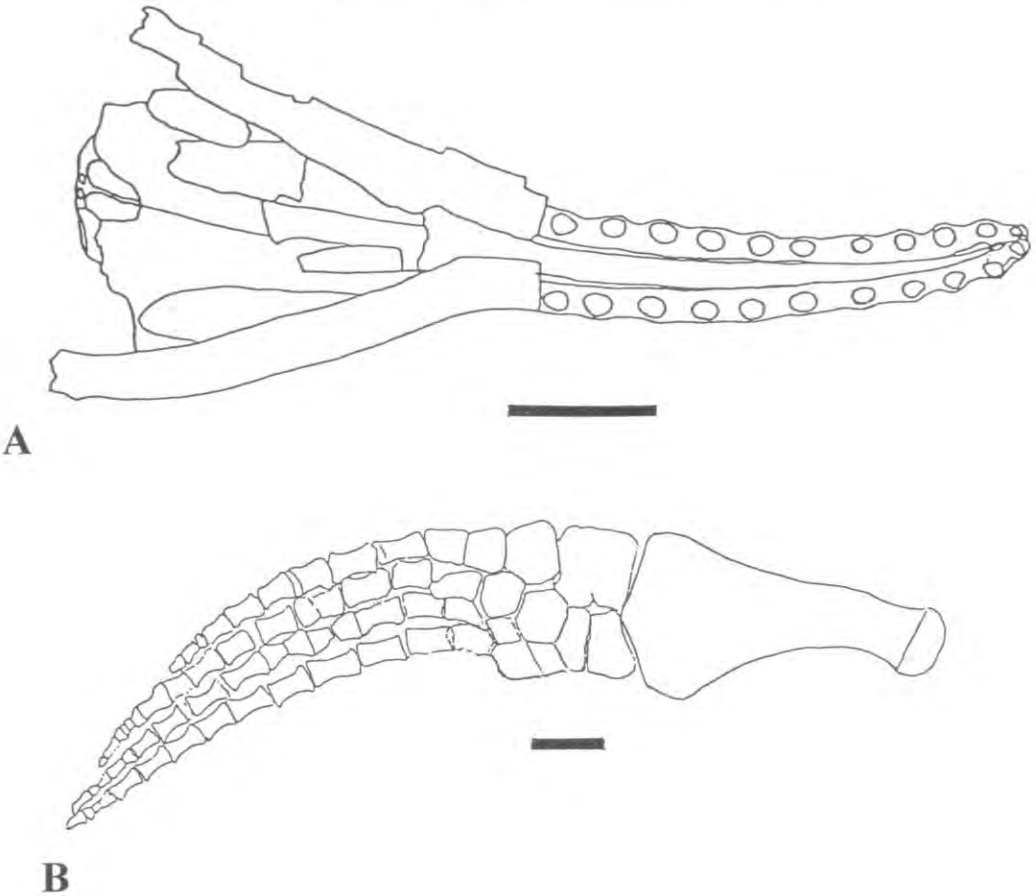


FIGURE 5 - Unnamed pliosauroid, AMM 98.1.1. A, Ventral view of skull with posterior portions of mandible in place. Scale bar = 10 cm; B, Left anterior paddle in dorsal view. Fifth digit is missing and ulna is broken transversely. Scale bar = 10 cm.

SQUAMATA Oppel 1811
?Squamata *incerte sedis*
(Fig. 6 D)

Referred specimen - SDSM 34992, one tooth.
Stratigraphic position - calcarenite bed immediately above the second major bentonite above the base of the Greenhorn Formation at Angustora Reservoir, Fall River County, South Dakota (Fig. 3).
Age - early late Cenomanian, *Dunveganoceras pondi* Zone.

This specimen is unlike any described fossil marine squamate tooth and may represent a new taxon. It is unusually slender, slightly accuminate, recurved, and has no carinae. Numerous coarse striations cover the middle of the crown but become very fine near the base and tip. The tooth is 5.7 mm in length including crown and a portion of the base. One other tooth of this type has been found in the late Cenomanian portion of the Boquillas Formation in Texas by the second author. This specimen is referred to Squamata based on a large, semilunate resorption pit similiar to most squamates. Although we acknowledge the possibility that this might be a teleost tooth, we note that the well-preserved, sharp tip does not exhibit any clear enameloid as is usually seen in that group.

DOLICHOSAURIDAE Gervais 1852
Coniasaurus crassidens Owen 1850
(Fig. 7 B-E)

Referred specimens - SDSM 25896, fragment of left maxilla with six teeth; SDSM 34993, one posterior half of a cervical vertebra, possibly juvenile; SDSM 34994, one mid caudal vertebra; SDSM 34995, one trunk vertebra, juvenile; SDSM 34996, one cervical vertebra; SDSM 34997, eight shed teeth; SDSM 34998, one shed tooth; SDSM 34999, one shed tooth; SDSM 35000, one anterior cervical vertebra.
Stratigraphic position - SDSM 25896 is from the basal Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota; SDSM 34993, basal calcarenite, Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir; Butte County, South Dakota; SDSM 34994, second calcarenite from base, Orman Lake Formation, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota; SDSM 34995, basal calcarenite, Orman Lake Member, Greenhorn Formation, Angustora Reservoir, Fall River County, South Dakota; SDSM 34996, basal calcarenite, Orman Lake Member, Greenhorn Formation, Angustora Reservoir, Fall River County, South Dakota; SDSM 34997, discontinuous calcarenite bed near the middle of the third member, Greenhorn Formation, Edgemont, Fall River County, South Dakota; SDSM 34998, calcarenite bed near middle of third member, Greenhorn Formation, Edgemont, Fall River County, South Dakota; SDSM 34999, basal calcarenites, Orman Lake Member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota; SDSM 35000, basal calcarenite, Orman Lake Member, Greenhorn Formation, Angustora Reservoir, Fall River County, South Dakota (Fig. 3).
Age - SDSM 25896, 34993, and 34994 early late Cenomanian, *Dunveganoceras pondi* Zone. SDSM 34995, 34996, and 35000 early late Cenomanian, *Plesiacanthoceras wyomingense/Dunveganoceras pondi* Zone. SDSM 34997 and 34998 late Cenomanian *Sciponoceras gracile* Zone.

The most common marine squamate in the Greenhorn Formation is the relatively poorly known lizard, *Coniasaurus crassidens*. The most

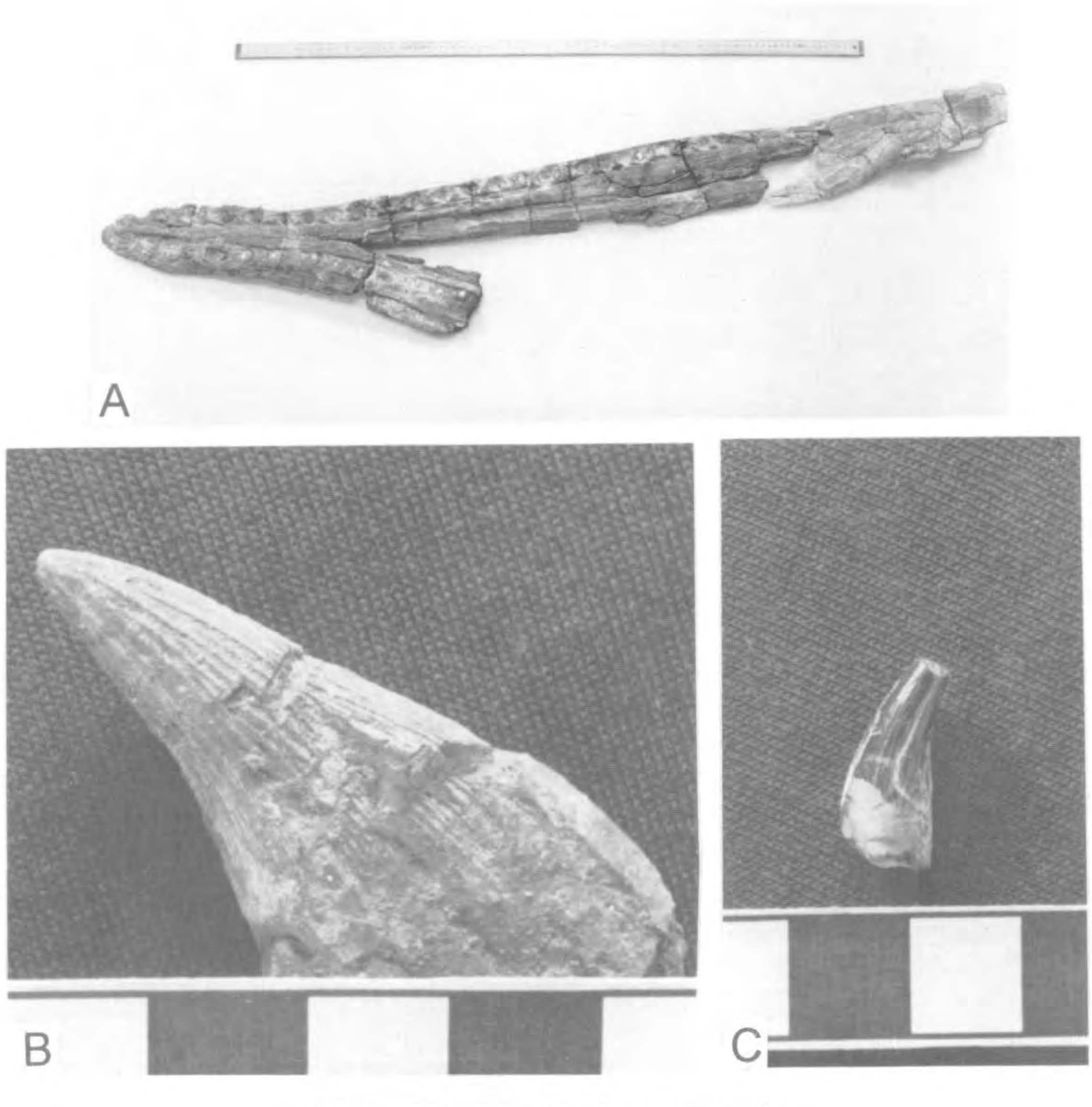


FIGURE 6 - A, *Polyptychodon interruptus* mandible, SDSM 34991. Dorsal view. Scale bar = 1 m; B, *P. interruptus* tooth crown, SDSM 34991, showing coarse unbranched striations. Scale in 10 cm increments; C, Tooth, indeterminate polycotylid. SDSM 35009, showing fine striations terminating low on crown. Scale in 10 cm increments; D, Tooth, indeterminate ?Squamata. SDSM 34992, showing resorption pit and striate enamel. Scale = 1 mm.

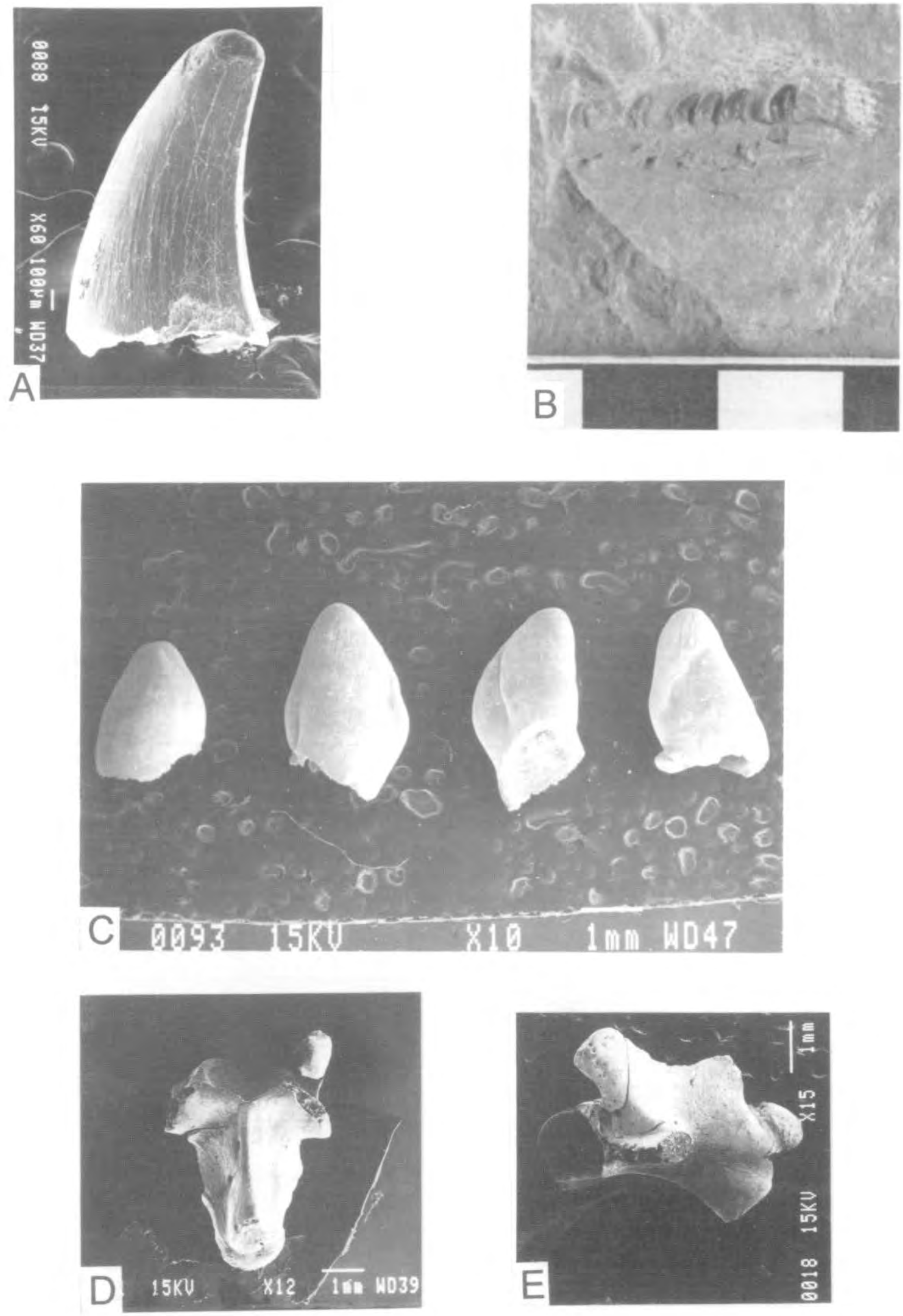


FIGURE 7 - A, Basal mosasauroid tooth, SDSM 35001. Posteromedial view showing striations and posterior carina. Scale = 1/10 mm; B - E, *Coniasaurus crassidens*: B, Portion of left maxilla with six teeth. SDSM 25896. Medial view. Scale in 10 cm increments; C, Shed teeth, SDSM 34997. From left to right: anterior, medial, lateral, and posterior views. Scale bar = 1 mm; D, Cervical vertebra, SDSM 35000. Ventral view. Scale bar = 1mm; E, Cervical vertebra, SDSM 35000. Left lateral view. Scale bar = 1mm.

common elements of this taxon found are shed teeth, occasionally an isolated vertebrae, or in the case of one unique specimen, a portion of the left maxilla. The teeth are bulbous and lingually expanded with fine crenulations on the anterodorsal; the crown also has a deep sulcus on the anterolateral (labial) face (Caldwell and Cooper, in press). *Coniasaurus* has subpleurodont implantation along the marginal tooth row. The vertebrae are procoelus with the condyle sloping posteriorly and slightly dorsal. Cervical vertebra have well developed, posteriorly positioned, fused hypapophyses (Bell et al., 1982).

MOSASAUROIDEA Camp 1923

Mosasauroidea *incerte sedis*

(Fig. 7 A)

Referred specimens - SDSM 35001, one basal mosasauroid tooth; SDSM 35002, one basal mosasauroid tooth; SDSM 35011, one basal mosasauroid tooth.

Stratigraphic position - SDSM 35001, calcarenite bed, uppermost fourth member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota; SDSM 35002 and SDSM 35011, vertebrate lag on top of oyster bed about 6" below Greenhorn/Carlile boundary, uppermost fourth member, Greenhorn Formation, Belle Fourche Reservoir, Butte County, South Dakota (Fig. 2).

Age - early middle Turonian, *Collignoniceras woollgari* Zone.

These recurved teeth have only a posterior carina. They lack the anterior carina commonly seen in more derived mosasauroids (Bell,1997). Anterodorsally there is a broadly swollen, rounded ridge in the position of an anterior carina. Fine, irregularly spaced striations trend the length of the crown; especially posteromedially. The teeth are rather small. Posterior height is 1.5 mm in SDSM 35001, 1.8 mm in SDSM 35002, and 1.0 mm in SDSM 35011. We assign these teeth to basal mosasauroids, near an aigialosaur-grade level, probably more closely related to the "russellosaurine" clade than the mosasaurine clade (Bell and VonLoh, this volume).

PTEROSAURIA

Pterodactyloidea

Taxon indeterminate

(Fig. 8)

Referred Specimen - SDSM 35003, complete metacarpal IV.

Stratigraphic position - calcarenite bed at the base of the third member, Greenhorn Formation, Angustora Reservoir, Fall River County, South Dakota (Fig. 3).

Age - late Cenomanian, *Sciponoceras gracile* Zone.

This is the first reported occurrence of a pterosaur in the Greenhorn Formation. The dorsal side of the proximal half of the bone is crushed inward. The total length of the specimen is 104 mm; it has a proximal width of 20 mm and a distal width of 11.2 mm. Its thickness is 12 mm, slightly crushed, proximally and 10.9 mm along the larger of the distal condyles. This pterosaur probably had a wingspan of less than 2 meters. The distal articulation lacks a medial ridge that is present in ornithocheirid pterosaurs, and the length/width proportions are much too low. At the moment, we cannot assign the metacarpal to a more specific taxon than Pterodactyloidea.

CONCLUSIONS

The greatest abundance and diversity of marine reptiles in the Greenhorn Formation appears to occur in the basal Orman Lake Member. This is distinctly the transgressive phase of the Greenhorn cyclothem, and relatively shallow marine conditions are reflected by the deposition of calcarenites within this member. These transgressive conditions may have allowed for radiation into or, exploitation of, new niches or larger ranges created by the spreading seaway. It is also likely that expansion of the shelf resulted in more biological productivity which would have provided increasing prey resources to these reptiles.

There is at least two and possibly three types of pliosauroids found in the Orman Lake Member. Coniasaurs found within this transgressing unit probably reflect their initial immigration into the Western Interior Seaway during the late middle Cenomanian. They were present in Texas during the early middle Cenomanian *Conlinoceras tarrantense* Zone (Kennedy, 1988). The lack of marine reptiles within the more clastic second member may reflect either more turbid conditions, less conducive to supporting active pursuit predators, but may also be due to lack of good exposure developed on this unit. Deposition of calcarenites within the third member probably reflects a return to environmental conditions prevalent during deposition of the Orman Lake Member. Recurrence of *Polyptychodon* and *Coniasaurus* supports this hypothesis. The fourth member was deposited during maximum transgression of the seaway. Although this interval contains a diversity of elasmobranchs and osteicthyians comparable to that in the Orman Lake Member, we have recovered no marine reptiles in that interval. The next youngest marine reptiles occur at the very top of this interval in bedforms that indicate distinct shallowing conditions. These beds may represent offshore bars, tidal shoals, or tidal flats. The only reptiles represented in these beds are new arrivals: the mosasauroids and polycotylid plesiosaurs. The presence of a neonatal chelonioid also implies proximity to a shoreline.

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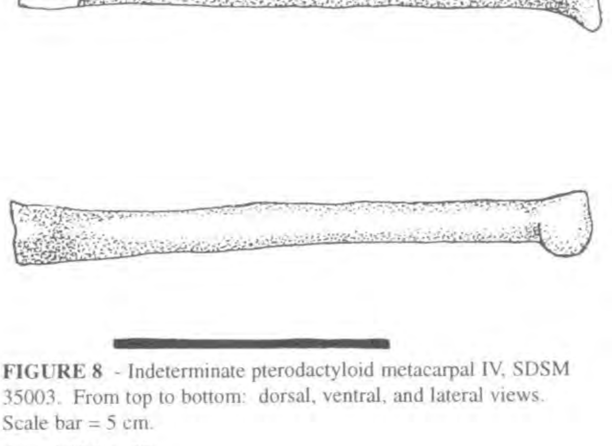

FIGURE 8 - Indeterminate pterodactyloid metacarpal IV, SDSM 35003. From top to bottom: dorsal, ventral, and lateral views. Scale bar = 5 cm.

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FOSSIL VERTEBRATES OF THE NIOBRARA FORMATION IN SOUTH DAKOTA

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ABSTRACT--The Niobrara Formation through the mid-continent of North America has been known classically for its assemblage of fossil fish, birds, and reptiles. Within this area, the Niobrara chalk of South Dakota has received relatively little attention. Only a few fish, two mosasaurs, a bird, and two plesiosaurs have been mentioned heretofore; those previously described are mentioned herein, as well as newly collected specimens. The fossil vertebrate assemblage from South Dakota now includes: *Squalicorax kaupi*, *Squalicorax falcatus*, *Microcorax*, *Cretoxyrhina mantelli*, *Echinorhynus*, *Ptychodus mortoni*, *Pachyrhizodus caninus*, *Pachyrhizodus minimus*, *Protosphyraena gladius*, *Protosphyraena nitida*, cf. *Apateodus*, *Ichthyodectes ctenodon*, *Xipactinus audax*, *Bananogmius evolutus*, *Cimolichthys nepaholica*, *Stratodus apicalis*, *Saurodon leanus*, *Saurocephalus lanciformis*, *Enchodus shumardi*, *Enchodus petrosus*, *Enchodus gladiolus*, cf. *Lophochelys*, Toxochelyidae, *Polycotylus latipinnis*, *Pteranodon*, *Clidastes propython*, *Platecarpus tympaniticus*, *Tylosaurus proriger*, cf. *Ichthyornis*, and *Hesperornis regalis*. Many of these taxa represent new records from the Niobrara Formation of South Dakota and indicate an early Coniacian to early Campanian age for the unit. This assemblage from the Niobrara continues into the suprajacent Pierre Shale with relatively few faunal changes.

The type specimens of *Enchodus shumardi* Leidy 1856 and *Cladocyclus occidentalis* Leidy 1856 (a taxon based upon fish scales which are most like those of *Ichthyodectes ctenodon*) are from the Niobrara Formation of South Dakota and may have been collected from deposits near the Cheyenne River.

INTRODUCTION

The wealth of fossil remains within South Dakota has long been noted particularly from the Pierre Shale, Hell Creek Formation, White River Group, and Ogallala Group. However, a similar fame for the Niobrara chalk in the central Great Plains has never been extensively extended to South Dakota, even though some of the first vertebrates recovered from this formation were found in the state (Simpson, 1942). Recently, our interests turned to the Niobrara Formation, partly because of its historical significance, but also because the lithostratigraphic unit lies interbedded between black shales which have been the primary focus of our biostratigraphic investigations since 1977.

This project was initiated some years ago and was meant to be part of a volume concerning the Niobrara chalk of the Western Interior that came as a result of a Niobrara Symposium at the Society of Vertebrate Paleontology meetings in Lawrence, Kansas, in 1990 (Martin and Parris, 1990). However, the volume languished, and in the meantime, the second author joined the project as part of his doctoral research (Schumacher, 1997) and additions were recorded by various authors (Martin and Varner, 1992; Schumacher and Martin, 1993, 1995). Some update of the original work was presented at the SD Academy of Science meetings in 1977 (Martin et al., 1997). Although this paper represents a compilation, we realize that this contribution may not be exhaustive; undoubtedly, additional specimens have been collected which we have not yet encountered. However, within our limitations, most taxa known from the Niobrara Formation in South Dakota are listed herein.

Abbreviations: **ANSP,** Academy of Natural Sciences of Philadelphia; **AMNH,** American Museum of Natural History, New York; **KUVP,** University of Kansas, Museum of Natural History, Lawrence; **PF,** Field Museum of Natural History, Chicago; **SDSM,** South Dakota School of Mines and Technology, Rapid City; **UCMP,** University of California Museum of Paleontology, Berkeley; **USD,** University of South Dakota, Department of Physics and Earth Science, Vermillion; **USNM,** United States National Museum of Natural History, Washington, DC; **WHO,** W. H. Over Museum, Vermillion, SD.

PAST INVESTIGATIONS

South Dakota has been considered to be classical for scientific investigations, especially in paleontology (Martin, 1989) and may have been the site of one of the earliest vertebrate fossils discovered during the Lewis and Clark expedition in 1804. On September 10, William Clark wrote:

> "...Passed the lower point of an Island covered with red Ceeder Situated in a bend on the L.S. ... we found the back bone of a fish, 45 feet long tapering to the tale. Some teeth &c. those joints were Separated and all Petrified." (Thwaites, R.G., ed., 1905)

This locality is north of the Nebraska-South Dakota state line between Niobrara and the former town of Wheeler. In this area, the Niobrara chalk is well exposed along the shores of the Missouri River. Although reported as a fish, the specimen which was collected, sent to Washington, and subsequently lost (Simpson, 1942) was more likely a mosasaur or plesiosaur.

The type specimen of *Saurocephalus lanciformis* Harlan (ANSP 5516) was also secured during the same expedition, but the location appears to be near Soldier's River, and depending upon from which side of the Missouri River the specimen was collected, the type locality is in either Washington County, Nebraska, or Harrison County, Iowa. This specimen may have been derived from the Niobrara Formation, but some doubt remains (Simpson, 1942). However, remains of other teleosts collected during the opening of vertebrate paleontology in the American West were definitely from the Niobrara Formation and from South Dakota. Specimens recovered during later expeditions frequently were attributed to Nebraska because that territorial name was then applied to much of the northern Great Plains region. Many "Nebraska" fossils obtained by Dr. John E. Evans (Owen, 1852) are attributable to South Dakota. One such example is *Enchodus shumardi* Leidy (1856) from the Niobrara Formation. By at least one account (Leidy, 1873), this small fish (USNM 2180) was collected from the Upper Cretaceous of Sage Creek, Dakota. This is the same locality from which *Cladocyclus occidentalis* Leidy (1856), a taxon based upon scales, was collected, probably from the Niobrara Formation. Although Bardack (1965:61) suggested the possibility of derivation of *Cladocyclus occidentalis* from the underlying Carlile Shale, we have restudied the specimens which Leidy apparently split between the Philadelphia Academy of Sciences and the National Museum. The matrix associated with specimens from both institutions suggests derivation from the Niobrara Formation.

Many authors, including Meek and Hayden (1857, 1862), Todd (1894), Rothrock (1931), Cobban (1951), and Knechtel and Patterson (1962) have commented on the common occurrence of fish scales and teeth in the Niobrara Formation of South Dakota, but descriptions and current reposition of these specimens are lacking. Other early fish type specimens attributed to the Niobrara Formation of South Dakota include seven teleost species described by Cope (1878). However, Bardack (1967) has convincingly demonstrated that these specimens came from Lebanon, not South Dakota as originally stated. The only other previously described teleost from South Dakota and surely from the Niobrara Formation is a nearly complete skeleton of *Xiphactinus audax* (SDSM 2510), first described by Bump (1926). The specimen is on exhibit at the Museum of Geology at the South Dakota School of Mines and

Technology and clearly appears to be from the Niobrara chalk. However, Bump (1926) originally attributed the specimen to the older Greenhorn Formation; the stratigraphic level was later changed to the Niobrara Formation on the Museum record in Bump's handwriting and was designated as such in Bardack's (1965) monograph. Bump could have added to the known paleofauna of the Niobrara chalk from the region by accurately describing and identifying five shark teeth which he mentioned as having been found in the digestive tract of SDSM 2510. The fate of these specimens is uncertain; they appear never to have been catalogued and do not appear with the mounted specimen. Moreover, we suspect that the teeth were not gastric residues, but probably were shed by sharks during attack and/or scavenging of the large fish.

The first authenticated reptilian specimen from the Niobrara Formation of South Dakota is a plesiosaur described by Cope (1894) as *Elasmosaurus* sp., based upon "forty-three centra and portions of the arches and limbs." The specimen was sent to Cope by N.H. Winchell, and the exact locality in South Dakota is unknown. Based upon the short, distorted vertebrae, Welles (1952:115) suggested the specimen was "pliosaurian" and not of the Elasmosauridae. Recently from the Niobrara Formation, we collected a complete skeleton of *Polycotylus latipinnis* as mentioned below and in Schumacher and Martin (1995).

Two specimens attributed to the Elasmosauridae were collected by Barnum Brown at the turn of the century. Both were collected from west of Edgemont, in extreme southwestern South Dakota. Brown (1904) mentioned one, AMNH 5803, as having been collected from the Niobrara Formation and as containing gastroliths and the remains of fish, "pterodactyl" bones, and seven scaphites. Carpenter (in Massare, 1987) referred this specimen to *Styxosaurus browni* Welles (1952). The second elasmosaurid is the type of *Styxosaurus browni* (AMNH 5835), a partial skeleton, also attributed to the Niobrara Formation. Interestingly, Russell (1988) in his check list of North American marine Cretaceous vertebrates noted no specimens collected from the Niobrara Formation of South Dakota and listed *Styxosaurus browni* as having been derived from the suprajacent Pierre Shale. Our observations of these specimens indicate that both specimens collected by Brown are indeed from the Pierre Shale. Both have matrix of the Pierre Shale associated, and many elements have gypsiferous matrix, a characteristic of the lower Pierre Shale. All specimens from which adequate locality data exists are from localities now mapped as Pierre Shale, and all are presently labeled as Pierre (or Fort Pierre) Formation, some apparently by Brown himself.

Rothrock (1931:7) mentioned another reptilian occurrence, a vertebra, collected from the James River Valley near Menno in Hutchison County. The disposition of this specimen, as well as that of the fish scales and shark teeth he described as occurring in southeastern South Dakota, is unknown.

No certain specimen of a mosasaur was described from the Niobrara chalk of South Dakota until Sevon (1957) published a brief description of a specimen which he described as *Clidastes tortor* from Yankton County in southeastern South Dakota. This disarticulated partial skull was restudied as part of this investigation and is noted herein with the systematic account of *Clidastes propython*. More recently, two skulls of *Tylosaurus proriger* have been secured from along the Missouri River by the Museum of Geology. One was described by Schumacher and Martin (1993), and the second more recently collected specimen is not yet prepared.

Concluding this brief list of historical accounts, Martin and Varner (1992) described the first avian occurrence from the Niobrara chalk of South Dakota. A diving bird, *Hesperornis regalis*, was found in the upper Niobrara Formation from south of the Black Hills in southwestern South Dakota.

Heretofore, faunal lists of the Niobrara taxa from South Dakota include the publications by Macdonald (1951) and Witzke (1981). Macdonald's list of the Niobrara paleofauna includes only the *Xiphactinus* specimen described by Bump (1926). Witzke (1981) noted only teleost fish remains from southeastern South Dakota.

DISTRIBUTION AND STRATIGRAPHY

The Niobrara Formation is exposed principally in three areas in South Dakota: 1) extreme southeastern South Dakota, 2) along the Missouri River from the Nebraska border to Ft. Thompson in central South Dakota, and 3) around the periphery of the Black Hills uplift in western South Dakota (Gries and Martin, 1985; Martin et al., 1996). Thickness of the Niobrara Formation decreases dramatically from a composite of 210 meters in Kansas (Stewart et al., 1990:3), to a total of over 76 meters in southeastern South Dakota (Bugliosi, 1986), to approximately 100 meters around the Black Hills (Schumacher, 1997). Although the Niobrara Formation was named for exposures near the southeastern South Dakota area at the confluence of the Niobrara and Missouri rivers in Nebraska by Meek and Hayden (1862), subdivision of the formation occurred in the thicker section of Kansas. Mudge (1876) utilized the name Fort Hays to designate the Benton and lowermost Niobrara Formation, but Williston (1892) restricted the Fort Hays to the chalky carbonates at the base of the Niobrara Formation. A few years later, Cragin (1896) named the upper chalky member the Smoky Hill Chalk Member.

The first investigator to extend the Kansas member-rank nomenclature to South Dakota was Loetterle (1937:13-14) in his description of microfossils of the Niobrara Formation. Loetterle noted 12.2 meters of chalky limestone (Fort Hays Limestone Member) overlain by 46-52 meters of chalk (Smoky Hill Chalk Member) in southeastern South Dakota and northeastern Nebraska. Bolin (1952:4-6) followed this example in his description of the foraminiferans and ostracods of South Dakota but found it was "...very difficult if not impossible to distinguish between the two members in the field... ." Bolin, therefore, utilized biostratigraphic criteria for differentiation of lithostratigraphic boundaries, a practice which has been universally abandoned. A couple years later when describing the geology of the Yankton area, Simpson (1960) retained the Fort Hays Limestone Member, which he characterized as containing a more massive bedding than the overlying Smoky Hill Chalk Member. However, he noted (1960:24) that in the field no members were recognized. Rothrock (1949:22) stated the case most succinctly, "The formation has no members within it ... on the surface and so far none ... in the examination of well cuttings." As a result, most workers in South Dakota are content to recognize the Niobrara Formation as undifferentiated owing to its relatively thin exposures, impossibility of delineating member contact, lack of clean carbonates at the base throughout the state, and argillaceous components in the upper portion to the west.

RECENT VERTEBRATE PALEONTOLOGICAL INVESTIGATIONS

Specimens have been slowly accumulated from the three areas of Niobrara outcrop in South Dakota during recent times. Those specimens collected earlier in southeastern South Dakota were due largely to the efforts of the University of South Dakota and South Dakota Geological Survey. Those derived more recently from the Missouri River and Black Hills areas were primarily accumulated by personnel of the South Dakota School of Mines and Technology Museum of Geology and New Jersey State Museum.

The major fossil-producing localities of southeastern South Dakota include the old cement plant quarry west of Yankton, a site near Marindahl Dam northeast of Yankton, and from along the Missouri River in the Yankton area. Fossils obtained from these areas include fish and mosasaurs.

The area of exposure of the Niobrara Formation along the Missouri River north of Yankton has produced few specimens, most of which have been washed from the chalk and were found along the shore. Those scattered fossils obtained include fish, mosasaur, plesiosaur, and bird remains.

A similar suite of specimens occurs in the outcrops formed by exposure of the Niobrara Formation around the Black Hills in western South Dakota. These exposures were formed after the chalk was uplifted during formation of the Black Hills as part of the Laramide Orogeny.

Subsequent erosion exposed the Niobrara Formation dipping away from the Black Hills core. Specimens were encountered as part of a continuing biostratigraphic study of Late Cretaceous marine units in western South Dakota. Since 1977, efforts have been directed to stratigraphic collections from the Pierre Shale; this field work indicated scattered outcrops of the Niobrara Formation occurred below the Pierre Shale around the southern Black Hills. Cooperative efforts between the South Dakota School of Mines and Technology Museum of Geology and the New Jersey State Museum produced most of the collections described herein.

SYSTEMATIC PALEONTOLOGY

Vertebrate taxa described herein are listed in Table 1.

Order Lamniformes
Family Anacoracidae
Genus *Squalicorax*
Squalicorax kaupi

Stewart (1990) noted the distribution in Kansas of this species only in the zone of *Hesperornis* at the top of the Niobrara Formation. In western South Dakota, the assemblage characteristic of this zone ranges up into the Gammon Ferruginous, Sharon Springs, and Mitten Black Shale members of the Pierre Shale, and even higher in central South Dakota.

Referred specimens-SDSM 22344, 3 teeth from SDSM V8918, .5 meter below the Niobrara/Pierre contact; 2 associated teeth from SDSM V9011, 1 meter below the Niobrara/Pierre contact; SDSM 22353, large tooth from SDSM V9010, from near middle of formation; SDSM 32692, tooth from SDSM V966, 8 meters below Niobrara/Pierre contact; SDSM 32697, tooth from SDSM V967, 4.5 meters below Niobrara/Pierre contact; SDSM 32698, tooth from SDSM V967, 1 meter below Niobrara/Pierre contact; SDSM 32700, tooth from SDSM V968, few centimeters below Niobrara/Pierre contact; SDSM 32705, tooth from SDSM V969, 5.4 meters below Niobrara/Pierre contact; SDSM 32719, tooth from SDSM V9612, 39.75 meters above Carlile/Niobrara contact; WHO-unnumbered, tooth from Marindahl Dam spillway, Yankton County, 4.6 meters below the Niobrara/Pierre contact.

Description-These teeth possess an arched anterior face and a posterior notch as is characteristic of *Squalicorax* (Fig. 1a). The teeth are generally triangular, have finely serrated margins and relatively high, thick roots. They range to 17 mm in height.

The teeth of SDSM 22344 were found while excavating a skeleton of a polycotylid plesiosaur, although their direct association could not be documented as all were found weathered out on the surface. Nevertheless, we suspect they were associated and concentrated as a result of feeding on the large reptile. WHO-unnumbered (Fig. 2g) was found on the chalk slab with a specimen of *Clidastes* (Sevon, 1957) and may represent a similar circumstance.

Discussion-As noted by various authors (e.g. Case, 1978), *Squalicorax kaupi* is a common constituent of Late Cretaceous paleofaunas. Some authors (e.g. Lauginiger and Hartstein, 1983) consider *S. kaupi* as a senior synonym of *S. falcatus*, but others such as Stewart (1990) in his zonation and Cappetta (1987) consider them distinct. We follow the latter authors and distinguish *S. kaupi* on the basis of overall greater size, less prominent heel, and relatively high, thick root.

The stratigraphic range of this species in South Dakota is greater than that reported by Stewart (1990) in Kansas. SDSM 22353 (Fig. 1b) occurs near the middle of the formation, and SDSM 32700 occurs at the Niobrara/Pierre contact. Therefore, the known range of the species in the Niobrara Formation appears to extend from the Santonian into the early Campanian.

Squalicorax falcatus

Stewart (1990) reported the species in the lower Smoky Hill Chalk Member in Kansas, extending from late Coniacian to the medial Santonian. Later, Shimada (1996) indicated an earlier first appearance in the Interior Seaway from the Fort Hays Limestone Member of medial Coniacian age.

Referred specimens-SDSM 32687, tooth from SDSM V936, 8.25 meters above Carlile/Niobrara contact; SDSM 32690, tooth from SDSM V9011, 6 meters below Niobrara /Pierre contact; SDSM 32696, tooth from SDSM V967, 5 meters below Niobrara/Pierre contact; SDSM 32699, tooth from SDSM V968, 7-8 meters below Niobrara/Pierre contact; SDSM 32704, tooth from SDSM V969, 5.4 meters below Niobrara/Pierre contact; SDSM 32746, 32747, 32748. 32749, single teeth from SDSM V937, 30-35 meters above Carlile/Niobrara contact; SDSM 32754, tooth from SDSM V9136.

Description-All teeth exhibit an arched anterior face, low moderately thick root, posteriorly inclined broad major cusp, a long and slightly convex mesial cutting edge, a short and slightly convex distal cutting edge, fine serrations on cutting edges, and a distinct distal heel.

Discussion-The occurrences of *S. falcatus* from South Dakota suggest an early Coniacian to early Campanian range. The latter represents a range extension in the Interior Seaway, although Russell (1988) reported a Maastrichtian occurrence in the Moreno Formation of California.

Genus *Microcorax*
Microcorax sp. indet.

Referred specimen-SDSM 32750, tooth from SDSM V937, 30-35 meters above the Carlile/Niobrara contact.

Description-SDSM 32750 possesses a relatively thin, tall, slightly recurved crown with unserrated cutting edges. As is characteristic of the genus, the lingual root lacks a nutritive pit and the heels are united broadly to the triangular primary cusp.

Discussion-SDSM 32750 was from an exceedingly fossiliferous bentonite layer and is likely late Coniacian or early Santonian in age.

Family Cretoxyrhinidae
Genus *Cretoxyrhina*
Cretoxyrhina mantelli

Stewart (1990) listed *C. mantelli* as occurring throughout the Smoky Hill Chalk Member in Kansas (although perhaps not from the upper 12 meters), and Shimada (1996) extended the range of the species down into the Fort Hays Limestone Member.

Referred specimens-SDSM 22354, lateral tooth from SDSM V9010, from near middle of formation; SDSM 32708, tooth from SDSM V9610, 1.75 meters below Niobrara/Pierre contact; SDSM 32722, tooth from SDSM V9613, 15 meters below Niobrara/Pierre contact; SDSM 32730, 22 associated teeth from SDSM V9616, 25-30 meters above the Carlile/Niobrara contact; SDSM V32731, tooth from SDSM V908, 45.4 meters below the Niobrara/Pierre contact; SDSM 32732, tooth from SDSM V908, 49.8 meters below the Niobrara/Pierre contact; SDSM 32740, weathered tooth from SDSM V919; SDSM 32751, tooth from SDSM V937, 30-35 meters above Carlile/Niobrara contact.

Description-SDSM 22354 (Fig. 1c) was found as the same locality and level as SDSM 22353. SDSM 22354 is 11.5 mm in anteroposterior

TABLE 1 - Faunal List from the Niobrara Formation of South Dakota.

- Anacoracidae
  - *Squalicorax kaupi*
  - *Squalicorax falcatus**
  - *Microcorax**

- Cretoxyrhinidae
  - *Cretoxyrhina mantelli**

- Echinorhinidae
  - *Echinorhynus**

- Ptychodontidae
  - *Ptychodus mortoni**

- Pachycormidae
  - *Protosphyraena gladius**
  - *Protosphyraena nitida**

- Ichthyodectidae
  - *Ichthyodectes ctenodon*
  - *Xiphactinus audax*

- Saurodontidae
  - *Saurodon leanus**
  - *Saurocephalus lanciformis**

- Plethodidae
  - *Bananogmius evolutus*
  - *Bananogmius* sp. indet.

- Pachyrhizodontidae
  - *Pachyrhizodus caninus*
  - *Pachyrhizodus minimus*

- Enchodontidae
  - *Enchodus shumardi*
  - *Enchodus petrosus*
  - *Enchodus gladiolus*

- Cimolichthyidae
  - *Cimolichthys nepaholica**

- Family *Incertae sedis*
  - cf. *Apateodus*

- Dercetidae
  - *Stratodus apicalis**

- Toxochelyidae
  - cf. *Lophochelys*
  - Toxochelyidae, sp. indet.

- Polycotylidae
  - *Polycotylus latipinnis*

- Ornithocheiridae
  - *Pteranodon*

- Mosasauridae
  - *Clidastes propython*
  - *Platecarpus tympaniticus*
  - *Tylosaurus proriger*

- Ichthyornithidae
  - cf. *Ichthyornis*

- Hesperornithidae
  - *Hesperornis regalis*

*Added to the assemblage as the result of investigation by the second author.

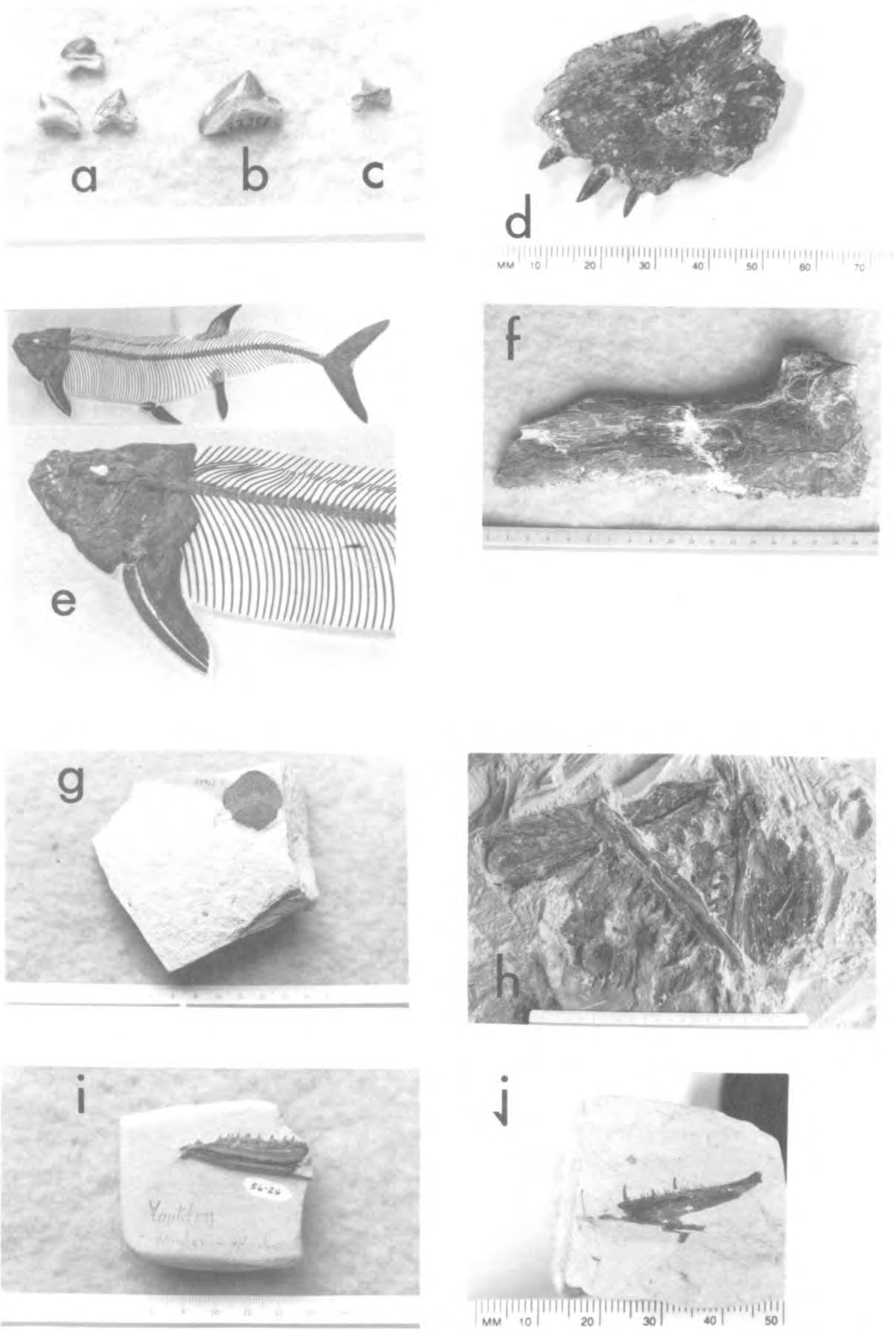

Figure 1 - 1a-*Squalicorax kaupi*, SDSM 22344, 3 teeth; 1b-*Squalicorax kaupi*, SDSM 22353, tooth; 1c-*Cretoxyrhina mantelli*, SDSM 22354, tooth; 1d-*Ichthyodectes ctenodon*, SDSM 22360, left premaxilla; 1e-*Xiphactinus audax*, SDSM 2510, skeleton; 1f-*Xiphactinus audax*, SDSM 17874, right maxilla; 1g-Ichtyodectidae, SDSM 17625, scale; 1h-*Pachyrhizodus caninus*, SDSM 22362, disarticulated skull; 1i-*Pachyrhizodus minimus*, USD 56-26a, left dentary; 1j-*Enchodus shumardi*, USD 60-163, left dentary. Scales in all photographs are in centimeters (20 cm maximum on scale), except photographs 1d and 1j, which are in millimeters.

length and is typical of the species in possessing a large root; short, slightly recurved principal cusp; smooth cutting edges; flat labial side with crenulations near root; curved lingual side without crenulations; and flanking accessory cuspules. Other referred teeth may or may not exhibit the lateral cuspules as evinced by the associated teeth of SDSM 32730.

Discussion-None of the specimens from South Dakota were found as low in the Niobrara Formation as that discussed by Shimada (1996); however, SDSM 32708 may represent the highest occurrence of the species in the formation.

Order Squaliformes
Family Echinorhinidae
Genus *Echinorhynus*
Echinorhynus sp.

Referred specimens-SDSM 26173, approximately 50 teeth from SDSM V925, 2 meters below Niobrara/Pierre contact; SDSM 23020, tooth from SDSM V9011, 1 meter below Niobrara/Pierre contact.

Description-These specimens are wider than tall, averaging about 1.5 mm wide and greatly compressed laterally. No cuspules exist. The primary cusp is recurved, thin, and possesses a long smooth mesial cutting edge and a short smooth distal cutting edge.

Discussion-The second author discovered these specimens and described them as a new species (Schumacher, 1997:103-104). The occurrence of the genus in North America is heretofore unpublished. Both Niobrara occurrences are in the uppermost portion of the formation and are early Campanian in age. The species will be named and discussed in a forthcoming paper by the second author.

SDSM 26173 includes numerous teeth which were associated with the tail section of a large mosasaur, *Tylosaurus proriger* (Schumacher and Martin, 1993), and SDSM 23020 was associated with a large skeleton of *Polycotylus latipinnis* (Schumacher and Martin, 1995). These associations provide evidence that these sharks, like some described above, were feeding upon large reptilian carcasses.

Order *Incertae sedis*
Family Ptychodontidae
Genus *Ptychodus*
Ptychodus mortoni

Shimada (1996) and Stewart (1990) indicated a medial Coniacian-late medial Santonian age for the species in Kansas, and a later occurrence in the southeastern United States (Stewart, 1988).

Referred specimens-SDSM 32718, tooth from SDSM V9612, 23 meters above Carlile/Niobrara contact; SDSM 32682, tooth from SDSM V936, float just above Carlile/Niobrara contact; SDSM 32683, tooth from SDSM V936, float 13.5 meters above Carlile/Niobrara contact; SDSM 32684, tooth from SDSM V936, float 11 meters above Carlile/Niobrara contact; SDSM 32685 from SDSM V936, float 13.5 meters above Carlile/Niobrara contact; SDSM 32686, tooth from SDSM V936, 9.1 meters above Carlile/Niobrara contact.

Description-These specimens are typical, rectangular, massive teeth with bulbous crowns which exhibit radiating enamel ridges from the low apex to the margins. The specimens range from 15 mm x 22 mm to 23mm x 35 mm in length x width dimensions, respectively.

Discussion-Based upon correlations of the associated invertebrate *Cremnoceramus browni* at SDSM V936, the South Dakota specimens of *P. mortoni* appear to be early medial Coniacian (Schumacher, 1997).

Class Osteichthyes
Order Pachycormiformes
Family Pachycormidae
Genus *Protosphyraena*
Protosphyraena gladius

Stewart (1988) subdivided the Smoky Hill Chalk Member of the Niobrara Formation based upon species of *Protosphyraena* and found that *P. gladius* ranges through the upper two-thirds of the member.

Referred specimens-SDSM 32691, partial pectoral fin from SDSM V9011, 6 meters below the Niobrara/Pierre contact; SDSM 32693, partial pectoral fin from SDSM V966, 10 meters below the Niobrara/Pierre contact.

Description-These two large fragments preserve the diagnostic serrated anterior fin edge characteristic of the genus. Moreover, they possess a wedge-shaped ossification between the two typical layers of fin rays, a characteristic of *P. gladius* (Stewart, 1988).

Discussion-SDSM 32691 and 32693 were found in the upper portion of the Smoky Hill Chalk Member and are regarded as early Campanian in age.

Protosphyraena nitida

Stewart (1988) indicated that *P. nitida* occurs in the late Coniacian of Kansas.

Referred specimen-SDSM 33670, partial skull and pectoral fin from Gregory County, SD, just below the Niobrara/Pierre contact (Keith Sperlich, per. comm., 1997).

Description-The specimen is relatively small and possesses the lanceolate rostrum characteristic of the genus and the smooth anterior edge of the pectoral fin with fine ridges trending normal to the leading edge characteristic of the species.

Discussion-Although Stewart (1988) noted that *P. nitida* occurs in the late Coniacian *Volviceramus grandis* Zone in Kansas, the collector indicated that SDSM 33670 came from near the contact with the overlying Pierre Shale. This stratigraphic position suggests a late Campanian occurrence, surviving much later than in Kansas.

Protosphyraena sp. indet.

Referred specimen-SDSM 4321, tooth from SDSM V9013, float upper Niobrara Formation.

Description-SDSM 4321 is an extremely laterally compressed, relatively long, sharp tooth, with non-serrated cutting edges. The tooth is broken at the base, and the tip of the dagger-like tooth is damaged. The preserved portion is 36 mm high.

Discussion-The morphology of SDSM 4321 is somewhat similar to those of the saurocephalids but is much larger and more laterally compressed.

Order Ichthyodectiformes
Family Ichthyodectidae
Genus *Ichthyodectes*
Ichthyodectes ctenodon

Stewart (1990) indicated that the species ranges in the Kansas Niobrara section from the base through the zone of *Spinaptychus stern-*

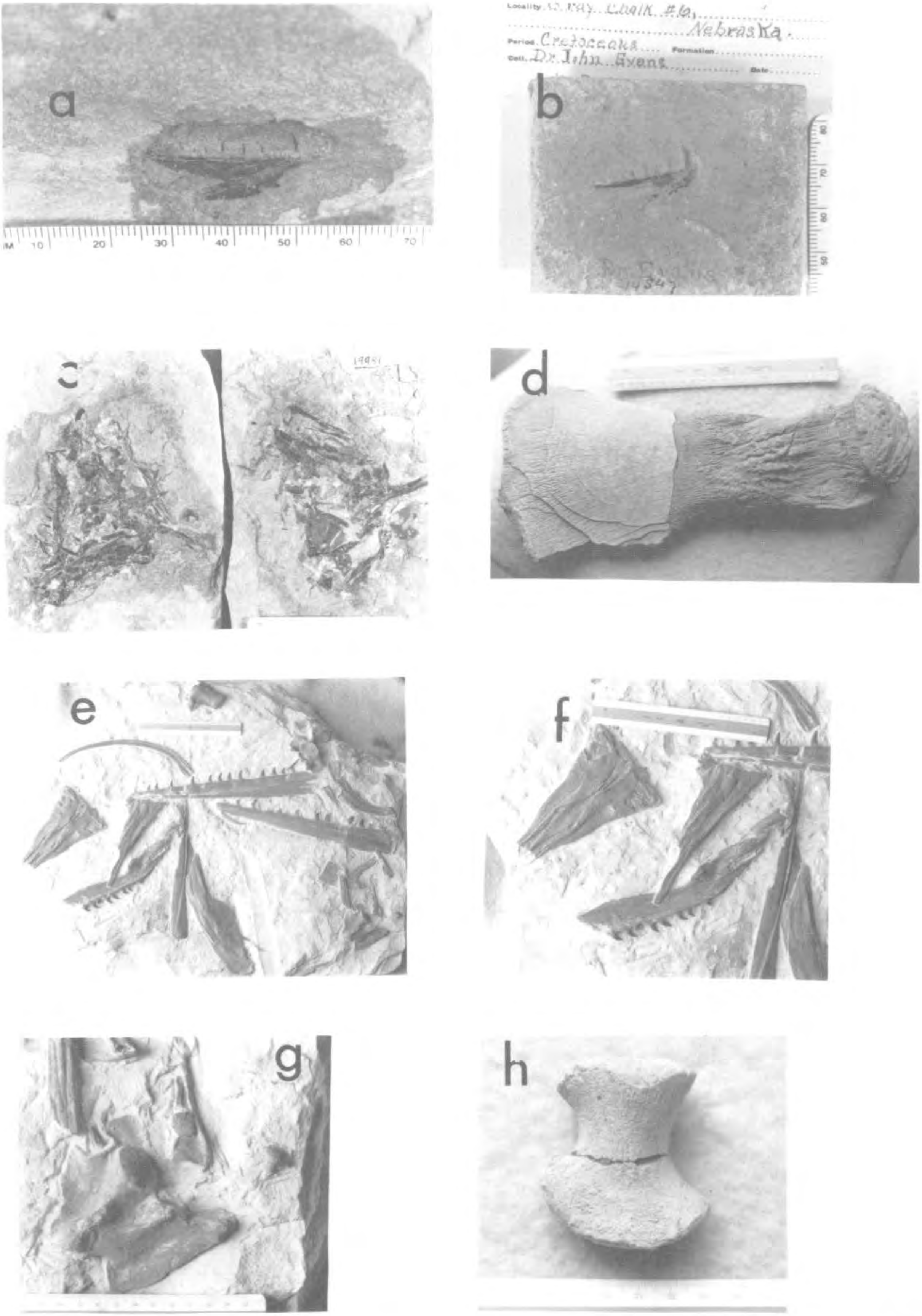

Figure 2 - 2a-*Enchodus shumardi*, SDSM 19984, right dentary; 2b-*Enchodus shumardi*, holotype, USNM 2180, right dentary; 2c-*Enchodus petrosus*, SDSM 19981, skull; 2d-Polycotylidae, SDSM 17727, propodial; 2e-*Clidastes propython*, WHO unnumbered; 2f-*Clidastes propython*, WHO unnumbered, detail of parietal and pterygoid; 2g-*Clidastes propython*, WHO unnumbered, detail of axis, note tooth of *Squalicorax* at far right; 2h-*Platecarpus*, SDSM 22351, right radius. Scales in all photographs are in centimeters (20 maximum on scale), except photographs 2a, 2b, and 2c, which are in millimeters.

bergi, but not in the overlying zone of *Hesperornis*. It has been found below the Niobrara and in the overlying Pierre Shale, so the species is expected from the *Hesperornis* Zone in Kansas.

Referred specimens-SDSM 17875, jaw fragment from SDSM V8922, float within 10 meters of Niobrara/Pierre contact; SDSM 22360, nearly complete left premaxilla with three teeth and three alveoli from SDSM V8921, upper Niobrara Formation; SDSM 32741, jaw fragment and associated elements from SDSM V919, middle of Niobrara Formation.

Description-These jaw fragments possess small, uniform, conical teeth, unlike the heterodont teeth of *Xiphactinus* or the minute marginal teeth of *Gillicus*. SDSM 22360 (Fig. 1d) is a relatively complete element, and additional portions of this individual have not yet been prepared.

Discussion-These specimens may augment another previously described occurrence of the species. The earliest known specimens may be the scales described as *Cladocyclus occidentalis* (Syntypes: USNM 51, ANSP 5325, ANSP 5326, and ANSP 5348) by Leidy (1856, 1873). Bardack (1965) referred ANSP 5348 to *Ichthyodectes ctenodon*. The specimens were collected by John Evans (Owen, 1852) along Sage Creek in South Dakota, the same area as was the type specimen of *Enchodus shumardi*. A discussion of this locality may be found in the discussion section of *Enchodus shumardi*.

These specimens were collected from the middle of the Niobrara Formation to the upper contact. We have also found the species in the suprajacent lower Pierre Shale in South Dakota. The Niobrara range lies within that previously known, and additional stratigraphic records are expected which may extend the biostratigraphic range in South Dakota.

Genus Xiphactinus
Xiphactinus audax

Stewart (1990) illustrated the same range for *Xiphactinus audax* as for *Ichthyodectes ctenodon*, and like *I. ctenodon, X. audax* occurs higher in the lower Pierre Shale.

Referred specimens-SDSM 2510, partial skeleton lacking dorsal, pelvic, and anal fins from SDSM V251; SDSM 17874, (Fig. 1f) right edentulous maxilla from SDSM V8921, uppermost Niobrara Formation; SDSM 32712, partial skull including neurocranium, premaxillae, maxillae, palatines, preopercule, quadrates, and dentaries from SDSM V9610, 3.5 meters below Niobrara/Pierre contact; SDSM 32717, scale from SDSM V9611, approximately 48 meters above Carlile/Niobrara contact; SDSM 32734, premaxillae and two vertebrae from SDSM V908, 48.3 meters below Niobrara/Pierre contact; SDSM 32764, scale from SDSM V921, uppermost Niobrara Formation.

Description-All of these large specimens match closely the descriptions of Stewart (1900) and Bardack (1965), and the latter author described SDSM 2510 (Fig. 1e) in his monograph. In addition to the specimens listed above are unprepared specimens collected from the upper Niobrara Formation at SDSM V8921.

Discussion-All of these specimens fall within the expected biostratigraphic range of the species.

Ichthyodectidae, gen *et* sp. indet.

Referred specimens-SDSM 17625, scale from SDSM V8919, middle Niobrara Formation; SDSM 17262, 2 scales from SDSM V8919, middle Niobrara Formation; SDSM 17877, pelvic actinosts from SDSM V8924, upper Niobrara Formation; SDSM 32688, vertebrae and fin spines from SDSM V936, 17 meters above Carlile/Niobrara contact; SDSM 32698, 6 vertebrae from SDSM V967, 1 meter below Niobrara/Pierre contact; SDSM 32721, 8 articulated vertebrae from SDSM V9612, 30.5 meters above Carlile/Niobrara contact; SDSM 32725, small vertebra, and SDSM 32726, vertebra, from SDSM V9614, 10 meters below Niobrara/Pierre contact; USD 56-26b, scale from Marindahl Dam Locality.

Description-SDSM 17625 (Fig. 1g) and USD 56-26b match closely in size (SDSM 17625=29 mm x 26 mm; USD 56-26b=34 mm x 22.3 mm) and morphology those illustrated by Bardack (1965) for *Ichthyodectes*. However, the lack of associated osteological specimens from their respective localities causes indefinite assignment. One of the scales of SDSM 17626 is incomplete but is at least twice the size of SDSM 17625. This large scale is probably that of an individual of *Xiphactinus*, but the poor preservation hinders assignment. SDSM 17877, pelvic actinosts, match the descriptions and illustrations by Stewart (1900) for those of the ichthyodectids. The isolated specimen is rather small, in the size range of adult specimens of *Ichthyodectes* or *Gillicus*.

Discussion-These specimens consist primarily of scales and vertebrae which are not identifiable below the familial level. However, the stratigraphic distribution of these and ichthyodectid specimens described above suggests a range of the family throughout the Niobrara Formation.

Family Saurodontidae
Genus *Saurodon*
Saurodon leanus

Stewart (1990) indicated that the species existed throughout the Smoky Hill Chalk Member of the Niobrara Formation and persisted into the overlying Pierre Shale.

Referred specimen-SDSM 32736, maxillary, dentary fragment, and numerous vertebrae from SDSM V908, 44.2 meters below the Niobrara/Pierre contact.

Description-SDSM 32736 possesses the thecodont, laterally compressed, smooth teeth characteristic of members of the family. Moreover, the dentary possesses the facet for articulation of a predentary, as well as the deep notches below the alveolar border, a feature characteristic of *Saurodon* (Stewart; 1900; Hay, 1903).

Discussion-The taxonomy of the genus is somewhat questionable, especially the existence of more than one species from the Niobrara Formation. Therefore, this specimen is assigned to the species with priority.

SDSM 32736 was collected from near the middle of the Niobrara Formation and lies well within the known biostratigraphic range of *S. leanus*.

Genus *Saurocephalus*
Saurocephalus lanciformis

Stewart (1990) suggested a first appearance of the species from the uppermost Niobrara Formation in Kansas.

Referred specimen-SDSM 32735, premaxilla, two dentaries, and predentary from SDSM V908, 44.8 meters below the Niobrara/Pierre contact.

Description-The dentaries of SDSM 32735 exhibit circular foramina below the alveolar border which are characteristic of *Saurocephalus* (Stewart, 1900; Hay, 1903), rather than the deep notches characteristic of Saurodon. The bone texture of SDSM 32735 is fibrous and compact, contrasting with the flaky bone of the *Saurodon* specimen described above (SDSM 32736).

Discussion-Similar to the case for *Saurodon*, specimens of *Saurocephalus* are referred to the species with the greatest published longevity.

The stratigraphic appearance of SDSM 32735 at 44.8 meters below the contact suggests a middle Niobrara occurrence. This position is lower than the first record in Kansas (Stewart, 1990) and may represent the first known appearance of the species.

Saurodontidae, gen. indet.

Referred specimen-SDSM 32698, two associated large vertebrae from SDSM V967, float just below Niobrara/Pierre contact.

Description-These vertebrae possess a rounded cross-section, large size, and similar geometry of the ossicles which are characteristic of members of the Saurodontidae.

Order Osteoglossiformes
Family Plethodidae
Genus *Bananogmius*
Bananogmius evolutus

Stewart (1990) listed *Bananogmius* as occurring in the zones of *Protosphyraena pernicosa* and *Spinaptychus sternbergi* and extending into the Pierre Shale. Therefore, the genus extends throughout the Niobrara Formation of Kansas, and *B. evolutus* extends through the upper half of the Smoky Hill Chalk Member.

Referred specimen-PF5376, complete neurocranium, Meade County.

Bananogmius sp. indet.

Referred specimens-SDSM 17876, 3 vertebrae from SDSM V8923, uppermost Niobrara Formation; SDSM 32769, 20 articulated vertebrae and caudal fin from Yankton County, and unprepared specimen from V8921, upper Niobrara Formation.

Description-SDSM 32769 closely resembles the descriptions for the genus by Hay (1903). The short vertebral centrae are ornamented by thin horizontal ridges and lack lateral ossicles characteristic of saurocephalid and ichthyodectid fish. Therefore, the centrae are relatively solid, similar to those of *Pachyrhizodus*. The distal portion of the caudal fin splits into many small, fine fin rays.

The partial skeleton from SDSM V8921 remains unprepared; therefore, a precise identification is not yet possible. However, the finely sculptured bone characteristic of the plethodids was observed in the field.

Order Elopiformes
Family Pachyrhizodontidae
Genus *Pachyrhizodus*
Pachyrhizodus caninus

Stewart (1990) listed both *P. caninus* and *P. minimus* as occurring throughout the Niobrara Formation.

Referred specimen-SDSM 22362, partial skeleton from SDSM V8718, collected from along the Missouri River by David Jones; SDSM 32702, jaw fragment from SDSM V968, 4-5 meters below the Niobrara/Pierre contact; SDSM 32710, vertebra from SDSM V9610, 0.9 meter below the Niobrara/Pierre contact; SDSM 32711, vertebrae and cranial fragments SDSM V9610, 0.1 meter below the Niobrara/Pierre contact.

Description-SDSM 22362 consists of a distarticulated skull and two associated vertebrae (Fig. 1h). The jaws are approximately 10-20 cm long and contain the typical alternating tooth and alveolus pattern and wide alveoli of *Pachyrhizodus*. The smooth teeth are strongly medially curved, possess a bulbous attachment, and occur along the internal margins of the tooth-bearing elements. The vertebrae exhibit the characteristic relatively long, solid centra. Although somewhat difficult to observe, the dentaries appear to possess the triangular tooth pattern at the symphysis, which is diagnostic of *Pachyrhizodus caninus*.

SDSM 32710 and 32711 are tentatively referred to the species based upon vertebral morphology. The vertebrae are large (up to 3.3 cm in height), about half as long as high, moderately concave, and ornamented by a series of prominent, sinuous ridges on the lateral faces.

Pachyrhizodus minimus

Stewart (1990) noted that *P. minimus* ranges throughout the Smoky Hill Chalk Member in Kansas.

Referred specimens-SDSM 32770, partial skeleton including nearly complete cranium and lower jaw from 1.2 meters below Niobrara/Pierre contact, Gregory County; USD 56-26a, lower jaw from Marindahl Dam locality.

Description-SDSM 32770 possesses a number of features characteristic of the taxon, including a large fossa on the posterior portion of the skull roof (Applegate, 1970), and a lower jaw with a single row of pleurodont teeth which are conical, smooth, and recurved. The vertebrae possess nearly solid centrae and are anteroposteriorly as long as they are dorsoventrally high.

USD 56-26a (Fig. 1i) is a left dentary broken anterior to the articular with eleven inwardly curved, smooth teeth. The jaw is small (39 mm long and 9 mm deep), delicate, and approximately the size of small species of *Enchodus*. However, the alternating, curved tooth pattern characteristic of *Pachyrhizodus* is exhibited by the specimen. Additionally, the specimen possesses the distinctive symphyseal bifurcation, downwardly deflected symphysis, and groove just below the dentition on the external side as described by Stewart (1899) for *Pachyrhizodus minimus*.

Discussion-SDSM 32770 was collected from the uppermost Niobrara Formation, whereas USD 56-26a was from the chalky middle to upper portion of the formation. Therefore, the ranges of these two specimens are consistent with those of known specimens from Kansas.

Order Aulopiformes
Family Enchodontidae
Genus *Enchodus*
Enchodus shumardi

Stewart (1990) documented the occurrence of *Enchodus shumardi* from the zone of *Clioscaphites vermiformis* and *C. choteauensis* to the top of the Smoky Hill Chalk Member of the Niobrara Formation in Kansas.

Referred specimens-USD 60-163 (Fig. 1j), lower jaw with dentition from old cement plant quarry; SDSM 19984, lower jaw with dentition (Fig. 2a), ectopterygoid, and palatine tooth from SDSM V908, middle Niobrara Formation; SDSM 19982, partially articulated skull from SDSM V908, middle Niobrara Formation; SDSM 19983, palatine tooth and lower jaws with dentition from SDSM V908, middle Niobrara Formation; SDSM 17624, lower jaw with dentition from SDSM V8919, middle to upper Niobrara Formation; SDSM 23020, associated marginal teeth from SDSM V9011, 1 meter below Niobrara/Pierre contact; SDSM 25796, associated marginal teeth from SDSM V925, uppermost Niobrara Formation; SDSM 32727, palatine from SDSM V9614, 10 meters below Niobrara/Pierre contact; SDSM 32575, frontals from SDSM V921, uppermost Niobrara Formation; SDSM 32758, dentary from SDSM V921, uppermost Niobrara Formation.

Description-These relatively small specimens have very long, straight, needle-like, barbed dentary teeth; minute marginal dentary teeth, and maxillary groove which ends just behind the tooth base. These features of the dentary are exemplified on the holotype of *Enchodus shumardi*, USNM 2180 (Fig. 2b), collected from ash-colored chalk in the Cretaceous deposits of the Upper Missouri River.

Discussion-This species of *Enchodus* presents an interesting problem in the interpretation of historical Niobrara specimens from South Dakota. The holotype of *Enchodus shumardi* is alleged to be from South Dakota and may well be from the Niobrara Formation according to Leidy's original description, in which the locality was somewhat vaguely given (associated with *Cladocyclus occidentalis*). Various authors have positively stated that the holotype came from South Dakota (Leidy, 1873; Goody, 1976) and undoubtedly from the Cheyenne River drainage, based on the discussions of Owen (1852), who described the explorations of Dr. John E. Evans, collector of the holotype. Although subsequently attributed to the Sage Creek area (Leidy, 1873) where only the Pierre Shale and White River Group are exposed, the labels and notes with the holotype make no mention of that locality, and the specimen is attributed only to the "Gray Chalk Number Six" of Owen's report and is clearly stated as coming from the Niobrara Formation.

Examination of the published report of Owen (1852) has given no certain indication of any explorations in areas where the Niobrara Formation is exposed, but the possibility cannot be totally excluded. The map of western South Dakota published by Owen illustrates Sage Creek and Cretaceous fossils are noted at the southern end. The narrative indicates that Cretaceous fossils were found in this area of Sage Creek only fifteen miles from outcrops of the White River Group. However, as noted above, the drainage of what is known as Sage Creek today drains the White River Group at its source and flows through the Pierre Shale near its mouth at the Cheyenne River. Evans' original field notes, if extant, might clarify the matter.

The only unequivocal evidence for the source is provided by the holotype, itself, which we have examined. USNM 2180 (Fig. 2b) is prepared in relief in a block of unquestionable chalk matrix. No such matrix is known from the Pierre Shale of western South Dakota, and we believe that the holotype came from the Niobrara Formation. Exposures of the Niobrara Formation occur farther west than Sage Creek in the Cheyenne River drainage, closer to the Black Hills. The matrix of the holotype is very similar to that of specimens from SDSM locality V908 near the Cheyenne River in Fall River County. Evans exploration map (Owen, 1852) shows details of the Cheyenne River near the Black Hills sufficient to indicate that he must have visited the area and may have made collections.

In view of the current restudy of many older localities within the Niobrara Formation and the stratigraphic implications of *Enchodus* species (Stewart, 1990), a more complete study of the holotype of *Enchodus shumardi* is warranted, particularly testing of the matrix for calcareous nannofossils, a group useful in correlations (Watkins et al., 1990). Stewart (1990) suggested that the species occurs in the upper half of the Smoky Hill Chalk Member, whereas these specimens suggest a somewhat longer range from the middle Niobrara to the top of the formation.

Incidentally, our restudy of the holotype of *Enchodus dirus*, ANSP 5347, recovered from the Fox Hills Formation along the Cannonball River in North Dakota (Leidy, 1873; Goody, 1976), confirms the accuracy of the collection data.

Enchodus petrosus

Stewart (1990) noted that *E. petrosus* extends from the base of the Smoky Hill Chalk Member into the suprajacent Pierre Shale.

Referred specimens-SDSM 22491, maxilla with dentition and palatine tooth from SDSM V8719, upper Smoky Hill Chalk Member; SDSM 22346, palatine tooth from SDSM V8918, middle Niobrara Formation; SDSM 19980, palatine tooth and lower jaws with dentition from SDSM V908, middle Niobrara Formation; SDSM 19981, cranium and lower jaws with dentition (Fig. 2c) from SDSM V908, middle Niobrara Formation; SDSM 19987, lower jaw with dentition from SDSM V908, middle Niobrara Formation; SDSM 23020 (part), palatine tooth from SDSM V9011, 1 meter below Niobrara/Pierre contact; SDSM 32694, palatine tooth from SDSM V966, 5 meters below Niobrara/Pierre contact; SDSM 32701, portions of both palatines, palatine tooth, and vertebrae from SDSM V968, 2.5 meters below Niobrara/Pierre contact; SDSM 32709, palatine from SDSM V9610, .9 meters below the Niobrara/Pierre contact; SDSM 32761, lower jaw from SDSM V921, uppermost Niobrara Formation.

Description-All palatine teeth (fangs) lack barbs, have anterior and lateral smooth cutting edges, a smooth anterolateral face, a striated medial face, and are asymmetrical. The dentary teeth likewise lack barbs, and marginal teeth are lacking. All specimens are relatively large with palatine teeth up to 3.5 cm in height.

Discussion-Stewart (1990) noted that this species ranges throughout the Smoky Hill Chalk Member in Kansas, and a similar stratigraphic distribution is indicated by the South Dakota specimens.

Enchodus gladiolus

Stewart (1990) described *E. gladiolus* as having a range throughout the Smoky Hill Chalk Member of the Niobrara Formation in Kansas. The holotype is an untraced AMNH specimen from near Butte Creek south of Fort Wallace, Kansas (Goody, 1976). Goody synonomized *Enchodus dolichus* with *Enchodus gladiolus*; the holotype of *E. dolichus* is AMNH 1820.

Referred specimens-SDSM 19986, operculum and lower jaw with dentition from SDSM V908, middle of Niobrara Formation; SDSM 32759, dentary from SDSM V921, uppermost Niobrara Formation.

Description-These specimens possess marginal teeth in addition to the larger, primary teeth and lack post-apical barbs on the primary dentary teeth.

Discussion-The species has been found in the upper member of the Niobrara Formation in Kansas and from the middle through the uppermost Niobrara in South Dakota, a similar biostratigraphic distribution in the formation.

Family Cimolichthyidae
Genus Cimolichthys
Cimolichthys nepaholica

Stewart (1990) noted that *C. nepaholica* ranges throughout the Smoky Hill Chalk Member of the Niobrara Formation in Kansas.

Referred specimens-SDSM 32733, hypural plate, 2 vertebrae, and fin spines from SDSM V908, 44.9 meters below the Niobrara/Pierre contact; SDSM 23020 (part) numerous teeth from SDSM V9011, 1 meter below the Niobrara/Pierre contact; SDSM 32752, tooth from SDSM V937, 30-

35 meters above Carlile/Niobrara contact.

Description-The hypural plate matches closely that figured by Goody (1970) and VP-11055 in the Sternberg Memorial Museum in Hays, Kansas. The vertebrae are spindle-shaped and ornamented by radiating, longitudinal ribs. Teeth attributed to *C. nepaholica* are relatively small, medial recurved cones which are robust near the root and quickly taper to a needle-like point. Small bony bases of attachment are frequently present (Schumacher, 1997).

Discussion-The South Dakota representatives of this species were collected from lower, middle, and upper Niobrara Formation, a similar range as found in Kansas.

Family *Incertae sedis*
Genus *Apateodus*
cf. *Apateodus* sp. indet.

Referred specimens-SDSM 25796, numerous teeth from SDSM V925, 2 meters below Niobrara/Pierre contact; SDSM 32763, impression of lower jaw from SDSM V921, uppermost Niobrara Formation.

Discussion-These specimens were identified by J. D. Stewart of the Los Angeles County Museum. Their occurrence in the uppermost Niobrara Formation does not conflict with the upper Smoky Hill Chalk distribution in Kansas (Stewart, 1990).

Family Dercetidae
Genus *Stratodus*
Stratodus apicalis

Stewart (1990) noted that *S. apicalis* occurs from relatively low in the Smoky Hill Chalk Member (zone of *Spinaptychus* n. sp.) into the overlying Pierre Shale.

Referred specimens-SDSM 23020 (part), 3 teeth from SDSM V9011, 1 meter below Niobrara/Pierre contact.

Description-Referred teeth of this fish are round in cross-section, and sigmoid-shaped laterally due to a recurved crown. As noted by Stewart (1900), the teeth are highly smooth and are entirely without striae, even when viewed under the microscope. Curiously, the referred specimens are dark blackish-brown, a feature not noted in the hundreds of other associated shark and bony fish teeth (Schumacher, 1997).

Discussion-These specimens were found associated with a skeleton of *Polycotylus latipinnis* which occurred just below the Niobrara/Pierre contact. This stratigraphic position lies within the biostratigraphic range of the species noted by Stewart (1990).

Osteichthyes, order indet.

Referred specimens-SDSM 4319, scales from SDSM V9013, upper Niobrara Formation; SDSM 22347, tooth from SDSM V8918, upper Niobrara Formation; SDSM 22348, scale from SDSM V8918, upper Niobrara Formation.

Class Reptilia
Order Chelonia
Family Toxochelyidae
cf. *Lophochelys* sp. indet.

Referred specimen-SDSM 22361, isolated peripheral bone from SDSM V8921, upper Niobrara Formation.

Description-SDSM 22361 has the distinctive serrated margin of peripherals of the Lophochelyinae but is not otherwise identifiable.

Toxochelyidae, sp. indet.

Referred specimens-USNM 357136, partial skeleton from along the Missouri River near Yankton, South Dakota; SDSM 32703, limb elements from SDSM V968, 8 centimeters below Niobrara/Pierre contact; SDSM 32698, limb elements from SDSM V967, just below Niobrara/Pierre contact.

Description-USNM 357136, collected by David Jones, is a juvenile toxochelyid consisting of a major portion of the carapace. However the specimen is unprepared, so no more precise identification was possible during our inspection. The other specimens also represent relatively small individuals of toxochelyids.

Discussion-Although this material is not exceedingly diagnostic at the present stage of preparation, we suspect specimens of *Toxochelys latiremis* will be identified in South Dakota based upon their relatively common occurrence in the Smoky Hill Chalk Member of Kansas.

Order Plesiosauria
Family Polycotylidae
Genus *Polycotylus*
Polycotylus latipinnis

This taxon has been the subject of repeated controversy. The type specimen from near Fort Wallace, Logan County, Kansas, consists of vertebrae, ilium, metapodials and phalanges which are split between two repositories: AMNH 1735 and USNM 27678. Some authors consider these elements to be undiagnostic and question the validity of this plesiosaur. However, Williston (1903, 1906, 1908) appears to have solved the problem when he described a paratype, YPM 1125, a nearly complete skeleton with skull elements from the upper Niobrara Formation near the Smoky Hill River at Fort Wallace, Logan County Kansas. The paratype is from the same area as the type specimens, and the types are indistinguishable from those represented in the skeleton of the paratype. Therefore, the erection of a new taxon for this species appears unneeded.

Referred specimen-SDSM 23020, nearly complete articulated skeleton from SDSM V9011, 1 meter below Niobrara/Pierre contact.

Description-SDSM 23020 is indistinguishable from YPM 1125 or the type elements. This taxon is distinct by the combination of the following characteristics: phalangeal proportions as noted by Schumacher and Martin (1995), possession of a supernumerary epipodial on both front and rear paddles, exceedingly long ischium, and deeply excavated facets for haemal arch articulation on the caudal vertebrae.

Discussion-This taxon appears in the upper Niobrara Formation in both Kansas and South Dakota. It persists into the Pierre Shale, based upon specimens found also in South Dakota. SDSM 23020 will be fully described by the first author in a later contribution.

cf. *Polycotylus* sp. indet.

Referred specimen-SDSM 32723, four distal phalanges from the leading edge of paddle from SDSM V9613, 15 meters below Niobrara/Pierre contact.

Description-These specimens are similar to those of SDSM 23020 in their squat, robust proportions (average maximum length/average maximum width = 1.27; 1.30 in SDSM 23020 (Schumacher, 1997).

Polycotylidae, gen. indet.

Referred specimens-SDSM 11763, 17727, 17728, 17729, 8 vertebral centra and portions of 3 propodials found as float, but probably associated and belonging to a single individual from SDSM V8918, uppermost Niobrara Formation; Partial skeleton send to E.D. Cope by N.H. Winchell from an unknown locality of the Niobrara Formation in South Dakota (Cope, 1894; Welles, 1952).

Description-SDSM 11763 and 17727-17729 (Fig. 2d) were all found in close proximity as float on the shoreline of the Missouri River. We kept the elements separate because we cannot prove their association as one individual, but similar size, preservation, and their close proximity suggests the probability that they do represent one individual. The elements are relatively large, almost twice as large as those of *Dolichorhynchops osborni* from the Niobrara Formation of Kansas. These specimens are more similar to those of SDSM 23020 discussed above.

Discussion-No specimen number was provided by either Cope (1894) or Welles (1952) in their discussions of a partial skeleton collected by N.H. Winchell. The present location of the specimen is unknown to us; it may reside in Philadelphia or New York, or may have been lost. Cope (1894) described the specimen as *Elasmosaurus* sp., but Welles (1952) considered the creature as a "pliosaurian." The specimen remains the first plesiosaur to be described from South Dakota, although the specimens noted by Lewis and Clarke (mentioned above) most likely was a plesiosaur.

Order Pterosauria
Family Ornithocheiridae
Genus *Pteranodon*
Pteranodon sp. indet.

Referred specimens-UCMP 137227, left distal portion of metacarpal and proximal portion of phalanx 1 from UCMP V71029, Niobrara Formation; SDSM 32756, impression of proximal half of humerus from SDSM V921, uppermost Niobrara Formation.

Discussion-During a field trip through southwestern South Dakota in 1969, J. Howard Hutchison collected the articulated portion of a left wing of the flying reptile, *Pteranodon*, from the Niobrara Formation in Shannon County. The impression of the humerus was collected and identified by J. D. Stewart. These specimens represent the only documented occurrences of flying reptiles from the Niobrara Formation of South Dakota. The specimen mentioned by Brown (1904) in the stomach region of *Styxosaurus browni* (AMNH 5803) is now considered to have been collected from the younger Pierre Shale.

Order Squamata
Family Mosasauridae
Genus *Clidastes*
Clidastes propython

Stewart (1990) listed the species as occurring only in the zone of *Hesperornis* at the top of the Smoky Hill Chalk Member in Kansas, whereas Sheldon (1996) indicated the species occurs in the upper half of the Smoky Hill Chalk Member. Russell (1967) proposed a bipartite subdivision of the Niobrara Formation based partially on the occurrence of *Clidastes propython* in the upper chalk and *Clidastes liodontus* in the lower portion.

Referred specimen-WHO unnumbered, a block of chalk containing frontal, prefrontal, pterygoid, two dentaries, jugal, four cervical vertebrae, trunk vertebrae, 10 ribs from near Marindahl Dam spillway, Yankton County, 4.6 meters below Niobrara/Pierre contact. Also associated on the chalk block are two molds of *Baculites* and a tooth of *Squalicorax kaupi*.

Description-Sevon (1957) originally discussed the specimen and noted that it represents the first definite mosasaur described from the Niobrara chalk of South Dakota. The specimen consists of a disarticulated skull (Fig. 2e), as well as ribs and vertebrae. The skull elements include a frontal which is not emarginated medially on its posterior end (Fig. 2f) and is 13 cm wide. The pterygoid (Fig. 2f) possesses eight preserved teeth and approximately five alveoli. Sevon (1957) illustrated a parietal, which has been subsequently lost. The distarticulated left lower jaw includes the articular, surangular, angular and dentary, containing 12 teeth and seven or eight alveoli and extending 38.5 cm. The right dentary contains 13 teeth and seven alveoli and is 40.4 cm long. Overall, the dentary tooth count is approximately 20 teeth. The cervical vertebrae exhibit functional zygosphenes as are characteristic of *Clidastes* (Russell, 1967). Only one vertebra (Fig. 2g) was positioned in the chalk so an anteroposterior measurement of 7.1 cm could be made. The ribs include those from both cervical and trunk regions.

Discussion-The characteristics of the frontal, and tooth counts of the pterygoid and dentaries support assignment to *Clidastes propython* (Russell, 1967, Bell, 1997). Sevon (1957) referred this specimen to *Clidastes tortor* ten years before Russell's (1967) monograph. The synonomy of *Clidastes tortor* with *Clidastes propython* indicates that Sevon was correct in his taxonomic assignment.

Clidastes sp. indet.

Referred specimens-SDSM 32713, proximal portions of right and left scapulae, trunk vertebral fragments from SDSM V9610, 1.2 meters below the Niobrara/Pierre contact; SDSM 32698, two associated small trunk vertebrae from SDSM V967, just below the Niobrara/Pierre contact.

Discussion-The vertebrae of both specimens possess well developed zygosphenes and zygantra, and the scapulae of SDSM 32713 possess an interdigitate suture with the coracoid. These characteristics are diagnostic of the Mosasaurinae Williston (Bell, 1997). *Clidastes* is the only mosasaurine genus known from the Niobrara Formation; therefore, these specimens are referred tentatively to this taxon. The vertebrae of SDSM 32698 represent a juvenile individual (approximately 20 cm in length) and occurred as stomach contents associated with a large mosasaur.

Genus *Platecarpus*
Platecarpus tympaniticus

Referred specimen-SDSM 32715, partial skeleton including a major portion of skull, cervical series, pectoral girdles, left humerus, trunk vertebrae, and ribs from SDSM V9610, 1.6 meters below Niobrara/Pierre contact.

Description-The tooth counts, lack of rostrum, morphology of the quadrate, humerus, and pectoral girdles indicate this specimen should be assigned to *Platecarpus*. The keel on the dorsal midline of the frontal is characteristic of *P. tympaniticus* (Bell, 1997).

Discussion-*Platecarpus tympaniticus* is known from approximately the upper half of the Smoky Hill Chalk Member is Kansas (Sheldon, 1996), and this specimen falls within this range. Interestingly, two ribs of SDSM

32715 were broken either at or shortly following the individual's death (Schumacher, 1997).

Platecarpus sp. indet.

Referred specimens-SDSM 22351, right radius from SDSM V9011, 7 to 8 meters below Niobrara/Pierre contact; SDSM 32771, portion of right quadrate, disarticulated lower jaw, coronoid, 4 cervical vertebrae, cervical rib from SDSM V9420, 4 to 5 meters below Niobrara/Pierre contact; SDSM 32742, femur and phalanges from SDSM V919, middle Niobrara Formation; SDSM 32707, dentary portion and atlas neural arch from SDSM V969, 5.4 meters below Niobrara/Pierre contact; SDSM 32728, weathered humerus and partial radius and ulna from SDSM V9615, 37 meters below Niobrara/Pierre contact; SDSM 32738, partial weathered skeleton from SDSM V908, 42.2 meters below Niobrara/Pierre contact.

Description-The radius (Fig. 2h) from the Black Hills region is small, only 56 mm along the proximal-distal axis. The proximal articulation is ovate, the shaft is relatively thick, and the distal expansion is not as great (51mm) as that of *Clidastes*. Overall relatively small size and the morphology of the quadrate, humerus, and vertebrae of the other listed specimens are consistent with that of *Platecarpus*.

Discussion-Most of these specimens were derived from the upper portion of the Niobrara Formation, and SDSM 32738 and 32742 were derived from the middle portion of the Niobrara. These occurrences fall within the illustrated range of *Platecarpus* from the entire Niobrara Formation in Kansas (Stewart, 1990).

Genus *Tylosaurus*
Tylosaurus proriger

Referred specimens-SDSM 32772, cranium and lower jaws, ribs, phalanges found by Mr. Ben Vrana from along the Missouri River, Yankton County; SDSM 25796, weathered cranium, lower jaw, articulated distal half of tail, rib, and phalangeal fragments from SDSM V925, 2 meters below Niobrara/Pierre contact.

Description-SDSM 25796 was described and figured by Schumacher and Martin (1993). The quadrate of SDSM 32772 bears a short suprastapedial process and a high, very large infrastapedial process which is diagnostic of *T. proriger*.

Discussion-This mosasaur species occurs in the upper third of the Smoky Hill Chalk Member in Kansas (Sheldon, 1996). SDSM 25796 occurred just below the Niobrara/Pierre contact, whereas SDSM 32772 occurred within a thick section of chalk of as yet undetermined position within the Niobrara Formation.

Tylosaurus sp. indet.

Referred specimens-SDSM 2493, 34 articulated caudal vertebrae from SDSM V244, Niobrara Formation; SDSM 17621, 2 anterior caudal vertebrae from SDSM V8918, upper Niobrara Formation; SDSM 17622, eight distal caudal vertebrae from SDSM V8918, upper Niobrara Formation; SDSM 22341, four caudal vertebrae from SDSM V8921, near top of Niobrara Formation; SDSM 25797, radius and 20 large caudal vertebrae from SDSM V921, upper Niobrara Formation; SDSM 32698, nine distal caudal vertebrae from SDSM V967, just below Niobrara/Pierre contact; SDSM 32729, 24 associated caudal vertebrae and haemel spines from SDSM V9615, 25.5 meters below Niobrara/Pierre contact; SDSM 32714, proximal end of ilium, distal ends of both femurs, caudal vertebra from SDSM V9610, just below the Niobrara/Pierre contact.

Description-SDSM 2493 was collected by the late James Bump, Museum of Geology, in 1924 from a locality "three miles southwest of Oral." Preservation of the vertebrae and the occurrence of chalk in this area suggests a Niobrara source. The caudal section includes 34 vertebrae, representing the distal end of the tail. Only one or two vertebrae from the tip of the tail appear to be missing. The neural spines of the anterior 12 vertebrae are directed anteriorly, those in the middle of the tail section are vertical, whereas the last three neurals angle posteriorly. Of interest is evidence of disease or injury on the lateral centra surfaces between the fourth and fifth vertebrae from the distal end.

SDSM 17621 and 17622 may represent the same individual, but because all specimens were found as float, we have been conservative and maintained separate specimen numbers. All vertebrae are twice the size of those of *Platecarpus* or *Clidastes*, and the anterior caudal vertebrae exhibit a triangular cross-section and shallow articular faces.

Discussion-The majority of tylosaurines thus far reported from South Dakota are from the upper Niobrara Formation.

Mosasauridae, gen. indet.

Referred specimens-SDSM 4399, tooth from SDSM V9013, upper Niobrara Formation; SDSM 22356, vertebra; SDSM 22357, 2 vertebrae; SDSM 22358, proximal and distal caudal vertebrae from SDSM V9014, upper Niobrara Formation; SDSM 32753, tooth from SDSM V937, 30 to 35 meters above Carlile/Niobrara contact; SDSM 32695, portion of dentary and associated fragments from SDSM V966, 8 meters below Niobrara/Pierre contact; SDSM 32773, weathered vertebra from SDSM V9616, 25 to 30 meters above Carlile/Niobrara contact.

Discussion-SDSM 32753 and 32773 are the lowest documented occurrences of mosasaurs in the Niobrara Formation of South Dakota.

Class Aves
Order Hesperornithiformes
Family Hesperornithidae
Genus *Hesperornis*
Hesperornis regalis

Stewart (1990) regarded the zone of *Hesperornis* for the uppermost portion of the Niobrara Formation. Many of the vertebrate taxa listed by Stewart (1990:30) as occurring within the zone also extend upward into the lower Pierre Shale. Moreover, *Hesperornis*, itself extends much higher in the Pierre Shale, so the terminus of the zone of *Hesperornis* requires refinement.

Referred specimens-SDSM 25005, left femur, tibiotarsus, and fibula from SDSM V919, upper Niobrara Formation; SDSM 32689, proximal portion of left femur, distal portion of tibiotarsus, fibula, tarsometatarsus, and 2 phalanges from SDSM V8922, 1 meter below Niobrara/Pierre contact; SDSM 32716, portions of tibiotarsus, distal portion of tarsometatarsus from SDSM V9614, 2 meters below Niobrara/Pierre contact.

Description-Martin and Varner (1992) described and figured SDSM 25005 after the initial paper concerning the Niobrara paleofauna was composed. The left leg elements of this individual are identical to those of *Hesperornis regalis* (Marsh, 1880). The femur and tibiotarsus of SDSM 32689 are similar to those of SDSM 25005, and the tarsometatarsus of SDSM 32716 is similar to that of SDSM 32689. Therefore, we consider all these large avian elements attributable to *Hesperornis regalis*.

Discussion-All these specimens were collected from the upper Niobrara Formation, a consistent position compared to similar specimens in

Kansas (Stewart, 1990), and confirming evidence of the zonation proposed by Stewart.

Order Ichthyornithiformes
Family Ichthyornithidae
Genus *Ichthyornis*
cf. *Ichthyornis* sp. indet.

Referred specimen-SDSM 32766, weathered limb fragments and impressions from SDSM V921, uppermost Niobrara Formation.

Discussion-This specimen consists of portions of small avian limb elements in a block of chalk found as float in the uppermost Niobrara Formation and identified by J. D. Stewart, Los Angeles County Museum.

Coprolites

Referred specimens-SDSM 22349, 4 coprolites from SDSM V8918, upper Niobrara Formation; SDSM 22350, coprolite from SDSM V8918, upper Niobrara Formation; SDSM 17627, coprolite from SDSM V8919, middle Niobrara Formation; SDSM 22362, coprolite from SDSM V8718, Niobrara Formation.

Description-The largest of the four coprolites assigned as SDSM 22349 and all others listed above contain fish remains. The coprolites are spheroidal to oval bodies which are usually harder that the surrounding chalk matrix. As such, they normally weather out as pebble-sized clasts, and when embedded in chalky matrix, are easily excavated. In contradistinction is SDSM 22362, a coprolite discovered in the chalk block containing the skull of *Pachyrhizodus caninus* (described above). This coprolite appears mostly as a cast, filled with delicate fish bones. The specimen is 7.5 mm in diameter and the preserved length is 22.5 mm. All of the other coprolites also contain very delicate fish elements and range in diameter from 10 mm (SDSM 17627) to 18.5 mm (SDSM 22350). The largest coprolite of SDSM 22349 contains two fish scales exhibiting the "fingerprint pattern" similar to that of SDSM 22348, noted above. Both SDSM 22349 and 22350 were found while excavating a plesiosaur skeleton but appear to be too small to be associated. Although conjectural, we suspect all these coprolites to represent those of larger fish.

SUMMARY

Even though the potential for vertebrate fossils from the Niobrara Formation has been known since the first organized explorations into what is now South Dakota, relatively few have been described. Prior to this contribution only specimens of *Xiphactinus audax*, *Enchodus shumardi*, *Tylosaurus proriger*, and *Hesperornis regalis* had been formally described, and the latter two came after this paper was initially sent for publication. Mention has also been made of a mosasaur, herein regarded as *Clidastes propython*, plesiosaurs, and sharks, although none was extensively described. Two specimens of the plesiosaur, *Styxosaurus browni* (Brown, 1904; Welles, 1952), previously attributed to the Niobrara Formation, were found to have been derived from the overlying Pierre Shale. We record from the Niobrara Formation of South Dakota the first described sharks: *Squalicorax kaupi*, *Squalicorax falcatus*, *Microcorax*, *Cretoxyrhina mantelli*, *Echinorhynus*, and *Ptychodus mortoni*; the first representatives of the fish: *Pachyrhizodus caninus*, *Pachyrhizodus minimus*, cf. *Apateodus*, *Ichthyodectes ctenodon*, *Bananogmius evolutus*, *Cimolichthys nepaholica*, *Stratodus apicalis*, *Saurodon leanus*, *Saurocephalus lanciformis*, *Enchodus petrosus*, and *Enchodus gladiolus*; the first turtles: cf. *Lophochelys* and seemingly another toxochelyid; the flying reptile, *Pteranodon*; the mosasaur, *Platecarpus tympaniticus*; and the bird, cf. *Ichthyornis*. The relatively brief time spent gathering these specimens gives us hope for future success.

Stratigraphic data are known for most of these specimens (see Systematic section) and can be compared to ranges documented in Kansas. Overall, the examples from South Dakota occur primarily in the middle and especially upper portions of the Niobrara Formation. Reptiles and birds are generally more common in the upper Niobrara Formation in both South Dakota and Kansas. Restriction of *Ptychodus mortoni* to early medial Coniacian time in South Dakota may indicate gradual, more southerly range restriction through the time of deposition of the Niobrara Formation. *P. mortoni* ranges into the late medial Santonian in Kansas and survives later in the southern United States. *Squalicorax falcatus* is reported from the late Coniacian to medial Santonian in Kansas but is known from the early Campanian of southwestern South Dakota; *Squalicorax kaupi* is reported from the early Campanian in Kansas but appears earlier in the Santonian of southwestern South Dakota. A tooth of *Cretoxyrhina mantelli*, which was found just below the Niobrara/Pierre contact, may represent the latest occurrence of this shark in the midcontinent. Teeth of *Echinorhynus* associated with reptilian skeletons represent the first record of this genus in North America. *Saurocephalus lanciformis* appears to first occur in Kansas from the early Campanian, but a specimen from southwestern South Dakota occurs in the Santonian. A partial skeleton of *Protosphyraena nitida* from the Missouri River may represent the first record of this taxon from the uppermost Niobrara Formation. *Hesperornis regalis* occurs in the uppermost Niobrara Formation of both Kansas and South Dakota (Schumacher, 1997). The latter distribution expands the geographic distribution and reinforces the validity of the zone of *Hesperornis* of Stewart (1990).

We are pleased with these gains in the study of the Niobrara paleofauna in South Dakota, particularly as some authorities are beginning to analyze the regional aspects of the Niobrara paleofauna (e.g. Stewart, 1990; Nicholls and Tokaryk, 1990). In order to better understand the paleofauna in South Dakota, additional specimens from the type areas of previously described taxa should be secured, and the succession should continue to receive careful, stratigraphic collection. In particular, the relationships to these taxa to bentonites which may be of regional extent should be documented.

These specimens are important because the distribution and biostratigraphy of specimens in South Dakota may be studied without the necessity of hindsight nor latter day determinations of the stratigraphic positions of old specimens. Thus, South Dakota has the potential for a relatively undisturbed sample which may be compared to classic exposures and taxa from elsewhere. The South Dakota specimens are generally identifiable, but are not so spectacular as to attract the interest of nonacademic collectors. We hope that the Niobrara Formation of South Dakota can be studied as an entire sample without loss of critical specimens and biostratigraphic and taphonomic information.

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UPPER CRETACEOUS STRATIGRAPHY OF BADLANDS NATIONAL PARK, SOUTH DAKOTA: INFLUENCE OF TECTONISM AND SEA LEVEL CHANGE ON SEDIMENTATION IN THE WESTERN INTERIOR SEAWAY

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ABSTRACT--The upper Pierre Shale and Fox Hills Formation (Late Cretaceous) are partially exposed along stream valleys throughout the Badlands National Park area. Stratigraphic and sedimentological characteristics of these exposures suggest that four cycles of eustatic sea level change occurred within the Western Interior Seaway during Late Campanian and Maastrichtian time. These cycles are recorded within a long term trend of regression associated with the withdrawal of the Western Interior Seaway and the onset of Laramide regional deformation. The oldest cycle exposed in the park spans the Western Interior ammonite zones of *Baculites compressus* to *B. reesidei* (Late Campanian - Verendrye Member of Pierre Shale). The second cycle extends from *B. baculus* through *B. clinolobatus* (earliest Maastrichtian - equivalent to the Virgin Creek, Mobridge, and Elk Butte members of Pierre Shale). A third cycle is recorded by the marine Fox Hills Sandstone (late Early Maastrichtian). A final cycle is recorded by a thin unnamed unit (included in the Fox Hills) representing Late Maastrichtian shoreline and terrestrial facies.

Stratigraphic sequences representing transgressive- regressive cycles are bounded by unconformities. Pedogenic weathering profiles are locally preserved beneath these unconformable surfaces. Progressive tectonic uplift in the Badlands region is indicated by the abundance of reworked sediments in some horizons (including fossil-bearing concretions), the occurrence of buried slumps near fault zones, and the thinning of strata associated with Maastrichtian ammonite range zones along the eastern flank of the Black Hills.

INTRODUCTION

Throughout the history of work on the Western Interior Seaway, the name "Pierre Shale" has been applied to the gray, fossiliferous, marine mudrocks exposed along the stream valleys of the Badlands region. F.B. Meek and F. V. Hayden reported in 1862 that the upper portion of their "Fort Pierre Formation" was exposed in the Sage Creek Valley (Agnew and Tychsen, 1965:147). The name, Pierre Shale, remains in usage for this interval throughout the Park and its surroundings.

In contrast, the brightly colored, variably sandy interval above the gray-colored Pierre shales has been referred to by many names, including, in the Badlands, variations of "Rusty Member," "Interior Zone" or "Interior Formation." In addition, field investigators debated whether the unit was equivalent to the Pierre Shale or Fox Hills (Agnew and Tychsen, 1965:104, 105, 162). However, Dunham (1961) established that ancient meteoric weathering along an irregular surface beneath the basal Eocene White River Group was responsible for the brightly colored, iron-stained sediments of the "Interior Formation." Pettijohn (1965) recognized that the ancient weathering profile affected strata equivalent to both the Pierre Shale and Fox Hills Formation in the vicinity of Badlands National Park. This weathering profile, which Pettijohn named the "Yellow Mounds Paleosol," is developed beneath an irregular unconformable surface throughout the park area and is locally missing beneath the basal White River Group.

Gill and Cobban (1966:plates II-III) established a reference section for the Pierre Shale along the northwest flank of the Old Woman Anticline near Red Bird, Wyoming. Gill and Cobban's report also included the first detailed chronology of Late Cretaceous ammonite biozonation for the Western Interior region. They subdivided the Pierre Shale into numerous units: Gammon Ferruginous Member; Sharon Springs Member; Mitten Black Shale Member; Red Bird Silty Member; Lower Unnamed Shale Member; Kara Bentonitic Member; and Upper Unnamed Shale Member, oldest to youngest, respectively. Of the seven members, only portions of the Lower and Upper Unnamed Shale Members correlate to the Badlands National Park region (Stoffer 1998).

Searight (1937) organized exposures of the Pierre Shale along the Missouri River Valley into five members: the Gregory Member; the Sully Member; the Virgin Creek Member; the Mobridge Member; and the Elk Butte Member, oldest to youngest respectively. Crandall (1958) subdivided Searight's Sully Member into three additional units: the Crow Creek Member; the DeGrey Member; and the Verendrye Member, oldest to youngest, respectively. Searight (1937:table 23) reported the occurrence of the ammonite, *Baculites compressus*, within his Sully Member, whereas Crandall (1958:15) recognized the species as occurring within his Verendrye Member. Searight (1937:table 23) recognized the ammonite, *Baculites grandis*, within both the Virgin Creek and Mobridge members, and *Baculites clinolobatus* as occurring exclusively within the Mobridge Member.

Member subdivisions of the Fox Hills Formation include the Fairpoint and White Owl Creek members in the northwestern portion of South Dakota (Pettijohn, 1967). Pettijohn interpreted the Fox Hills as representing deltaic deposits with typical complex stratigraphic relationships. Equivalent members in northern Missouri Valley region of South Dakota include the Trail City Member, Timber Lake Member, and Iron Lightning Member, oldest to youngest, respectively (Landman and Waage, 1993). Gill and Cobban (1973) demonstrated that the Fox Hills Formation represents a structurally-controlled, eastward-prograding, complex deltaic sequence. Their studies based on ammonite biozonation indicate that the Fox Hills Seaway withdrew from the Wyoming region in Early Maastrichtian time, and from the northern and central region of South Dakota progressively in Late Maastrichtian time.

It is clear from this abbreviated account that the stratigraphy of the Pierre Shale/Fox Hills interval is still not well correlated across the seaway, and that much remains to be done before a well developed regional stratigraphic picture has been achieved. It is also clear that the Badlands National Park region occupies a geographically crucial central location in the outcrop belts of Upper Cretaceous Seaway strata. Thus, clarifying the Upper Cretaceous stratigraphy of the Badlands, and correlating Badlands strata with areas both east and west, should be a key element in elucidating the regional geology of the Seaway, and in advancing interpretation of Seaway paleogeography, paleoecology, tectonism, and eustacy.

We have examined exposures of strata in the Pierre/Fox Hills interval from the Badlands area, elsewhere in South Dakota and in Wyoming. Badlands sites studied in this project, the focus of the present paper, are shown in Fig. 1.

GENERAL GEOLOGY OF THE BADLANDS AREA

Late Cretaceous-age strata crop out beneath younger sedimentary cover of the Tertiary White River Group in the Badlands National Park area. The lower portion of the Cretaceous section consists of gray, fossiliferous marine mudrocks of the upper Pierre Shale. Fossils observed within the Park correlate with the Western Interior ammonite range zones from *Baculites compressus* (Late Campanian) to *Hoploscaphites birkelundi* (Early Maastrichtian)(Kennedy et al., 1995:fig. 1; Larson et al., 1997:19-41). These strata are overlain by brightly colored yellow to reddish brown sandstone and shale units that are generally barren of fossils, but are probably of Late Maastrichtian age. These younger strata are heavily altered due to severe weathering by meteoric water associated with subaerial exposure following the withdrawal of Western Interior

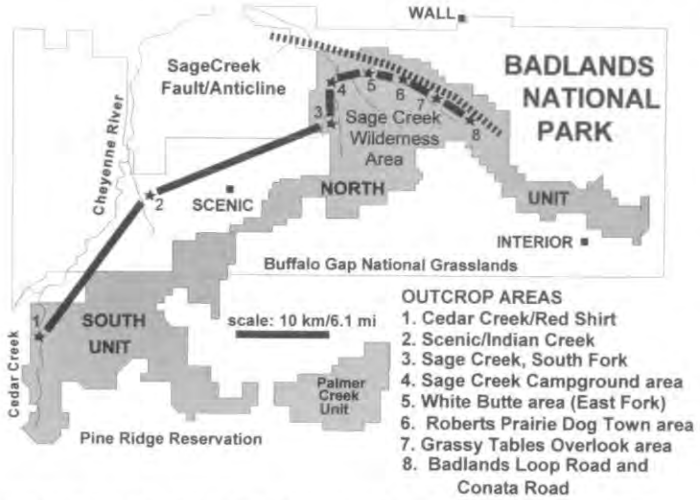


FIGURE 1 - Map of Badlands National Park showing the locations of measured sections.

Seaway at the end of Cretaceous time. Within the deeply weathered sedimentary profile of the uppermost Cretaceous section, glauconitic sand facies of the Fox Hills Formation are preserved in the North Unit of the Park.

Badlands Stratigraphy and Correlation

A composite columnar Cretaceous section for the Park is presented in Fig. 2. This composite is based on measured sections within the Sage Creek Wilderness Area shown in Fig. 1, and illustrates the general character of sedimentary features and biozonation for the Sage Creek Wilderness area within the North Unit of Badlands National Park. The diagram includes Western Interior ammonite biozonation after Kennedy et al., (1995: fig. 1) and Missouri River Valley stratigraphic nomenclature for the Pierre Shale after Crandall (1958), applied to the Badlands as described by Stoffer (1998). We propose for the Badlands the use of Missouri River Valley member designations of the Pierre Shale. This usage is appropriate because in terms of ammonite biozonation, lithological characteristics, and stratigraphic boundaries, the Badlands section is remarkably similar to the Missouri River exposures, as discussed in detail by Stoffer (1998).

Badlands survey data indicate that thicknesses of stratigraphic units of the Pierre Shale across the area are highly variable, particularly for Maastrichtian units (Fig. 3). Fig. 4 illustrates the equivalent thickness of Pierre Shale stratigraphic units, based on the thickness of Late Cretaceous ammonite range zones, between Badlands National Park and the two type areas of the Pierre Shale in the region: Redbird, Wyoming (Gill and Cobban, 1966) and near Mobridge, South Dakota (Searight, 1937; Stoffer, 1998). The stratigraphic section of the Pierre Shale exposed in the Badlands National Park area is less than half that of equivalent units in the Missouri River Valley region and between a quarter to one tenth as thick as equivalent units along the western flank of the Black Hills. Searight (1937) demonstrated that the thickness of members of the Pierre Shale varied considerably along the Missouri River Valley through South Dakota. His measurements of just the Virgin Creek, Mobridge, and Elk Butte Members near Mobridge totaled about 180 meters. The total thickness of equivalent stratigraphic units within the Pierre Shale described by Crandall (1958) is approximately 150 meters in the Pierre area in central South Dakota. Measurements prepared by Gill and Cobban (1966:50-53) reported a thickness of approximately 320 meters for the equivalent stratigraphic interval within the Pierre Shale in the Red Bird area (Niobrara County, Wyoming).

In the South Unit of Badlands National Park the interval between the lowest exposures of the *Baculites compressus* Zone to the top of the exposed fossil-barren, slightly sandy interval above the *Baculites clinolobatus* Zone (below the pre-Chadron unconformity) is approximately 40 meters thick. This interval thickens to roughly 55 meters in the vicinity of the Sage Creek Campground in the North Unit of Badlands National Park. It progressively thickens to approximately 90 meters along the hillsides north of Wasta, South Dakota, on the Tom Trask Ranch in Sec. 23, T. 3 N., R. 14 E.

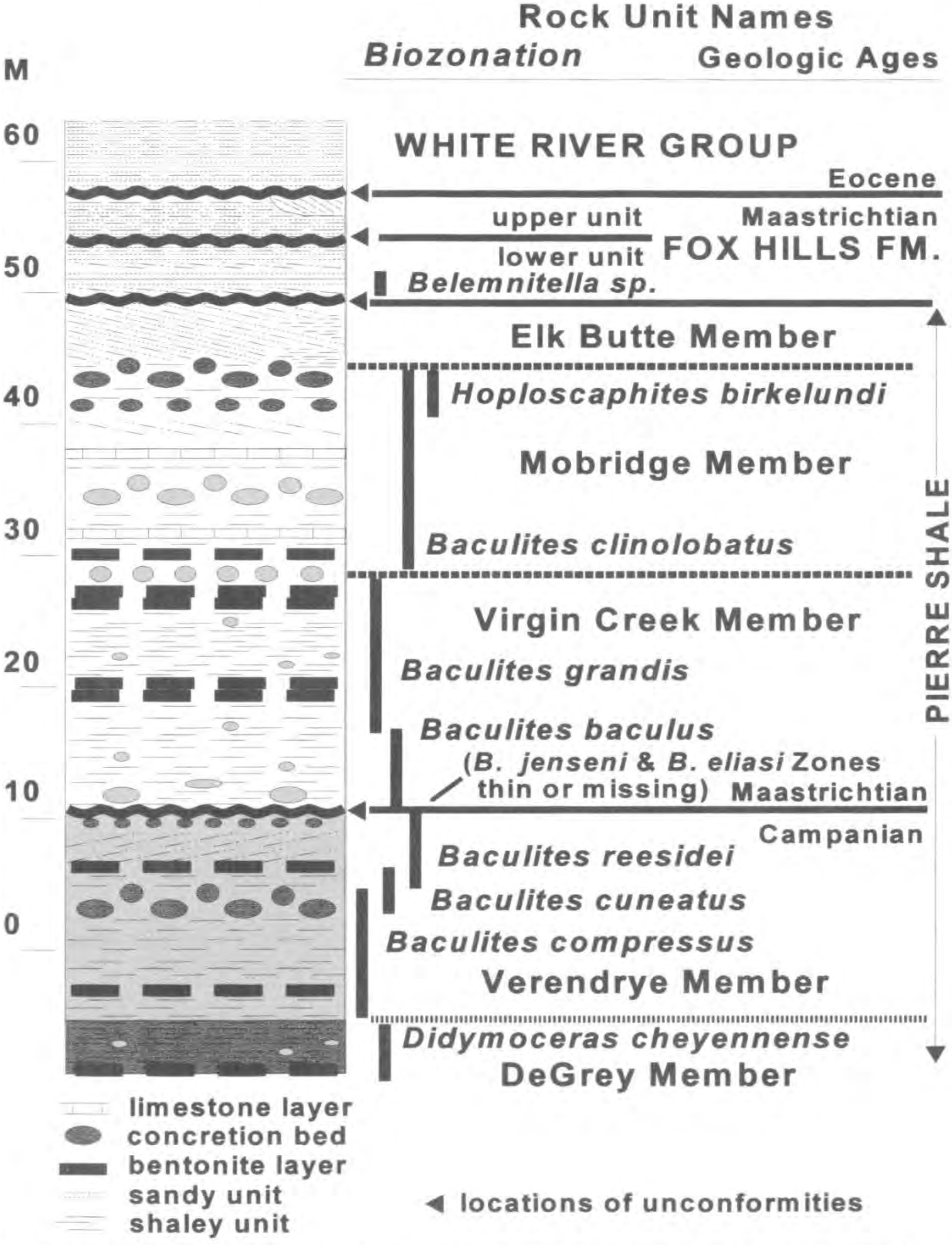
Correlation of the Fox Hills Formation within the Park area, and regionally, is particularly difficult due to 1) a general lack of fossils; 2) the highly variable character of sedimentary facies between exposures; and 3) the influence of structural movement along the Sage Creek anticline/fault system (see Fig. 1) contemporaneous with the deposition of the Cretaceous sediments of the region. The interpretation of the stratigraphic thickness variation of the Fox Hills Formation across the Western Interior region and in the Badlands area is problematic. First, it is evident from the fossil record that the Fox Hills was deposited in eastern Wyoming earlier than it was in the Missouri River Valley area of South Dakota (Gill and Cobban, 1973). For example, the Fox Hills fossil, *Hoploscaphites nicolletii*, occurs within fine-grained sediments typical of Pierre Shale facies near Mobridge (Stoffer, 1998). Second, in both the eastern Wyoming area and in the northern central region of South Dakota, the upper members of the Fox Hills contain massive, coarse-grained, cross-bedded, quartz sandstone units. The Fox Hills Formation is greater than 200 meters thick in the Red Bird, Wyoming area (Landman and Waage, 1993:fig.5). Pettijohn (1967) described a thickness for the Fox Hills in a range between 150 and 200 meters in northwestern South Dakota. The Fox Hills Formation approaches 50 meters in thickness in north central South Dakota (Landman and Waage, 1993:fig.4). North of Wall, South Dakota, 50 meters of Fox Hills Formation crops out beneath high tension powerlines in NW¼, Sec. 34, T. 3 N., R. 15 E. Southward from this location the Fox Hills crops out along hilltop exposures along the valley of the Cheyenne River. Based on our survey in the Badlands, the Fox Hills is a maximum of about 28 meters thick along the northern boundary of the North Unit of the Park. It progressively thins toward the south until the last significant coarse quartz sandstone layers vanish along the southern drainage area of Sage Creek in the Park. South, east, and west of the Sage Creek area in Badlands National Park area these massive quartz sandstones were either never deposited or are not preserved. However, the occurrence of thin sandy shales bearing a sparce Fox Hills fauna is indicative of Fox Hills throughout the Park area.

STRATIGRAPHIC CYCLES

Global eustatic changes in sea level during the Late Campanian and Maastrichtian have been interpreted from stratigraphic sections around the world (Haq et al., 1987; King and Skotnicki, 1994; Barrera, 1994; and Hancock, 1993). Evidence of eustatic changes in sea level are preserved within the Pierre Shale/Fox Hills interval with at least four transgressive-regressive episodes recorded in the exposed Cretaceous section within Badlands National Park. Each cycle is bounded by unconformable surfaces which locally preserve evidence of exposure to meteoric weathering. The variation in the thickness of units is probably related to both the early stages of tectonic uplift of the Black Hills Arch and related structural elements in the region, and to the influence that these structural features and water depth had on the flux of sediment into the seaway covering the Badlands National Park area during the Late Cretaceous.

Cycle #1

In the Missouri River Valley region of South Dakota, a Late Campanian transgressive-regressive cycle encompasses the Crow Creek, Degrey, and Verendrye members of the Pierre Shale. Within Badlands National Park, the lower portion of this cycle is not exposed. The uncovered upper portion is defined by the Western Interior ammonite zones of *Baculites compressus*, *B. cuneatus*, and *B. reesidei* (Late Campanian - Verendrye Member). In Badlands, the oldest beds containing *B. compressus* are found at the base of exposures cut by streams at a variety of



BADLANDS NATIONAL PARK

Cretaceous Biostratigraphy and Lithostratigraphy

FIGURE 2 - Composite columnar section for Cretceous rocks of Badlands National Park. Solid lines for stratigraphic boundaries represent unconformities. Dashed boundaries are conformable.

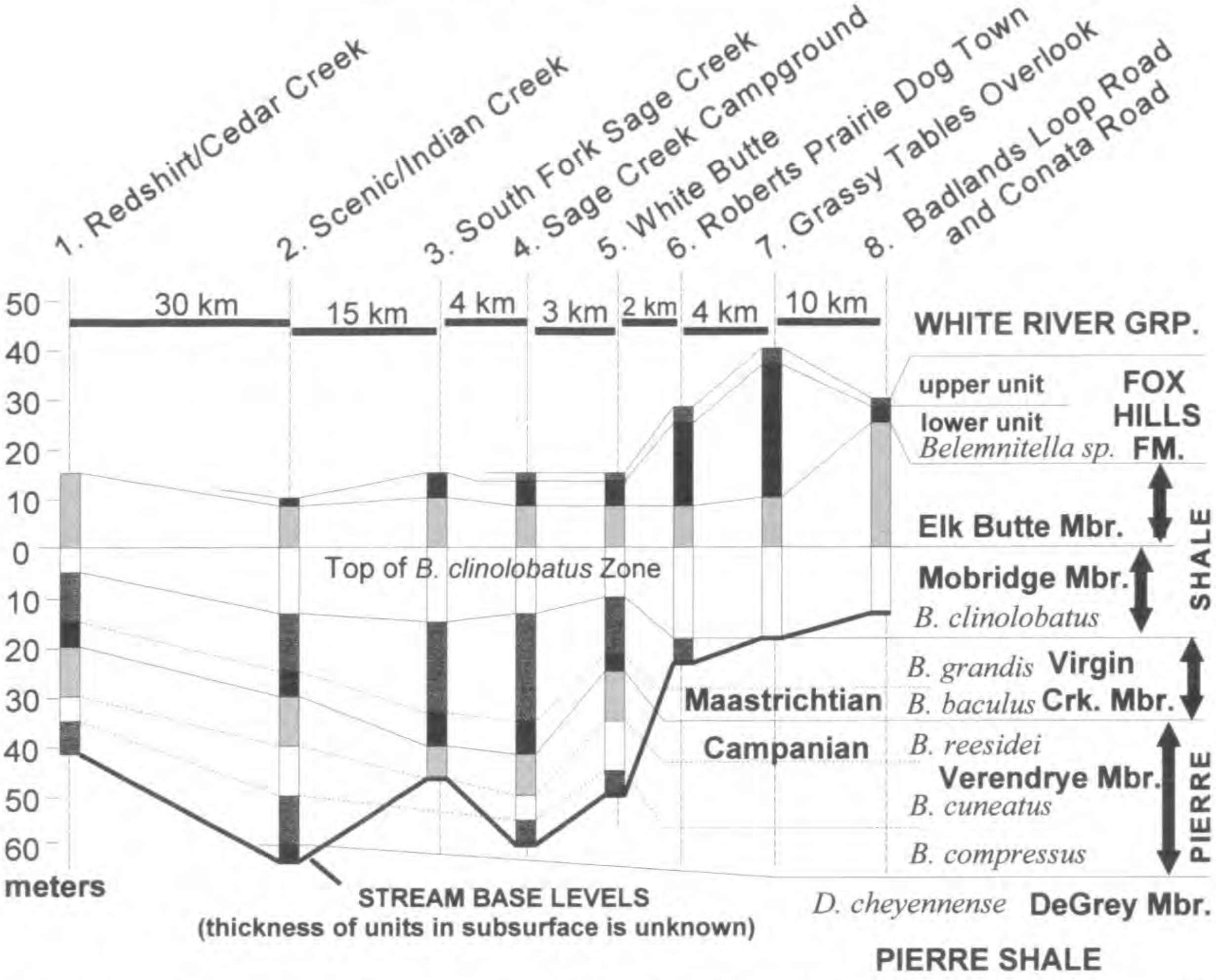


FIGURE 3 - Comparison of the thickness of ammonite range zones between Badlands National Park and type sections of the Pierre Shale near Redbird, Wyoming (Gill & Cobban, 1966) and near Pierre, South Dakota (after Searight, 1937; Crandall, 1958).

sites within the park. The *B. compressus* Zone crops out intermittently along stream level north of the Sage Creek Campground in the North Unit of Badlands National Park. In the Park's South Unit, the *B. compressus* Zone crops out intermittently at stream level along Cedar Creek.

Along the Cheyenne River Valley and tributaries west of the Park, sediments bearing *Didymoceras cheyennense* and other older ammonite range zones crop out. These dark gray sediments bearing bentonite layers and ironstone concretions are equivalent to the DeGrey Member (beneath the Verendrye Member). The existence of bentonite beds and the occurrence of large articulated inoceramids and fragile, yet complete, baculite shells suggest that these sediments were deposited in water depths greater than wave base. Sea level fell during late *B. reesidei* time resulting in both submarine erosion and subaerial exposure in the study area. This episode is represented by an unconformity that defines the boundary between sediments of Campanian and Maastrichtian age throughout the vicinity of Badlands National Park. The Western Interior ammonite zones of *B. jenseni* and *B. eliasi* are very thin or missing along this unconformity. Evidence for this unconformity includes the intermittent occurrence of lag deposits of phosphatic pebbles, mud intraclasts, reworked concretions, and fossils hash. It is also indicated by a general color change of the shale from dark gray below, to light brownish-gray above. This unconformity defines the top of the Verendrye Member and the base of the Virgin Creek Member. An exposure of a pedogenic weathering profile along this unconformity is preserved along the South Fork of Sage Creek approximately 2.5 kilometers south of the Sage Creek Campground in NE¼, Sec. 23, T.2 S., R. 14 E. This layer approaches 2 meters in thickness and consists of reddish-brown clay with limonite crusts impregnating desiccation cracks and root traces. In the Park's South Unit along Cedar Creek, this unconformable boundary between the Verendrye Member and the Virgin Creek Member is highlighted by an abundance of concretions that contain a shell hash representing a mix of several ammonite zones including *Didymoceras cheyennense*, *Baculites compressus*, *B. cuneatus*, and *B. reesidei*. Specimens of *Jeletzkytes crassus* discovered in the South Unit of the Park suggests that sediments equivalent to the upper *B. eliasi* Zone may be locally represented within the reworked lag at the top of this cycle. A one-meter thick reddish (limonite-stained) shale unit above the unconformity suggests that the sediments were partially derived from subaerially exposed source areas nearby.

In eastern Wyoming, the Kara Bentonitic Member is a prominent 3-10 meter thick, ridge-forming marker horizon along the western flank of the Black Hills, separating the Lower and Upper unnamed shale members of the Pierre Shale (Gill and Cobban 1966). The Kara Bentonitic Member occurs within the lower *B. eliasi* Zone. Together, the *B. eliasi* Zone (including the Kara Bentonitic Member) and the underlying *B. jenseni* Zone approach 100 meters in thickness in the Redbird section (Gill and Cobban, 1966). This interval is either missing or insignificant east of the Black Hills because of the unconformity. Within the Sage Creek Wilderness Area in the Park's North Unit, *Baculites reesidei* were observed just beneath the unconformity, whereas specimens of *Baculites baculus* were observed within an interval bearing several thin bentonite beds approximately 2 meters above the unconformity (Fig. 5).

Cycle #2

The second cycle extends from the *B. baculus* through *B. clinoloba-*

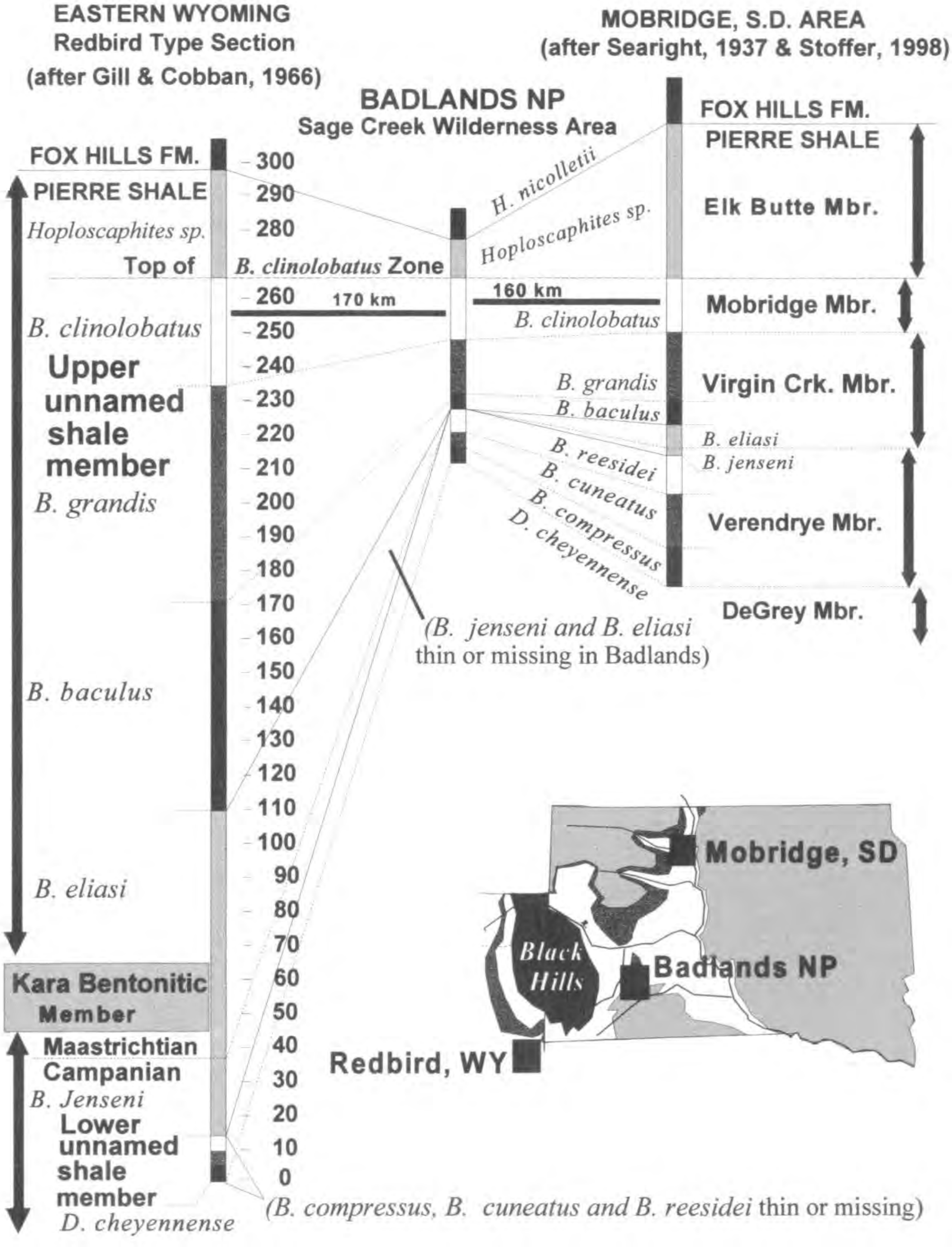


FIGURE 4 - The cross section through Badlands National Park shows the variation in thickness of selected stratigraphic units and Western Interior ammonite zones. Datum is the highest position of the *Baculites clinolobatus* which occurs in association with a bed of gray limestone concretions along the interface between the uppermost gray shales and the overlying colored "weathered zone" in the Pierre Shale.

tus zones (earliest Maastrichtian - equivalent to the Virgin Creek, Mobridge, and Elk Butte members of Pierre Shale). In the Park area, the equivalent strata of the upper Virgin Creek and Mobridge members contain three laterally-continuous limestone concretion beds, with additional concretion beds occurring in some localities. In some locations the concretions approach one meter in thickness, or become laterally linked forming continuous concretionary limestone beds. The occurrence of an abundant and diverse molluscan fauna, arthropod fragments, and sharks' teeth suggests that normal marine conditions persisted across the Badlands National Park region through *B. clinolobatus* time. The presence of several thin bentonite beds within the *B. grandis* Zone and at least one within the *B. clinolobatus* Zone suggests that water depths were great enough to prevent wave scour from destroying ash layers. These ash beds are well exposed in cut banks along the South Fork of Sage Creek, approximately 2 kilometers south of the campground (as illustrated in Fig. 5). They are also well exposed in cut bank exposures on the south side of White Butte along the East Fork of Sage Creek in SE¼, Sec. 5, T. 2 S., R. 14 E.

Fossils of *Baculites clinolobatus* and *Hoploscaphites birkelundi* occur in a 4 meter thick, light bluish-gray, calcareous, ledge-forming, concretion-bearing shale unit that forms the top of the gray, unaltered Pierre Shale throughout the South Fork of the Sage Creek drainage area. Based on the occurrence of the fossils and the high calcareous content of the sediment, this unit is equivalent to the Mobridge Member in the Missouri Valley region.

Above this zone the sediment becomes increasingly sandy and displays the imprint of intense meteoric weathering. Large limonite-cemented sandstone pedogenic concretions occur through this interval (Retallack, 1985). In the North Unit of Badlands National Park, this interval displays thin sand sheets which are often highlighted by limonite crusts. Many of these sand sheets display a southward dip direction, suggesting that they were deposited along the advancing front of a southward prograding clinoform-style mud bank. Based on their biostratigraphic position these sediments represent a sandy phase equivalent to the Elk Butte Member, the youngest member of the Pierre Shale in the Missouri Valley region. This unit increases in thickness and becomes less sandy to the east along the valleys of the Cheyenne and White rivers.

An easily accessible location where clinoform bedding is exposed within sediments of the Elk Butte Member exists along the north and east side of the Badlands Loop Road, approximately 1 kilometer west of the intersection of Conata Road, in SW¼, Sec. 21, T. 2 S., R. 16 E. Here, the beds display bright coloration from limonite staining associated with ancient weathering by meteoric waters. Thin sand sheets highlight the southward dip angle of the clinoform bedding; in some locations south of the Sage Rim Road and in the Dillon Pass area the dip angle of the beds approaches 20 degrees toward the south-southeast. Whether the over-steepened character of these beds is a result of movement along a basement structure associated with the Sage Creek Anticline is unclear.

Additional evidence suggesting that these sediments were deposited on a southward advancing clinoform mud bank includes an abundance of drag marks, flute markings, and soft-sediment roll and slump features. These sedimentological features are common in outcrop exposures throughout the drainages south of the Sage Creek Rim Road, west of the High Pinnacles area. Large ancient slumps in the Elk Butte Member are exposed along the creek beds throughout an area encompassing nearly a square kilometer in the vicinity south of the Grassy Tables Overlook in SE¼, Sec. 13, T.2 S., R. 15 E. Chaotic bedding exposed in cut banks and in giant limonite-cemented sandstone concretions preserves slump glide planes and roll structures, indicating soft-sediment movement toward the south. Similar clinoform-style bedding features are evident through creek bed exposures on either side of the wilderness access trailhead near the Roberts Prairie Dog Town along the Sage Rim Road (SW¼, Sec. 3, T. 2 S., R. 15 E.). Whether the slumping and steep dip angle of the beds have been enhanced by contemporaneous movement of the Sage Creek anticline/fault system is unclear. Clastic dikes, and ancient springs and pond deposits preserved in the Chadron and Brule formations throughout the Sage Creek Wilderness Area, the Pinnacles, and in the Dillon Pass areas may have their origin partly in association with structures of the underlying Pierre Shale.

The occurrence of a southward prograding clinoform mud bank in the Badlands area is consistent with an interpretation of the eastward progradation of the Maastrichtian Sheridan Delta of Gill and Cobban (1973:fig.19). They suggested that a deltaic system prograded eastward in Early Maastrichtian time along the Wyoming/Montana border into South Dakota. The geometry of the southward-dipping clinoform beds in the Badlands region suggests that uplift in the Black Hills deflected the sediment wedge eastward prior to wrapping around the eastern front of the rising uplands. A counter-clockwise current gyre within the remaining seaway would have transported sediment derived from the delta southward into the Badlands area.

The boundary between the Pierre Shale (top of the Elk Butte Member) and the base of the Fox Hills Formation may be an unconformable surface throughout the central South Dakota region. Within the National Park, it is exposed along the creek bed draining from the High Pinnacles area on the west side of the Badlands Loop Road, in the center of SE¼, Sec. 20, T. 2 S., R. 16 E. Along the creek bed thick-bedded-to-massive layers of fine glauconitic sandstone rest unconformably on top of the sandy shale of the Elk Butte Member. The glauconite is apparently unstable in the presence of meteoric water, ultimately breaking down to form limonite, clay, and silica (hence the bright colors of the strata). Small pods of unaltered, bright-green glauconitic sandstone surrounded by limonite-stained weathering rinds crop out along the creek.

A unique exposure of the Pierre Shale/Fox Hills unconformity occurs in a cut bank on the south side of a prominent small hill in the Grassy Tables Overlook area in SE¼, SW¼, Sec. 8, T. 2 S., R. 15 E. (Fig. 6). Stream erosion has exposed chaotic bedding associated with a Maastrichtian slump or series of slumps in the upper Elk Butte Member. The interval bearing the slumps is erosionally truncated and overlain by flat-lying greenish-drab colored sandstone beds of the basal Fox Hills Formation. In contrast, the underlying Pierre Shale beds are brightly colored, suggesting that they were affected by meteoric weathering and erosion prior to deposition of the Fox Hills beds. The flat-lying character of the sediments overlying the top of the slumped beds suggests that wave scour had beveled the surface prior to the deposition of the basal glauconitic sandstone of the Fox Hills Formation.

Cycles #3 AND #4

The sandstone beds in the lower portion of the Fox Hills are depleted in quartz grains, whereas pelloidal glauconitic grains and calcareous detritus make up to 90% of some unweathered samples. Quartz sand grains occur in increasing abundance up-section. Within the Fox Hills Formation is a resistant (bench-forming) unconformable surface that crops out throughout the Sage Creek Wilderness Area. This unconformity defines the boundary between lower and upper units of the Fox Hill Formation in the Park area. Sediments immediately below the unconformity are densely cemented by limonite and silica. The lower unit of the Fox Hills Formation represents the third transgressive-regressive cycle preserved in the Cretaceous section within the park. The upper unit represents a minor fourth transgressive-regressive cycle.

The occurrence of belemnites, scaphitid ammonites and bone fragments of swimming reptiles (mosasaurs) in the lower unit supports an age assignment of Maastrichtian (similar to the Trail City Member in the Missouri River Valley region). Sr^{87}/Sr^{86} values of eight belemnites from the base of the lower unit in the Roberts Prairie Dog Town area provided a mean value of .707812 (SD .000005), a value consistent with Late Maastrichtian reported by McArthur et al. (1994). A lack of identifiable fossils in the upper unit hinders a definitive age assignment, however, the unit possibly represents sediments deposited either during the Late Maastrichtian (equivalent to the Timber Lake or Iron Lightning Members in the Missouri River Valley region) or possibly Danian sediments (Hell Creek Formation). Unfortunately, without definitive fossils or absolute

FIGURE 5 - Cut bank exposure along the South Fork of Sage Creek in Badlands National Park, North Unit (NE¼, Sec. 23, T. 2 S., R. 14 E.). The person is standing on the unconformable contact between the Verendrye and Virgin Creek Members. The top of the Verendrye yields numerous fossil-barren concretions. About 4 meters above the unconformity is a zone of three bentonite beds which yielded specimens of *Baculites baculus*. Between 10 and 12 meters above the unconformity is an interval with several bentonite beds that yielded *Baculites grandis*. *Baculites clinolobatus* occur in the gray calcareous shale at the top of the exposure (Mobridge Member).

dates the age of this upper unit is unknown. The sedimentological composition, however, more resembles the Fox Hills than the White River Group. Both units are heavily altered by Yellow Mounds-style meteoric weathering.

In the Grassy Tables Overlook area, the lower unit of the Fox Hills Formation consists of numerous southward dipping sand sheets with shale partings. The sand layers preserve *Diplocraterion* sp. and *Nerites* sp. traces, and display abundant flute casts and drag marks. These features suggest that a clinoform-style lobe prograded southward across the erosionally scoured top of the Pierre Shale during Cycle 3. This interval representing the lower unit grows progressively thinner in exposures to the east and west, pinching out near the boundaries of the North Unit of the Park area.

A ledge-forming, limonite-cemented layer beneath the unconformity between the upper and lower units of the Fox Hills Formation forms a low hilltop bench throughout the eastern drainage basin of Sage Creek. In the Grassy Tables Overlook area the boundary between the two units stands out as a very visible change in lithology (seen in Fig. 6). Sediments of the upper unit above the unconformity are even-bedded alternating sandstone and shale. The upper unit reaches a maximum thickness of about 5 meters in the Grassy Tables Overlook area. Immediately below the basal unit of the White River Group, a discontinuous orange-colored bed about 1 meter thick displays multidirectional cross-bedding consistent with tidal creek or terrestrial stream channel migration. These channel deposits are overlain by a thin red clay layer along the base of White River Group throughout the vicinity of the North Unit of the Park. This layer is up to two meters thick in exposures throughout the Sage Creek Wilderness Area, but pinches out in many places, particularly in the vicinity of faults, such as in the vicinity of the intersection of Badlands Loop Road and Conata Road. The name, Interior Red Clay, was used for this red layer by Retallack (1985); Terry and Evans (1994) include this layer within their Eocene Chamberlain Pass Formation where sediment reworking of the Upper Cretaceous sediments prior to deposition of the White River Group has incorporated Eocene fossils into this zone along the basal unconformity.

The unconformity between the lower and upper units of the Fox Hills Formation is also well-exposed in the vicinity south of the wilderness access trailhead, west of the Roberts Prairie Dog Town. A western spur of the trail leads to a series of small yellow mounds, approximately 3-5 meters high (SW¼, Sec. 3, T. 2 S., R. 15 E.). These small yellow mounds represent the upper unit and consist of alternating quartz sandstone and shale layers that are heavily altered by pre-Chadron weathering. These mounds rest on the resistant unconformable surface between the lower and upper Fox Hills units.

Southward along Sage Creek the sandy layers of the lower unit of the Fox Hills gradually vanish. Cut bank exposures of Cretaceous sediments along the White River west of Interior, South Dakota, and in the South Unit of the Park do not display sandstone beds equivalent to the Fox Hills Formation in the North Unit of the Park. Whether the Fox Hills is missing beneath the basal White River beds or it grades laterally into fine-grained sediments similar to the uppermost Pierre Shale is unclear. South of the Sage Creek Wilderness Area, the Fox Hills Formation may have been stripped away by pre-White River erosion. In the Dillon Pass area, the Fox Hills Formation is very poorly exposed. However, the boundary between the Lower and Upper Units is reflected by a change from glauconite-rich sandstone in the lower unit to quartz-rich sandstone in the upper unit. Both are heavily altered by post-depositional meteoric weathering.

The unconformity between the lower and upper units of the Fox Hills along the northern portion of the Sage Creek Wilderness Area may reflect erosional scour along the rising crest of the Sage Creek Anticline during deposition.

CONCLUSIONS

The Late Campanian and Maastrichtian section exposed in the Badlands National Park area is less than half as thick as equivalent strata along the Missouri River Valley and strata exposed along the western flank of the Black Hills. The thinning of stratigraphic units in the vicinity of Badlands National Park is probably a result of uplift of the region east of the Black Hills, compounded by uplift in the vicinity of the Sage Creek Anticline during Maastrichtian time. These structural features blocked or deflected the flux of sediment from western source areas into the seaway covering the Badlands National Park region. The occurrence of four unconformable surfaces, each preserving evidence of subaerial meteoric weathering, within the upper Pierre Shale and Fox Hills Formation is an indication that marine waters withdrew episodically from the Badlands National Park area during Maastrichtian time. Periods of sedimentation and non-deposition were probably influenced by both local and regional tectonism and by the development and destruction of accommodation space for sediment storage created by at least one Late Campanian and at least two (probably three) Maastrichtian eustatic cycles. The exact age of the uppermost cycle is unknown. During low standing seas, storm wave energy reworked and winnowed sediments. High areas were subjected to greater erosion and possibly to subaerial exposure. The gradual color change in the sediments up-section may be a result of the increasing incorporation of reworked material derived from nearby uplifts as well as their contact with oxygenated groundwater during both ancient and recent subaerial exposure.

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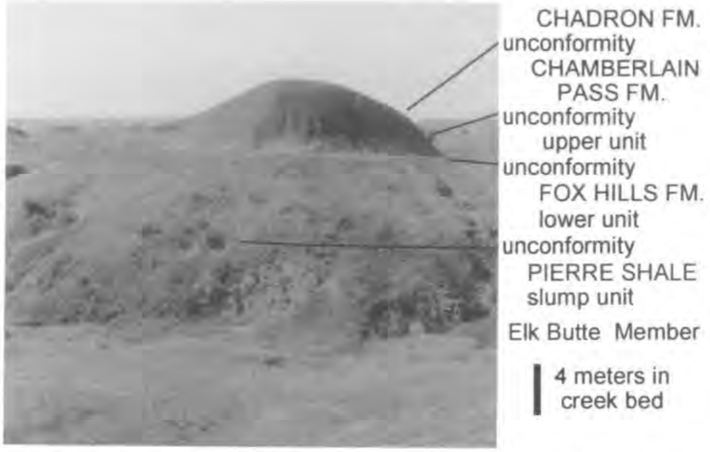

FIGURE 6 - Grassy Tables Overlook area, Badlands National Park, North Unit (SE¼, SW¼, Sec. 8, T. 2 S., R. 15 E.). North-oriented view of a cut bank at the base of a prominent small hill. Cretaceous slumped beds (red weathering) in the Elk Butte Member crop out through 5 meters at the base of the outcrop. The Pierre Shale/Fox Hills Fm. unconformity is exposed approximately 5 meters above creek level. The grass covered lower unit of the Fox Hills Fm. consists of glauconitic sandstone and shale. The unconformity between the lower and upper units of Fox Hills Fm. stands out as an erosional bench. The upper portion of the hill consists of about 2 meters of the upper unit of the Fox Hills, 2 meters of Chamberlain Pass Fm., and capped by 2 meters of gray Chadron Fm.

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A SURVEY OF THE SPECIES OF ENTELODONTS (MAMMALIA, ARTIODACTYLA) OF THE JOHN DAY BASIN, OREGON

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ABSTRACT--Entelodonts are bunodont artiodactyls that are found in North American fossil deposits of Chadronian to earliest Hemingfordian age. Best known from the White River and Arikaree deposits of the Great Plains, entelodonts have also been collected in the John Day strata of Central Oregon. Entelodonts occur in a variety of volcaniclastic sediments and appear by the latest Chadronian, and continue in heterogeneous forms until the late Arikareean. In this paper we review the valid taxa and stratigraphic occurrences of all the available entelodont specimens from the John Day Formation.

In the John Day strata there is at least one valid species of the genus *Archaeotherium* (*A. caninus*) and one species of indeterminate designation (*"A. imperator"*). The genus *Daeodon* is represented by two species (*D. shoshonensis* and *D. humerosum*). A fifth species, represented by UCMP 953, is tentatively recognized as *Archaeotherium calkinsi*. Previously reported John Day taxa not recognized by us include *Archaeotherium robustum* and *A. superbum*.

INTRODUCTION

In 1866 Thomas Condon discovered the first entelodont fossil in the John Day Basin, later described by Joseph Leidy as *Archaeotherium imperator* (Leidy, 1873). Since that time, no fewer than five genera have been described from John Day strata (*Archaeotherium, Daeodon, Choerodon, Boochoerus,* and *Entelodon* [=*Elotherium*]). Unfortunately, most descriptions are either vague or based upon inadequate type material. The large number of poorly defined taxa makes assignment of newly discovered specimens difficult. In this study we discuss the taxa we consider valid and chart their stratigraphic occurrences based on the accessible entelodont material from the John Day Basin.

The eastern exposures of the John Day Formation can be divided into four members, from earliest to youngest: Big Basin, Turtle Cove, Kimberly, and Haystack Valley (Fisher and Rensberger, 1972; work elevating these units to formation status is in progress (Fremd et al., in prep) (Fig. 1). Entelodonts were one of only two genera of fossil mammals (the other was *Rhinoceros*) reported by Merriam and Sinclair (1907) from the lowest division (Big Basin Member). Currently the faunal list is larger, although preservation in the Big Basin Member seems to be biased toward more resistant dental material from larger mammals. Merriam and Sinclair (1907) reported a large assemblage of fossil mammals from the middle division (Turtle Cove Member) and upper division (Haystack Valley Member). The middle and upper divisions yield such a diversity of fossils that Wortman (1898) proposed subdividing them into fossil zones, the lower *Diceratherium* beds and the upper *Merycochoerus* beds. Entelodonts, while rare finds, had been discovered in every division by 1907 (Merriam and Sinclair, 1907) and continue to be found in nearly every level of the John Day Formation.

Deposits which include complete skeletons or multiple individuals of entelodonts tend to be taphonomically associated with watering holes, such as the "waterhole bonebed" at Agate Fossil Beds National Monument (Hunt, 1990) or the Pig Dig fossil quarry at Badlands National Park (Foss, 1995; Stevens, 1996). Although entelodont specimens are locally common in these unusual deposits, they are less abundant elsewhere, as is the case with other large ungulates from the Arikaree Group strata of the Great Plains (Hunt, 1998, pers. comm.). Middle Arikareean entelodonts are so rare in the Great Plains that occasional discoveries from the middle to upper John Day are important in that they document the continued presence of the family in North America from the Chadronian (Colbert, 1937) to the earliest Hemingfordian (Hunt, 1990; Lucas et al., 1997).

The paleontological staff of John Day Fossil Beds National Monument has embarked on an aggressive campaign to survey, prospect, and excavate fossiliferous exposures in the John Day Basin in order to build a more complete collection of stratigraphically documented vertebrate fossils. This prospecting has resulted in the discovery of specimens which document a continued presence of entelodonts throughout the John

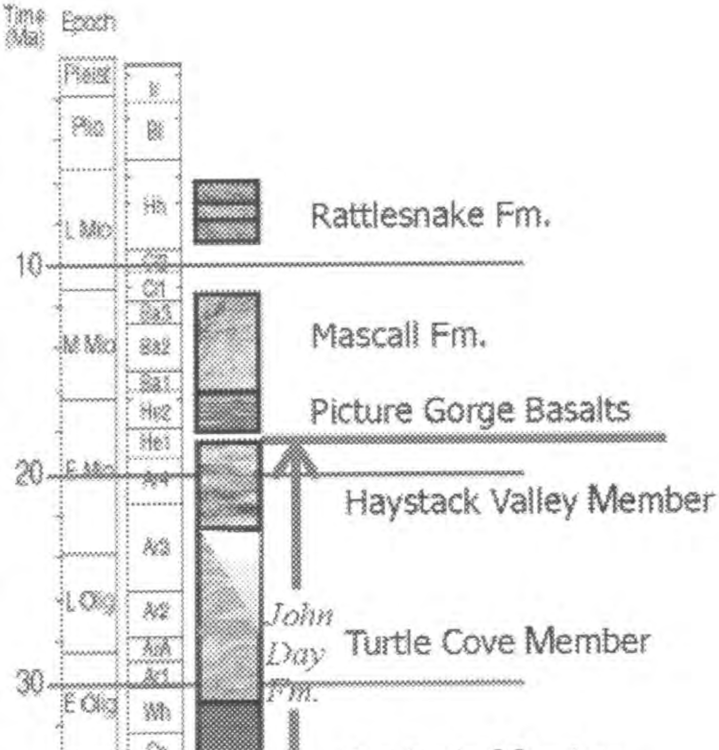

FIGURE 1 - General section of John Day Basin strata with relative time and North American Land Mammal Ages.

Day strata.

Institutional Abbreviations--AMNH, American Museum of Natural History, New York; **CMNH**, Carnegie Museum of Natural History, Pittsburgh; **JODA**, John Day Fossil Beds National Monument, OR; **LACM**, Los Angeles County Museum, Los Angeles; **UCMP**, University of California Museum of Paleontology, Berkeley; **UNSM**, University of Nebraska State Museum, Lincoln; **USNM**, United States National Museum, Washington D.C.; **UWBM**, University of Washington Burke Museum, Seattle; **YPM**, Yale Peabody Museum of Natural History, New Haven.

ENTELODONTS FROM THE JOHN DAY BASIN

The John Day Formation has yielded at least one valid species of the genus *Archaeotherium* (*A. caninus*) and one species of indeterminate designation (*"A. imperator"*). The genus *Daeodon* is represented by two species (*D. shoshonensis* and *D. humerosum*). A fifth species, represented by UCMP 953, is tentatively recognized as *Archaeotherium calkinsi*. *Archaeotherium robustum* is a junior synonym of *A. mortoni* (Leidy, 1854), and we regard *A. superbum* as a *nomem dubium*.

SYSTEMATIC PALEONTOLOGY

Class Mammalia Linnaeus, 1758
Order Artiodactyla Owen, 1848
Family Entelodontidae Lydekker, 1883

Archaeotherium caninus (Troxell)

Choerodon caninus Troxell, 1920
Archaeotherium caninus Simpson, 1945

Archaeotherium (=*Choerodon*) *caninus* was originally described by Troxell (1920) from YPM 11665, a complete skull and dentary (Fig. 2). Troxell suggested that the long recurved canines, long flanges, and large size set it apart from other species (445), especially its Great Plains contemporaries, and he gave it the generic definition of *Choerodon*. In fact, the especially long and complex flanges, great size, and large anterior mandibular tubercles are shared by Whitneyan Great Plains *Archaeotherium*, specifically those formerly known as *"Pelonax,"* *"Scaptohyus,"* and *"Megachoerus."*

The only feature that sets the type specimen, YPM 11665, apart from its contemporaries is its long "recurved" canine teeth. This condition is common in very mature specimens of entelodonts. The teeth, as they wear, continue to push out of their sockets until there is often more root than enamel exposed. This specimen was a very old individual, as evidenced by the advanced wear on all teeth, and the canines had simply protruded an unusual distance. In this individual, the lower canines occluded with the base of the upper canines, leaving the upper canines unworn near their tips. Measurement of the canine enamel shows that this is not an unusual individual: when measured from the base of the enamel to the tip of the canine (and not at the emergence of the tooth from the socket), the tooth was typical not only of its contemporaries, but of all archaeotheres. In the absence of unique features, we consider the genus *Choerodon* (YPM 11665) to be a junior synonym of *Archaeotherium*. The large $_{P/3}$ and relatively short diastema in both the skull and dentary are sufficiently different from other contemporary specimens, however, that we recognize *A. caninus* as a valid species.

Archaeotherium imperator (Leidy), *nomen dubium*

Elotherium imperator Leidy, 1873
Archaeotherium imperator Peterson, 1909

The description of *A. imperator* was based upon a canine, an incisor, and a portion of a premolar (Leidy, 1873). The lack of diagnostic features in this material makes it impossible to describe this species, and Peterson (1909:69) correctly noted that the material is inadequate for use as a type specimen. Furthermore, the present location of the type material is in question as well. Peterson (1909:69) stated that the material is housed at the USNM without a catalog number. While we were unable to locate the specimen at the USNM, we did find an incisor at YPM (#12490) that was referenced to Leidy, 1873. It may be that the specimen, at least the incisor, now resides at YPM. Cope (1878b) referred unspecified material to this species; however, its location and nature were never identified. The present location of the referred material is unknown. While *A. imperator* may not be valid taxonomically, it is of importance historically, as this specimen collected by Thomas Condon at Bridge Creek, is the first entelodont to be reported from the Pacific Northwest.

Daeodon shoshonensis Cope, 1878a

Daeodon shoshonensis (Fig. 3) is known from the symphyseal portion of a mandible, which is consistent in morphology with *D. hollandi*. These features include a squared-off distal incisor arrangement, progressively enlarged incisors, robust round canines, and a small canine - P_1 diastema. The anterior mandibular tubercles are absent. When describing the specimen in 1878, Cope was unaware of the existence of entelodonts which are larger and appear later in the fossil record than *Archaeotherium*. He suggested that the jaw belonged to a large perissodactyl (Cope, 1878a) and subsequently placed it in the Menodontidae (Cope, 1887). Peterson (1909) correctly recognized the specimen as belonging to the Entelodontidae.

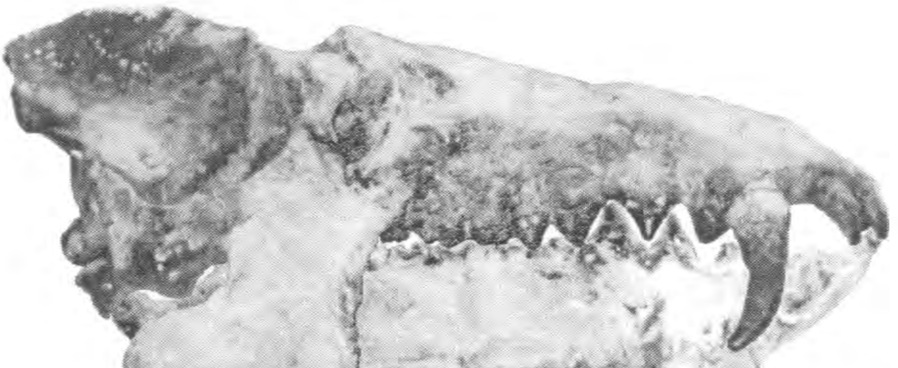

FIGURE 2 - YPM 11665, *Archaeotherium caninus*.

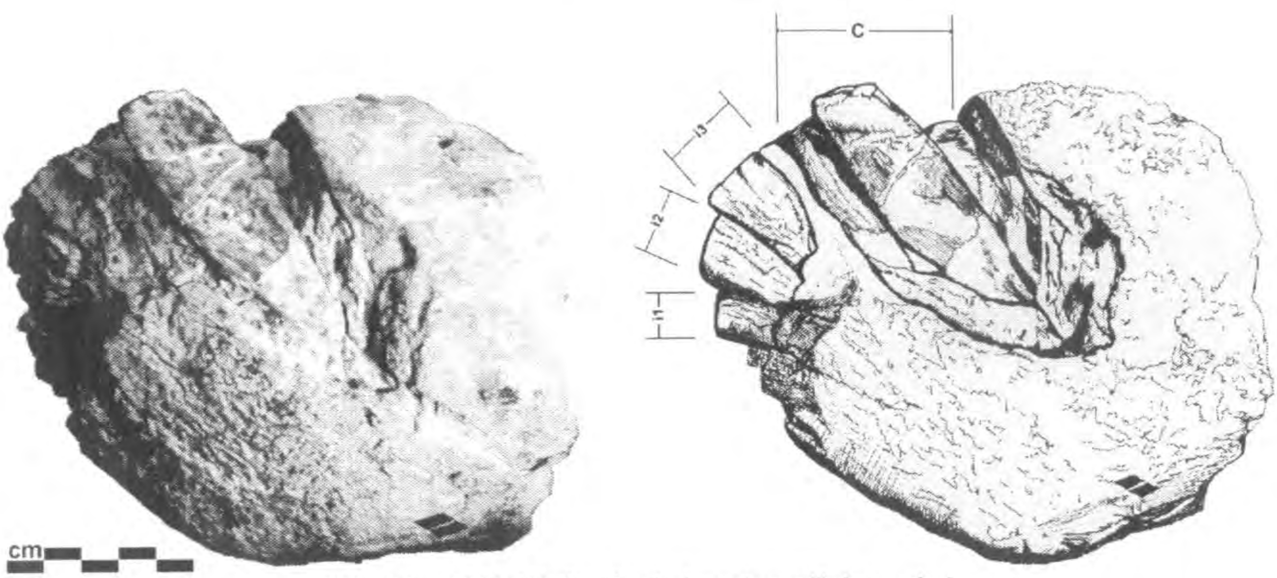

FIGURE 3 - AMNH 7387, *Daeodon shoshonensis*, mandibular symphysis.

Fragmentary remains of *Daeodon* have been reported in South Dakota, California, New Jersey, North Carolina, Florida and Texas; only Wyoming and Nebraska have yielded complete skulls, and only Nebraska and Oregon have yielded extensive postcrania. Although its geographic distribution is widespread, *Daeodon* is never a common fossil.

Daeodon is known in the John Day strata from both cranial and postcranial elements. The type specimen of *D. shoshonensis* (AMNH 7387) is known only from the symphyseal region of the mandible and isolated tooth fragments. The best-preserved specimen is the type specimen of *D. humerosum* (AMNH 7380), which includes an entire humerus, fused radius-ulna, complete manus and pes, partial pelvis, and femoral head. Discovered by Charles Sternberg in Haystack Valley (Sternberg, 1909:186), it is still the most complete entelodont postcrania that has been reported from the John Day (Appendix 1). Because the lack of corresponding material makes it impossible to compare these type specimens directly, we tentatively accept them as distinct species. Further discoveries may elucidate a more accurate specific distribution of *Daeodon* in the John Day Basin.

Daeodon is the senior synonym for *Dinohyus* and *Ammodon* (see Lucas et al., 1996; Lucas et al., in press), and *Boochoerus* as discussed here. This synonymy of *Daeodon* (=*Dinohyus*, =*Ammodon*, =*Boochoerus*) has been suggested previously, in various parts, by many authors (Simpson, 1945:144; Brunet, 1979:98; McKenna and Bell, 1997:412).

Daeodon humerosum (Cope)

Boochoerus humerosus Cope, 1879a
Elotherium humerosum Merriam and Sinclair, 1907
Boochoerus humerosus Peterson, 1909

After directly comparing casts of *Boochoerus humerosus* (AMNH 7380) with *Daeodon* (=*Dinohyus*) *hollandi* (CMNH 1594) and *Daeodon* (=*Dinohyus*) *hollandi* (UNSM 1150), we conclude that AMNH 7380 possesses no features that warrant its separation from *D. hollandi* at the generic level. The specimen, AMNH 7380, does not differ from the more complete holotype of *D. hollandi* and at the same time shows evident distinctions from *Archaeotherium* (Fig. 4).

The humerus is robust in all specimens of *Daeodon*, although it is more so in *D. humerosum*. The greater tuberosity measures 6 cm in length and is much heavier in AMNH 7380 (*D. humerosum*) than in UNSM 1150 (*D. hollandi*), where it measures 5 cm in length and is noticeably less robust. This accounts for the 1 cm difference in the lengths of the two humeri (42 and 41 centimeters, respectively). Unfortunately, the greater tuberosity is lost on the type specimen of *D. hollandi* (CMNH 1594). The deltoid ridge is heavy and prominent, as is the supinator crest. The distal condyle is wide, measuring 12 cm for AMNH 7380 and 11 cm for both UNSM 1150 and CMNH 1594. The fused radius-ulna are subequal in length between the two species, with *D. humerosum* consistently more robust. The transverse diameter at the head of the ulna is wide in all specimens: 10 cm at the widest point for all three specimens. The olecranon process is slightly longer in AMNH 7380 but is otherwise identical in its stout shape.

On the manus, the lunate is distally enlarged and nearly reaches the third metacarpal and thus prevents the magnum and unciform from contacting one another. The scaphoid is large and has an enlarged lunate process (Peterson, 1909). The shape and articular surfaces of the scaphoid, lunate and pyramidal bones compare well although the pyramidal of *D. hollandi* is noticeably more oblique in its lateral position. The trapezoid of *D. hollandi* is compressed antero-posteriorally to a slightly greater extent than its counterpart in *D. humerosum*, although they maintain the same overall shape. On the magnum the facet for metacarpal five meets the facet for the pyramidal at 90 degrees. This is not the case in *Archaeotherium*, where there is a convex surface separating the two facets (Peterson, 1909:122). Metacarpals three, four, and the phalanges are considerably more robust and slightly shorter in *D. humerosum* than in the two specimens of *D. hollandi*, although they share the same shape and orientation.

The pes of all specimens of *Daeodon* lacks the articular surface for a small fifth metatarsal, a feature that is present in both *Entelodon* and *Archaeotherium* (Scott, 1898). The astragalus is similar to both *D. leidyanus* and *D. hollandi*. In morphology, the calcaneum and navicular compare favorably between *D. leidyanus* and *D. hollandi*, although *D. hollandi* yields longer measurements. As Peterson (1909:138) pointed out, the cuboid articulates with the calcaneum and astragalus in nearly equal proportions (*Archaeotherium* has a greater proportion of the bone articulating with the astragalus). The cuneiform bones are present, although a fused reconstruction of UNSM 1150 makes direct comparison difficult. Metatarsal three has a fibular angle which articulates with the cuboid; this is not the case for Oligocene archaeotheres (Peterson, 1909:140). The type specimen of *D. humerosum* has incompletely preserved metatarsals and so this diagnostic feature cannot be compared. Finally, metatarsals three, four, and the phalanges are similar between the two species, except that *D. hollandi* shows proportionally longer measurements.

Although morphologically similar to *D. hollandi*, *D. humerosum* has a more robust forelimb and relatively shorter hindlimb. With only three reasonably complete postcranial specimens of *Daeodon*, all compared in

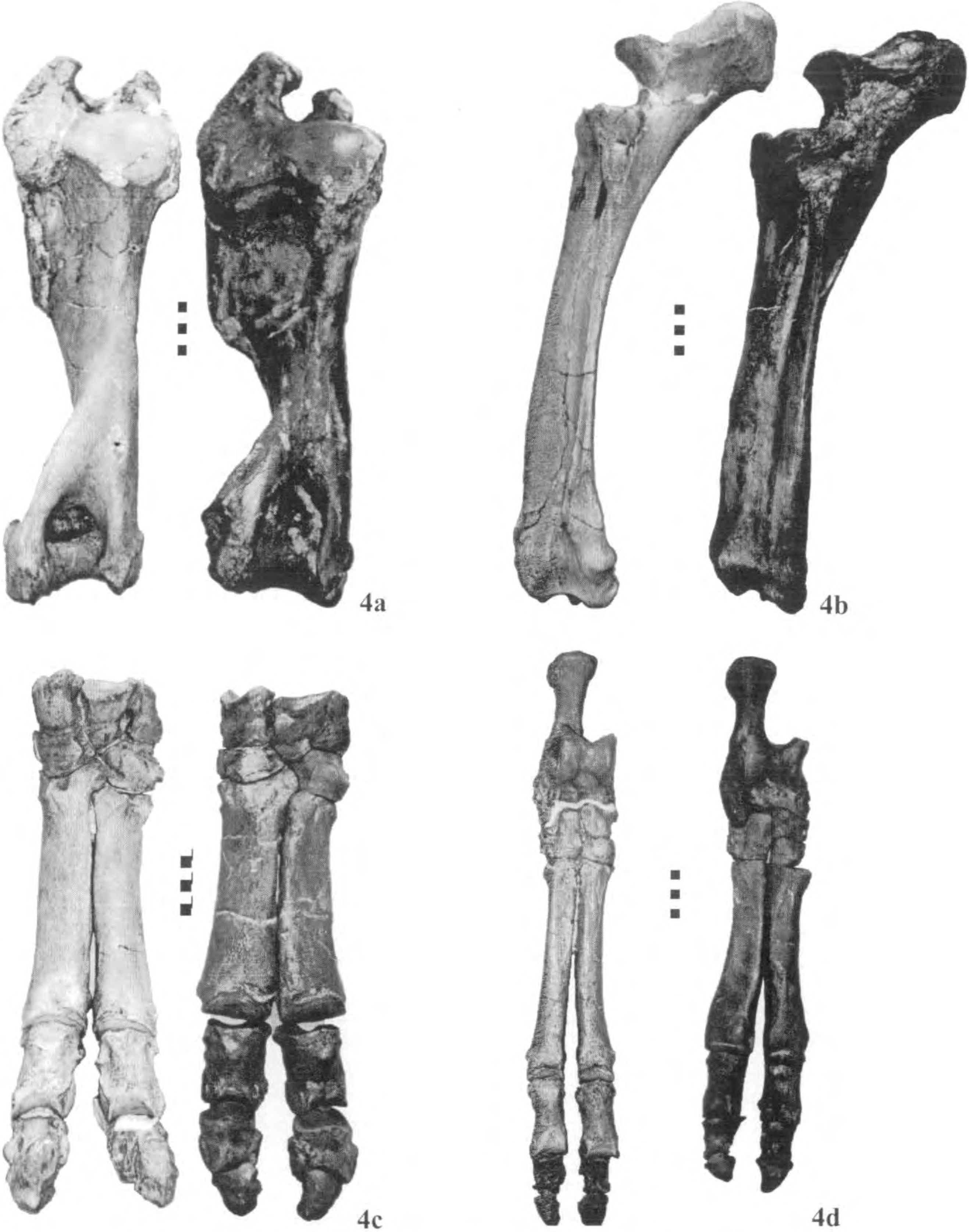

FIGURE 4 - *Daeodon hollondi* (right), *D. humerousm* (left): a. humerus, b. fused radius/ulna, c. manus, d. pes

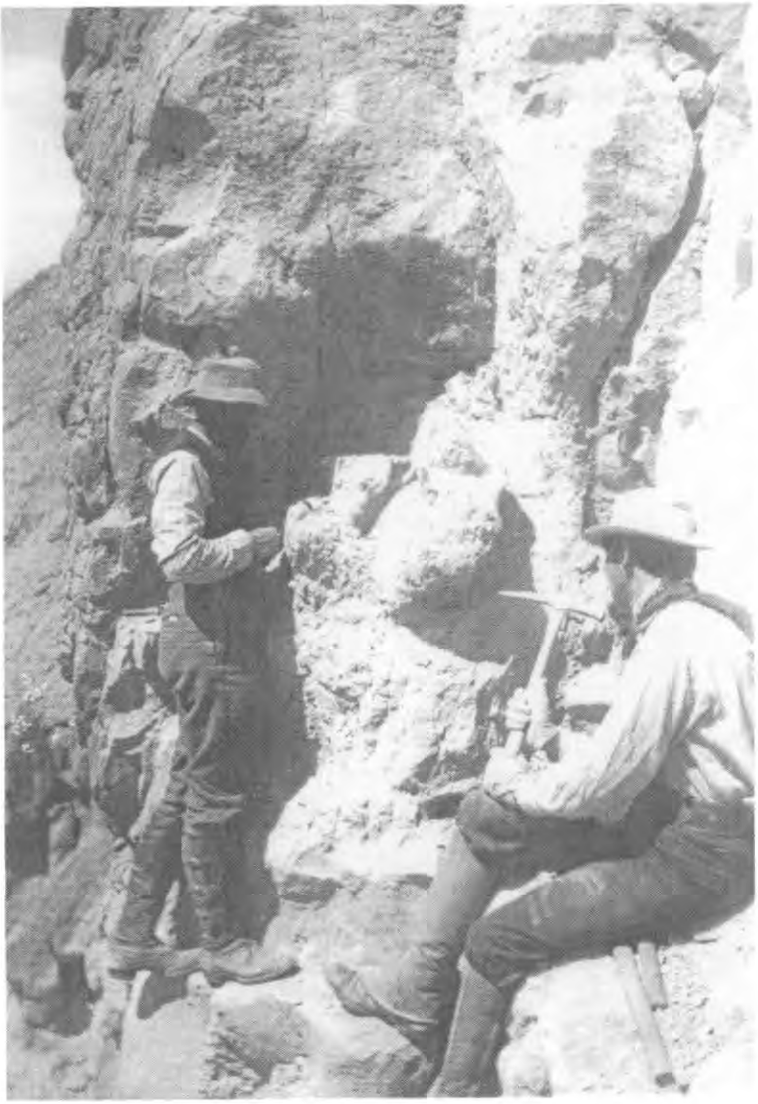

FIGURE 5 - J. C. Merriam (left) and Loye Miller (right) excavating UCMP 953. Photo taken between June 1 and June 12, 1899. (from: Miller, 1972)

this study, it is impossible to tell whether this difference is attributable to individual or population-level variation or if it is evidence of sexual dimorphism. We believe, however, that the differences outlined above do not justify separation at the generic level.

Archaeotherium calkinsi (Sinclair)

Elotherium calkinsi Sinclair, 1905
Daeodon calkinsi Peterson, 1909
Choerodon calkinsi Troxell, 1920
Archaeotherium calkinsi Simpson, 1945

Discovered by a University of California fossil collecting party in 1899 (Merriam, 1901; Miller, 1972) and described in 1905 by Sinclair (132), UCMP 953 (Figs. 5, 6) has undergone taxonomic revision virtually every time it has been discussed. Although the genus *Elotherium* is not recognized today, Leidy's (1858) revival of the genus was in effect until Peterson (1909:43) suggested suppressing it in favor of *Archaeotherium*.

It should be noted that Leidy named the first North American entelodont *Archaeotherium* (Leidy, 1850), subsequently revising the name to *Entelodon* (Leidy, 1854) and then to *Elotherium* (Leidy, 1858) as he became aware of previous literature. Bush (1903) discussed the dates of publication for *Entelodon* and *Elotherium* and concluded that *Entelodon* should be considered the senior synonym. Peterson (1909:43) concluded that the North American forms are sufficiently distinct from the European and Asian forms to resurrect *Archaeotherium* as the favored genus for all North American species that had previously been named *Elotherium*. This division has been recognized by subsequent workers for all specimens with the single exception of *Entelodon coarctatus* (Cope), which Troxell (1920:249) cited as an exception because of the similarities of its premolars with those of *E. magnum* (Aymard) of France. This is discussed further by Scott (1940), who maintained, "Were the skull of the European species of this genus practically unknown, I should advocate the reference of the American species of *Archaeotherium* to *Entelodon*" (427).

Peterson (1909:65) singled out UCMP 953 as unique because of its lack of mandibular tubercles and perhaps because it was collected in the Bridge Creek beds of the John Day Basin. For these reasons, he put it into the genus *Daeodon*. Troxell (1920) placed UCMP 953 into his new genus *Choerodon* (see *Archaeotherium* above) based on general tooth shape and geographic location. Whereas UCMP 953 shares small anterior tubercles and moderate jugal flange size with *Daeodon*, the skull and postcrania differ in many ways and may be more similar to *Archaeotherium*.

The differences from *Daeodon* are most apparent in the bones of the manus. Although the lunate is not present, both the right and left unciform bones are. It is possible to observe that the lunate was not distally enlarged, as it is in *Daeodon*, and that the magnum and unciform freely contact one another on the dorsal surface. This feature is typical of *Archaeotherium* (Scott, 1898:306; Peterson, 1909:117). Viewed from the dorsal side, the ulnar articular surface of the magnum is convex and thus the corresponding radial facet for the magnum on the lunar should be concave. This is a condition is also seen in *Archaeotherium* and not in *Daeodon* (Peterson, 1909:117).

Other diagnostic features, such as the presence or absence of the trapezium on the manus or the presence or absence of a contact between metatarsal three and the cuboid on the pes, cannot be discerned on this specimen. Because this specimen has features that distinguish it from both *Archaeotherium* and *Daeodon*, it is worthy of its own species designation separate from any other above-mentioned John Day form. The complete skull, mandible, and partial postcranial skeleton of UCMP 953 will be described elsewhere (Foss, Fremd, and Lucas, in prep.). At this time we are unable to refer with confidence any other fragmentary material from the John Day Basin to this group, although UCMP 570 and YPM 10212 are labeled with this identification (Appendix 1). With a better characterization of the tooth morphology, these identifications may prove to be correct.

Referred taxa not recognized in the John Day

Archaeotherium robustum (Leidy), junior synonym of *A. mortoni*

Arctodon Leidy, 1851
Archaeotherium robustum Leidy, 1852
Archaeotherium (*Entelodon*?) *robustum* Leidy, 1853
Entelodon mortoni, Leidy 1854
Elotherium mortoni, Leidy 1858
Archaeotherium mortoni, Peterson 1909
Archaeotherium robustum, Troxell 1920

In his discussion of *Archaeotherium robustum*, Troxell (1920) said, "This species was made on rather an important specimen in the collection of Doctor Owen, from the John Day region, and the name may someday be revived by a careful study of the original material, the location of which is not known at present" (250). The specimen was collected by the Owen party of 1850 on its expedition into the Nebraska Territory, which

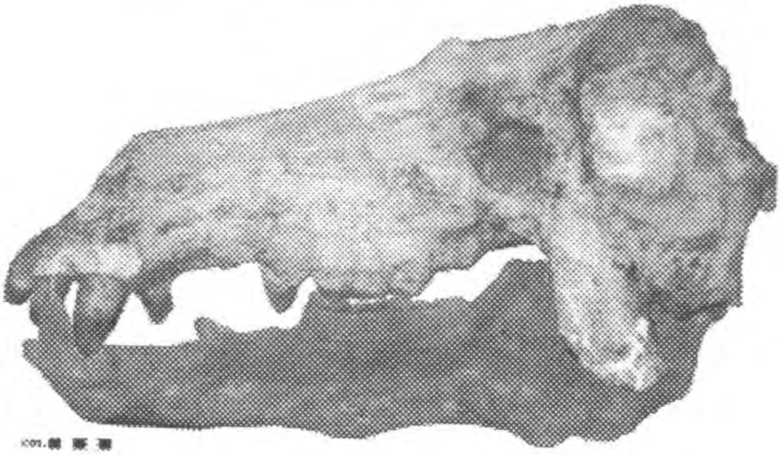

FIGURE 6 - UCMP 953, *Archaeotherium calkinsi*

included what is now known as the White River Group of South Dakota, Nebraska and Wyoming. In his original discussion, and in all subsequent works, Leidy identified the origin of the specimen as the Nebraska Territory (Leidy, 1851, 1852, 1853, 1854). Troxell's identification of the John Day region as the source for the fossil is clearly a mistake, as Leidy himself (1873) identified *Archaeotherium imperator* as the first reported entelodont fossil from the John Day Basin. The location of the type material, M2-M3 and a fragment of canine, is unknown, and the geographic origin is vague.

Archaeotherium robustum Leidy (1852) was the second species of *Archaeotherium* named from North America. It replaced the temporarily designated genus *Arctodon* Leidy (1851) which is *nomen nudem* because the original description failed to name a species, and generic characters were not given. Leidy (1854) recognized the holotype of *A. robustum* as a specimen of the North American genus *A. mortoni*. Only one specimen had been assigned to *A. robustum* by 1874 when it was synonymized with *A. mortoni*, and the location of that material is unknown.

Archaeotherium superbum (Leidy), *nomen dubium*

Elotherium superbus Leidy, 1868
Elotherium superbum Leidy, 1869
Archaeotherium superbum Peterson, 1909

The type specimen of *A. superbum* is from Douglas Flat, Calaveras County, California, and consists only of a single tooth that, based on the description (Leidy, 1868), seems to be a large premolar. The specimen was not figured and a specimen number was not reported. Peterson (1909:69) suggested that "the record of this species should be regarded as only possessing value from the standpoint of history and geographical distribution."

The only additional specimen that has been referred to this species was discovered by Thomas Condon in the Bridge Creek drainage of the John Day Basin and described by Leidy as "...a huge species of *Elotherium*, perhaps the *E. superbum*" (Leidy, 1870:112). Although Leidy's description of Condon's specimen is vague and the location of the specimen is unknown, it is possible that this was a specimen of *Daeodon*, as the type specimens of *Daeodon shoshonensis* (AMNH 7387) and *Daeodon* (= *Boochoerus*) *humerosus* (AMNH 7380) are both from this area.

The holotype of *A. superbum*, from Calaveras County, California, was reported by Leidy to be from a "stratum of the same age as that from which a lower jaw of *Rhinoceros hesperius* was taken" (Leidy, 1868:177), which suggests an Orellan or Whitneyan age for the material. Also from Calaveras County, California, *R. hesperius* was compared to *R. occidentalis* (now *Subhyracodon*) and founded to be more robust, but otherwise similar (Leidy, 1869). Osborn (1904:309) reports that although the location of the type material for *R. hesperius* is unknown, "it may be of Oligocene age." *Subhyracodon* is found in the lower Brule Formation of the White River Group (Scott, 1941) and seems to suggest an Orellan or Whitneyan age for *R. hesperius* and consequently the original specimen of *A. superbum*. This correlation, although admittedly tenuous, suggests that entelodonts may have been present in California much earlier than previously reported. To date, the only confirmed entelodont specimens from California are early Hemingfordian in age (Lucas et al., 1997).

DISCUSSION

The lack of complete skeletons makes it difficult to make direct comparisons between different specimens. Sometimes it is even impossible to make comparisons between different taxa (as is the case with *Daeodon shoshonensis* and *D. humerosum*). Until overlapping material can be described, it will remain difficult to assign specific entelodont specimens to the appropriate taxa. Skull shape, morphology of the jugal flanges and jaw tubercles, and dental patterns need to be characterized for each species.

Archaeotherium seems to be the only entelodont genus that is found in the lower and middle John Day Formation (Big Basin and Turtle Cove Members). The uppermost John Day Formation has a distinctly different entelodont, *Daeodon*, as well as some entelodont specimens that are not easily identified, even at the generic level (Fig. 7).

The John Day fauna is often different from its presumed contemporaries on the Great Plains and generally displays a greater diversity of species (Fremd et al., 1994). Species such as *Archaeotherium caninus* and *Daeodon shoshonensis*, with their apparent similarities to Great Plains contemporaries (such as *Archaeotherium ingens* and *Daeodon hollandi*, respectively), may aid in the correlation of these two vastly different but temporally similar faunas.

Entelodonts have a relatively continuous record on the Great Plains from the Chadronian through the latest Arikareean - earliest Hemingfordian (though finds are sparse in the middle Arikareean). The record of entelodonts from the John Day Formation, as presently constituted, covers the same period with specimens that are found in the late Chadronian through the late Arikareean (Appendix 1). Although the John Day Formation covers the same temporal range as the entire entelodont radiation in North America, it seems unlikely that any of the specimens found in the lower Big Basin or upper Haystack Valley members will significantly increase the temporal range of entelodont discoveries in North America.

Previous authors have advocated a second distinct radiation of large entelodonts to North America from Asia in the Early Miocene (Brunet, 1979; Lucas et al., 1997; Lucas et al., in press). Such a scenario explains

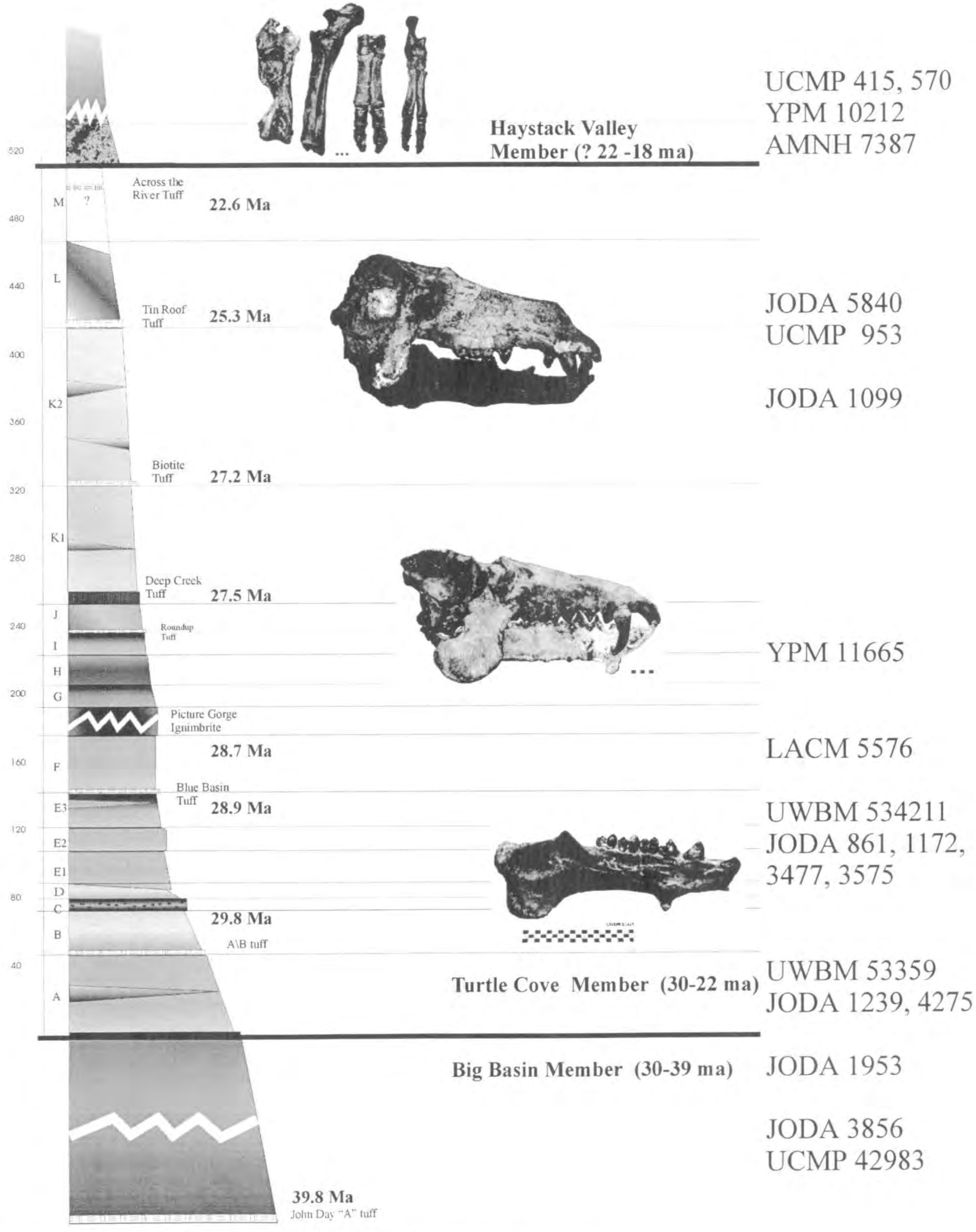

FIGURE 7 - Section of John Day Basin strata with the stratigraphic location of certain entelodont specimens noted.

general molar similarities between the Asian *Paraentelodon* and North American *Daeodon* as well as the apparent sudden morphological change between Chadronian - earliest Arikareean *Archaeotherium* and latest Arikareean - earliest Hemingfordian *Daeodon*. Admitting the reasonable nature of this scenario, we suggest that an alternative explanation may include intermediate North American forms (such as UCMP 953). Only with the discovery and characterization of new material will the temporal and geographic distribution of entelodonts during this period become apparent.

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APPENDIX 1 - Entelodont specimens from the John Day Formation with their approximate stratigraphic position

Institution	#	Horizon	Locality/Notes
AMNH	7380	Haystack Valley	HOLOTYPE, col. C. Sternberg, 1878; Cope, 1879a,b; Peterson, 1909
AMNH	7387	Bridge Creek	HOLOTYPE, col. Wortman, 1878; Cope, 1878; Matthew, 1909 Peterson, 1909; Lucas et al., (in press)
JODA	330	Turtle Cove E?	Blue Basin
JODA	861	Turtle Cove E?	Blue Basin
JODA	1099	Turtle Cove K2	Sheep Rock
JODA	1172	Turtle Cove E2	Blue Basin
JODA	1239	Turtle Cove B	Blue Basin
JODA	1953	Turtle Cove A	Blue Basin
JODA	2868	Turtle Cove	Green Cove Beds, Painted Hills
JODA	3058	Turtle Cove	Carroll Rim West, Painted Hills
JODA	3477	Turtle Cove E3	Blue Basin
JODA	3551	Turtle Cove E?	Logan Butte
JODA	3575	Turtle Cove E2	Foree
JODA	3856	Big Basin Mbr.	White Cap Knoll
JODA	4725	Turtle Cove B?	Sorefoot Creek
JODA	5840	Turtle Cove L?	Lonerock
JODA	9975	Turtle Cove A	Carroll Rim, Painted Hills
LACM	5411	Big Basin Mbr.	White Cap Knoll
LACM	5414		S. of Logan Butte
LACM	5576	Turtle Cove	N. face of Sheeprock
LACM	5622		Corn Cob Basin
LACM	29673		S. of Logan Butte
UCMP	415	Haystack Member	
UCMP	570		near Spray, OR
UCMP	953	Kimberly member	HOLOTYPE, Locality 801, near "Hatch's Gulch", Bridge Cr, what was then Wasco Co., OR (now Wheeler Co.), Sinclair, 1905; Peterson, 1909
UCMP	42983	Big Basin	Deer Gulch
UWBM	53359	Turtle Cove D	
UWBM	534211	Turtle Cove F1	Branson Creek, below PGI, dentaries, RP/3 - M/3, LP/4 - M/3,
UWBM	534212	Turtle Cove F1	L & R dentary
YPM	10212	Haystack	
YPM	10214		Olig. OR

APPENDIX 1 - continued

Institution	#	Horizon	Locality/Notes
YPM	10350		John Day Valley, OR
YPM	10351		John Day Valley, OR
YPM	10353	Turtle Cove	"10 miles below cove"
YPM	11665	Turtle Cove	HOLOTYPE,"the Cove", John Day fm., Troxell, 1920
YPM	12490		Bridge Creek, Sutton Mountain, col. T. Condon, Leidy, 1873
YPM	14156		John Day Valley, OR; pathological ankle joint
YPM	14314		John Day Valley, OR
YPM	14342		John Day Valley, OR
YPM	14346		Bridge Creek or Shoofly Creek
YPM	14347		John Day Valley, OR

AN EMBEDDED TOOTH IN AN OREODONT CRANIUM: EVIDENCE FOR FEEDING HABITS OF OLIGOCENE ENTELODONTS

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ABSTRACT--A small entelodont tooth fragment discovered embedded in the cranium of an Oligocene oreodont, *Merycoidodon major*, from Badlands National Park is direct evidence of fossil species interaction. The tooth fragment exhibits both coronal and mesial wear facets, a lingual-distally positioned vertically-oriented sulcus, and thin enamel. The tooth fragment is probably a left, deciduous, second, lower incisor of the Oligocene entelodont *Archaeotherium*. The presence of this broken entelodont tooth lodged in the oreodont cranium is evidence for scavenging or active predation of another species by Oligocene entelodonts.

INTRODUCTION

Bite marks on fossil bones facilitate paleoecological interpretations of species interactions. For example, Haynes (1983) suggested that a predator or scavenger not physically represented by body fossils in a fossil assemblage may be inferentially included in the fossil fauna when a suite of characteristic bite marks can be identified. In unusual cases, the characteristic morphology of an individual bite mark may allow the identification of a particular species (Erickson and Olson, 1996).

Late Eocene-early Oligocene sediments of the White River Group in Nebraska and South Dakota have yielded a diversity of fossil mammals. Many White River fossils provide direct evidence for predation and scavenging. Bone processing styles noted in a large sample (5000+) of post cranial material from the White River sediments of northwestern Nebraska have been used to infer aspects of carnivore paleoecology (LaGarry, 1995). Similarly, bite marks in oreodont crania from South Dakota were interpreted as evidence of prey selection by the Oligocene carnivore *Hyaenodon* (Tanke et al., 1992).

In the studies mentioned above, varying degrees of inference are included in the interpretation of bite marks and bone processing modes. However, if the tooth of the "biter" remains lodged in a skeletal element of the "bitten," concrete conclusions may be drawn concerning species interactions. A thorough literature review indicates that the present report on an identifiable mammalian tooth embedded in the cranium of a White River mammal is the first of its kind. The purpose of this paper is: (1) to describe a mammalian tooth fragment found lodged in the cranium of an Oligocene oreodont; and (2) to discuss the tooth's significance concerning the feeding habits of Oligocene entelodonts.

MATERIALS AND METHODS

A Whitneyan (North American Land Mammal Age) oreodont skull, *Merycoidodon major* (Mammalia, Artiodactyla), from the Cedar Pass area (Poleslide Member, Brule Formation) of Badlands National Park, South Dakota, possesses a mammalian tooth fragment embedded (Fig. 1) in the cranium dorsal to the left external auditory meatus. The skull (#3880) is housed in the Georgia College and State University Vertebrate Paleontology (GCVP) collection. The lower jaw of the oreodont is absent, the left auditory bulla is crushed, and the left zygomatic arch and postorbital bar were apparently destroyed by recent weathering.

Initial analysis of the skull and tooth fragment entailed transverse and sagittal CT scans. The tooth fragment was then extracted and macroscopically compared to teeth of White River fossils in the University of Nebraska State Museum (UNSM), South Dakota School of Mines Museum of Geology (SDSM), and GCVP collections, and to figured specimens in the following White River mammalian families: Hyaenodontidae (Mellett, 1977); Canidae (Wang and Tedford, 1996); Nimravidae (Bryant, 1996); Amphicyonidae (Hunt, 1996); Agriochoeridae, Anthracotheriidae, Camelidae, Entelodontidae, Merycoidodontidae, and Tayassuidae (Scott, 1940); Merycoidodontidae (Stevens and Stevens, 1996); and Helaletidae, Hyracodontidae, Rhinocerotidae, and Tapiridae (Scott, 1941). Scanning electron microscopic (SEM) comparisons of surface features were accomplished using epoxy replicas of the tooth fragment and an adult entelodont incisor. Physical manipulation of the oreodont cranium with skulls and jaws in the UNSM and GCVP collections was employed to determine if any particular White River mammal was mechanically capable of inflicting the wound in the noted region of the temporal fossa.

RESULTS

The position and orientation of the tooth fragment in the oreodont cranium was determined using a sagittal CT scan (Fig. 2). The tooth fragment is oriented anteriorly, lodged under intact squamosal bone. Immediately posterior to the tooth fragment, a ragged-edged hole in the squamosal indicates where the initial cranial puncture occurred. The inferred direction of tooth movement prior to breakage was from posterior to anterior through the temporal fossa.

Macroscopic analysis of the tooth fragment (Figs. 3A, B) revealed six identifying characteristics: (1) a coronal wear facet with exposed dentine, the buccal enamel polished surface wider (0.4 mm) than that on the lingual side (0.2 mm); (2) lingual enamel facet roughly abraded and level with the incisal edge, buccal enamel facet polished smooth and cervically (towards the root) dipping; (3) an angled mesial wear facet with exposed dentine; (4) thin (~ 0.3 mm) enamel on the tooth; (5) a lingual-distally positioned vertically-oriented sulcus running the length of the crown; and (6) small size, 3.2 mm buccal-lingual thickness 5.5 mm below the highest portion of the crown (incisal edge). SEM analysis did not reveal defining microscopic characteristics.

FIGURE 1 - Left lateral view of the *Merycoidodon major* skull (GCVP 3880). The black arrow marks the position of the embedded mammalian tooth fragment.

Macroscopic comparisons of the tooth fragment to the teeth of White River mammals in the Agriochoeridae, Amphicyonidae, Anthracotheriidae, Camelidae, Canidae, Entelodontidae, Helaletidae, Hyaenodontidae, Hyracodontidae, Merycoidodontidae, Nimravidae, Rhinocerotidae, Tapiridae, and Tayassuidae indicate significant differences in tooth morphology and/or size for the examined specimens in all of these families except the Entelodontidae. The tooth fragment appears to be the coronal portion of a left, deciduous (di2) from an Oligocene entelodont. SDSM 32113, an Orellan juvenile *Archaeotherium*, possesses a left di2 with the characteristic coronal and mesial wear facets and a lingual-distally positioned vertically-oriented sulcus. The polished enamel band on the buccal edge of the coronal wear facet of SDSM 32113 is cervically dipping and wider than that on the lingual edge. The tooth is 4.7 mm thick (buccal-lingual) 5.0 mm below the incisal edge. The enamel thickness (~ 0.3 mm) is comparable to that of the fragment in question. The wear facet morphologies on the right di2 of SDSM 32113 are more similar (in reverse) to those of the unknown tooth fragment. This di2 is also larger than the unknown fragment, 5.0 mm buccal-lingual thickness 4.0 mm below the incisal edge. An additional right di2 from SDSM 3638, an Orellan *Archaeotherium*, is morphologically more similar (in reverse) to the unknown fragment in wear facet morphologies and approximately the same size, 4.0 mm buccal-lingual thickness 6.1 mm below the incisal edge.

A Whitneyan juvenile entelodont was not available for comparison, but the stratigraphic distribution of the entelodont *Archaeotherium* (Scott, 1940; Effinger, 1987) is concurrent with the stratigraphic level from which the oreodont skull was collected. Mechanical constraints also support the identification of the tooth fragment as that of an entelodont. Physical manipulation of juvenile entelodont jaws (SDSM 32113, 3638) and the *Merycoidodon* skull indicates that a bite stroke with the lower incisor row moving anteriorly through the temporal fossa is mechanically possible. The nimravids, with their long thin canines, were the only other White River mammals mechanically capable of inflicting the wound in the observed region of the temporal fossa while producing the correct orientation for the tooth fragment. However, the morphology and size of the unknown tooth fragment precludes it from belonging to a nimravid.

FIGURE 2 - Sagittal CT scan radiograph of the *Merycoidodon major* cranium (GCVP 3880) illustrating the position and orientation of the embedded tooth fragment (arrow). Anterior is to the left. M, posterior maxilla labial to M2; O, orbit; P, postorbital process of the frontal; T, anterior region of the temporal fossa; S, squamosal; N, nuchal crest. Scale = 1 cm.

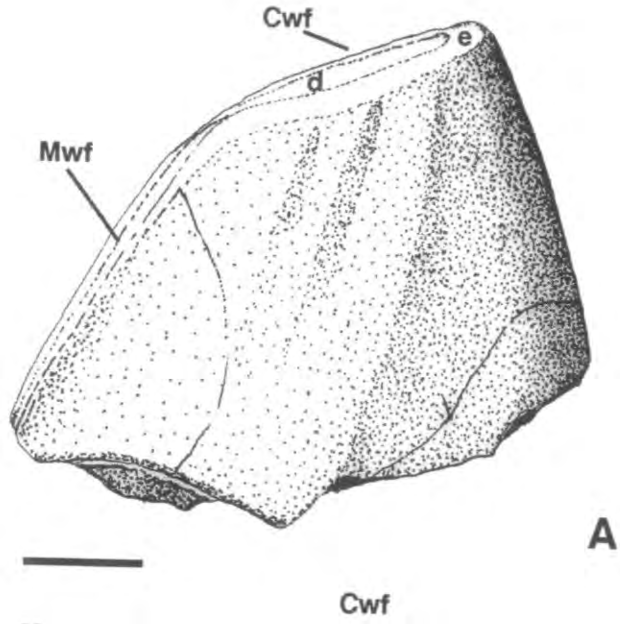

FIGURE 3 - A, Buccal and B, coronal views of the tooth fragment (a juvenile entelodont left di2) removed from the *Merycoidodon major* cranium (GCVP 3880). Cwf, coronal wear facet; Mwf, mesial wear facet; d, dentine; e, enamel; s, sulcus. Scale = 1 mm.

DISCUSSION

Inherent individual variation dictates that finding an "exact" match for the embedded tooth fragment is unlikely. As discussed, variations were noted in the degree of tooth wear and facet morphology development between the left and right di2's in the same entelodont jaw (SDSM 32113). Similarities in size and facet morphology between the unknown fragment and juvenile entelodont incisors strongly suggest that the "biter" was an entelodont. Due to the sub-conical nature of the entelodont di2, the degree of coronal wear, probably a reflection of relative age, will determine the observed buccal-lingual thickness at a given distance below the maximum crown height and supports the assumption that an "exact" size match should not be expected.

Entelodont incisors do not form a continuous row of laterally abutting teeth. The upper and lower incisors are widely spaced (Scott, 1940:plate 38.1a) and do not occlude crown to crown, but interlock in a alternating fashion (Scott, 1940:plate 40.1) producing wear along the lateral edges and resulting in both lateral and coronal wear facets. The slightly procumbent orientation (Scott, 1940:plate 38.1; Russell, 1980:fig. 15) and wide spacing between the lower incisors would allow an individual incisor to puncture the skull and subsequently break off while the neighboring incisors and canines fail to penetrate the bone. Breakage of incisors and canines apparently was not uncommon in entelodonts. In SDSM 32113 and 3638, di1 and di3, respectively, are broken and polished, indicating premortem breakage. Joeckel (1990) reported that premortem incisor and canine breakage is evident also in adult entelodonts.

Various feeding habits have been proposed for the North American entelodonts. Scott (1940) inferred pig-like root-pulling behaviors based on incisor and canine wear. Russell (1980) used dental arcade morphology to infer browsing habits for *Archaeotherium*. Based on jaw mechanics, tooth morphology, and tooth wear, Joeckel (1990) concluded that entelodonts might have been scavenging omnivores. More recently, Hunt (1992) used puncture marks on bones as evidence of scavenging by entelodonts from the Miocene Agate Bone Beds in western Nebraska.

This entelodont incisor in the cranium of an oreodont indicates some kind of carcass processing by a juvenile entelodont. The ragged nature of the squamosal puncture in the oreodont cranium implies that post-bite healing did not occur and that the oreodont was not alive for any significant length of time after the bite occurred. The tooth fragment does not directly indicate active predation. The oreodont may have been dead or alive when the bite occurred. Considering the evidence presented by Joeckel (1990) and Hunt (1992), it is more probable that the cranial puncture and tooth breakage occurred during scavenging of the *Merycoidodon* temporalis muscle by a juvenile entelodont.

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RESOURCE MANAGEMENT

Paleontological and Archaeological Research in the Eastern Third of the National Petroleum Reserve-Alaska: a Call For Symbiosis
Roland A. Gangloff

Using Radiological Surveying Instruments to Locate Subsurface Fossil Vertebrate Remains
Ramal (Ray) Jones, Gregory H. McDonald, and Daniel J. Chure

The Toadstool Park Trackway Site, Oglala National Grassland, Nebraska
Hannan E. LaGarry, W. Brantley Wells, Dennis O. Terry, Jr., and David A. Nixon

Fossil Vertebrate Tracks in National Park Service Areas
Vincent L. Santucci, Adrian P. Hunt, and Martin G. Lockley

Bridger Formation (Middle Eocene) of Southwest Wyoming: Widespread Marker Units and Subdivisions of Bridger B Through D
Emmett Evanoff, Leonard R. Brand, and Paul C. Murphey

Geologic and Paleontologic Investigation of the Cimarron National Grassland, Morton County, Kansas
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Stratigraphy, Depositional Environments, and Fossil Resources of the Chadron Formation in the South Unit of Badlands National Park, South Dakota
Dennis O. Terry, Jr.

PALEONTOLOGICAL AND ARCHAEOLOGICAL RESEARCH IN THE EASTERN THIRD OF THE NATIONAL PETROLEUM RESERVE-ALASKA A CALL FOR SYMBIOSIS

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ABSTRACT--The eastern third of the National Petroleum Reserve-Alaska (NPR-A) contains significant records of Quaternary vertebrates, an extensive record of Mesozoic plants, and the most abundant and diverse record of polar dinosaurs found in either hemisphere. The bulk of this paleontological record geographically overlaps numerous archaeological sites along the Colville and Ikpikpuk rivers. These areas are now contained in the Northeast Planning Area of the NPR-A. Most of the fossil vertebrate record came to light within the last 15 years due to the efforts of university-based researchers, while most archaeological sites were discovered by archaeologists working for Federal management and research agencies. The reality of shrinking budgets and the desirability of an interdisciplinary approach has led to a call for symbiosis between paleontological, archaeological, and biological researchers. It is proposed that logistic and research strategies be integrated and linked to Special Areas offering the greatest potential for needed research in these disciplines. The early oil exploration site, Umiat, should be upgraded and developed as a key logistical operations base. The native settlement, Nuiqsut, just north of the Colville River Special Area plays a pivotal cultural and logistic role at present. Both are vital to any future research on the archaeological and paleontological history of the eastern third of the NPR-A.

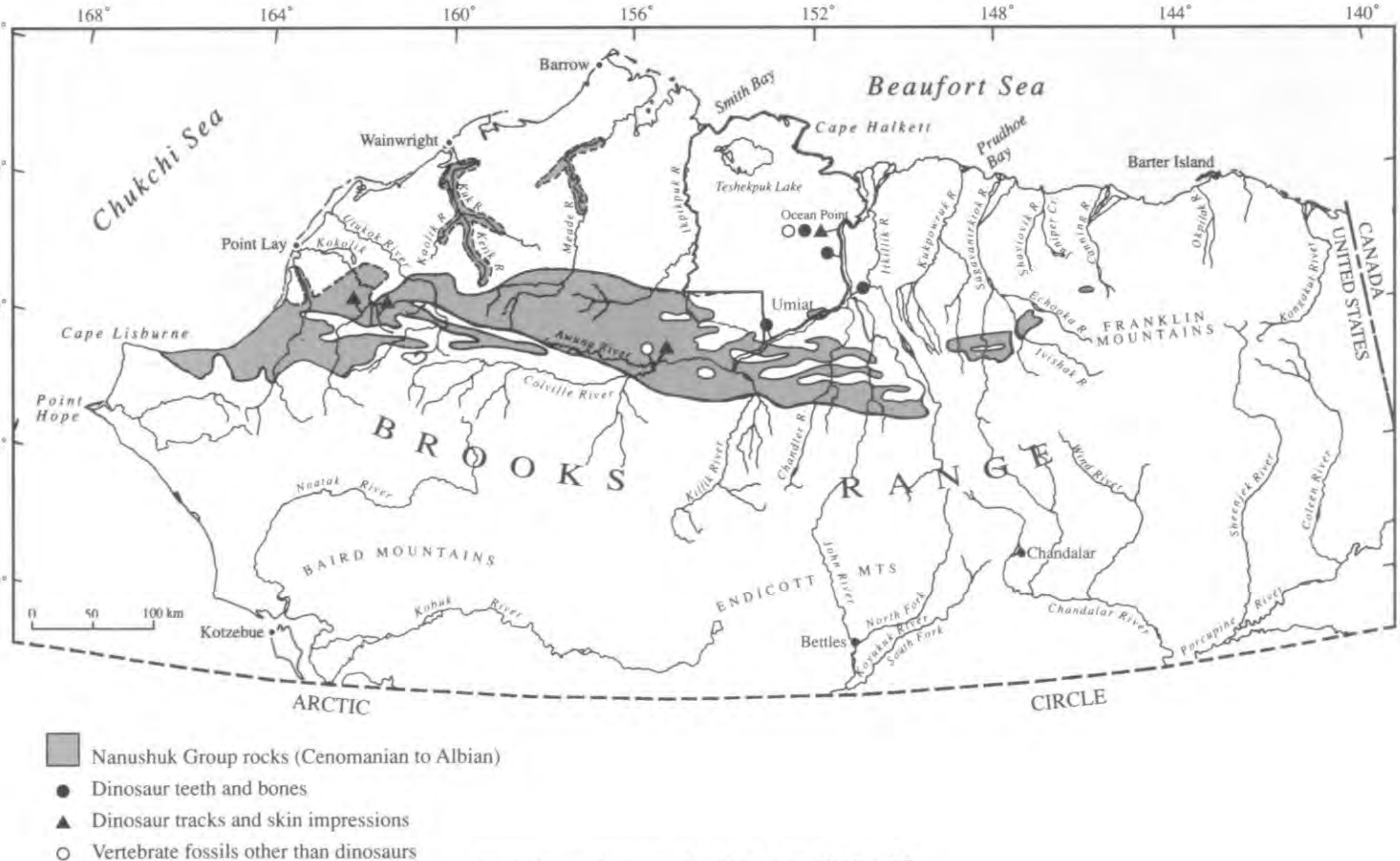
INTRODUCTION

The area presently designated as the National Petroleum Reserve-Alaska (NPR-A) encompasses more than 25,000 square miles (Fig. 1) and was partially mapped and explored geologically for the first time in 1901 (Dutro, Jr., 1987). The first noteworthy mapping and fossil collecting was connected with the United States Geological Survey's exploration (1923-1926) of the recently established Naval Petroleum Reserve No. 4. The next 42 years witnessed additional regional geologic mapping by the United States Geological Survey, followed by intensive exploration for oil and gas, climaxing in the world class Prudhoe Bay oil discovery in the late 1960's. Despite this long history of field investigation, only a Paleozoic to Mesozoic fossil invertebrate record combined with a Quaternary paleontological and archaeological record had been somewhat documented. It was not until the 1980's that the world was to learn of an extensive Mesozoic vertebrate record. From 1985 to 1987 occurred the most significant polar dinosaur discovery in both hemispheres (Brouwers et al., 1987; Parrish et al., 1987; Gangloff, 1994; Rich et al., 1997).

DISCUSSION

The following discussion will focus on a 7,000+ square mile subunit of the NPR-A that includes the Northeast Planning Area and contiguous lands making up the eastern third of the NPR-A. This paper will concentrate on the fossil vertebrate record from these lands, denoting closely related archaeological sites. The eastern third of the NPR-A contains the best documented record of vertebrate paleontological remains, and is

FIGURE 1 -Geographic trend of Cretaceous age (Albian to Cenomanian) rocks of the Nanushuk Group, northern Alaska, with dinosaur sites indicated. The Northeast Planning Area of the National Petroleum Reserve-Alaska is outlined. Modified from Huffman, Jr. (1985).



presently being evaluated for possible oil and gas exploration by the Department of the Interior. The most abundantly fossiliferous vertebrate sites are to be found within the zone of highest oil and gas potential (Hammond, 1997). In addition, the majority of known archaeological sites are found in this same zone. It is the primary aim of this paper to discuss the vertebrate paleontological research and potential for this research within the eastern third of the NPR-A. Secondarily, this paper will recount the recent history of cooperation between paleontological and archaeological researchers in the NPR-A and the need for more such cooperation in the planning and execution of future research by these two disciplines.

The Arctic Alaska Dinosaur Program

The summer of 1985 witnessed the beginning of what has evolved into a long-standing research program focused on high paleolatitude dinosaurs and associated fossil vertebrates. The 1985 field season brought together the U.S. Geological Survey, the Bureau of Land Management, the University of California at Berkeley, and the University of Alaska (see Gangloff, 1997 for a more detailed summary), and set the tone of cooperation that has prevailed since. In 1990, the Arctic Alaska Dinosaur Program (AADP) was born as a cooperative venture between the Bureau of Land Management's Northern District Office and the Earth Science Department of the University of Alaska Museum. To date, this research program has resulted in over 3,000 prepared and curated fossil vertebrate (mostly dinosaurs) specimens of Late Cretaceous age. The field work that forms the core of this program has, thus far, been primarily confined to the banks of the Colville River, extending from a site near the confluence with the Awuna River to the middle of the big bend of the Colville near Ocean Point (Fig. 1). The vast majority of skeletal remains were collected from a series of five Late Cretaceous age (Campanian to Maastrichtian) sites over a distance of 12 river miles. Recently (1997), the discovery of slightly older bone concentrations some 30 river miles to the south promise to expand the diversity of dinosaurs found at high paleolatitudes. A volunteer field crew in the summer of 1997 added significantly to Alaska's polar dinosaur data base by discovering the first dinosaur trackways in lower to mid-Cretaceous (Albian to Cenomanian) sedimentary rocks of the Nanushuk Group. This impressive record was accrued despite short field seasons that typically span a period from late July to middle August. To date, the fossil collections and contextual data gathered since 1990 have been the basis for six refereed journal articles, nine published abstracts and oral presentations at regional and national professional meetings, four popular and encyclopedic contributions, 12 reports and brochures, and one permanent museum exhibit (Clemens and Nelms, 1993; Clemens, 1994; Gangloff, 1990; Rich et al., 1997; Gangloff, 1997) (Table 1).

The prevalence of continuous permafrost, combined with slumping and sliding of steep cliff faces at most dinosaur sites along the Colville River, has led to an innovative plan to apply permafrost tunneling and mining techniques to the mapping and recovery of dinosaur remains at selected sites near Ocean Point. Studies begun in 1993 in cooperation with Thomas and Patricia Rich of the Victoria Museum of Melbourne Australia, and initially supported by a grant from The Dinosaur Society (Gangloff and Rich, 1994) have set the stage for the application of modern permafrost tunneling techniques. This approach would contribute substantially to the dinosaur skeletal data set already compiled and would greatly simplify future logistics for the research program as a whole. A Mitsui S-125, or equivalent, road header machine is proposed for use in late winter or early spring to excavate horizontal tunnels at several sites near Ocean Point. The tunnels would be dug just above targeted bone-rich beds and would be followed in expanded summer field seasons by mapping and excavation of the tunnel floors. The tunnels could then

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TABLE 1 - Cretaceous dinosaur and associated vertebrate and megafloral record in the eastern third of the NPR-A. The data presented is based on the following sources: Smiley (1969), Scott and Smiley (1979), Roehler and Stricker (1984), Grande (1986), Davies (1987), Parrish et al. (1987), Spicer et al. (1987), Witte et al. (1987), Parrish and Spicer (1988), Nelms (1989), Nelms and Clemens (1989), Lidgard and Crane (1990), Spicer and Parrish (1990), Clemens (1991), Clemens and Nelms (1993), Gangloff (1994), Rich et al. (1997), Parrish et al. (1998), and the University of Alaska Museum Earth Science Department collections and records.

I. DINOSAURS

A. HADROSAURS
    Edmontosaurus sp., most common duckbill, noncrested, juveniles and young adults dominate
    Kritosaurus sp., noncrested duckbill, teeth only
    Lambeosaurid ? crested duckbill, teeth and upper jaw
B. CERATOPSIANS
    Pachyrhinosaurus sp., partial upper cranium and other skull fragments, rare form found only in Alaska and Alberta, Canada
    Anchiceratops-like form, part of the rear end of the skull
C. HYPSILOPHODONTID
    Thescelosaurus sp., small bipedal herbivore, teeth and toe bone
D. THEROPODS
    1. Tyrannosaurids
        Albertosaurus sp., moderate to large bipedal carnivore, numerous isolated teeth and rare bones
        Tyrannosaurus sp.? single tooth
    2. Troodontid
        Troodon sp., small, lightly built, large-brained, bipedal carnivore, isolated teeth and skull fragment
    3. Dromaeosaurids
        Dromaeosaurus sp., small, lightly built, large-brained, bipedal carnivore, isolated teeth only
        Saurornitholestes sp., similar to *Dromaeosaurus*, isolated teeth and vertebra

II. OTHER VERTEBRATES

A. Fish
    Acipenser sp., an early sturgeon, vertebrae and dorsal spines
    Chandlerichthys strickeri, a primitive teleost, preserved as thin carbon film
B. Turtle, possible dermatemydid pond turtle with Asian affinities. This is the earliest turtle from above the Arctic Circle, partial internal mold of carapace
C. Plesiosaur, a single tail vertebra tentatively assigned to this marine reptile group
D. Crocodilians and amphibians conspicuously absent

TABLE 1 - Continued

E. Mammals
  1. Multituberculates, a form closely resembling *Cimolodon nitidus* and an unidentified genus based on isolated teeth
  2. Eutherian (placental) small mammal referable to *Gypsonictops* sp., isolated teeth
  3. Metatherian (marsupial) small-bodied pediomyid, isolated teeth

III. PLANTS

Forests consisted of coniferous trees with low-diversity angiosperm understory and ground cover. Ground cover included horsetails, ferns and some aquatic plants. Closest living analog is the coastal high-latitude, mixed coniferous forests of western North America. The plants listed are those that are found most closely associated with the dinosaurs.

A. Wood
  Xenoxylem latiporosum and six other taxa of conifers
B. Deciduous conifer
  Parataxodium wigginsi, needles and fronds
C. Rushes
  Equisetites sp., impressions and casts of stems, rhizomes and tubers
D. Angiosperms
  Hollickia quercifolia, leaf and fruit(?) impressions
  Quereuxia angulata, leaf impressions

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serve as storage facilities between summer field seasons. This approach to dinosaur excavation would require a new set of techniques and protocols for mapping and recovery of fossil bone and teeth, and if successful, could be exported to other Arctic sites where similar conditions exist. Thomas Rich (Rich and Rich, 1989) has used tunneling and underground mining techniques to recover dinosaur remains at Dinosaur Cove, southeastern Australia.

Another interesting aspect of dinosaur research along the Colville River involves the discovery and measurement of dinosaur and other vertebrate trackways. Prior to the summer of 1997, only a few isolated tracks of dinosaurs had been documented on the North Slope of Alaska. Field work conducted in July of 1997 near the confluence of the Awuna and Colville Rivers, and near the confluence of the Killik River and the Colville, established, for the first time, the presence of dinosaur trackways on the North Slope. In fact, the only other documented trackway in all of Alaska is found in Late Jurassic beds of the Naknek Formation near Black Lake on the Alaskan Peninsula. Detailed mapping in the summer of 1997 combined with sedimentological and paleoecological interpretation based on regional studies by the United States Geological Survey (Ahlbrandt, 1979; Huffman, Jr., 1985) strongly suggests that at least several more sites and horizons should yield trackways near the mouth of the Awuna and Killik rivers, as well as along Ninuluk Bluff. Further exploration for new sites and horizons combined with better photographic documentation and the production of molds and casts of individual tracks as well as trackways, is planned for the summer of 1998.

Quaternary Mammal and Archaeological-Cultural Record

The record of pre-Inupiat human occupation and use within the Northeast Study Area and the partially contemporaneous Quaternary fossil mammal record are poorly known. Little systematic research has been done on either of these aspects to date. However, the documented record points to great potential for future archaeological and paleontological research (Hammond, 1997; Reanier, 1997). The only systematic archaeological investigations have been conducted around Teshekpuk Lake and along the north coastal area in conjunction with earlier petroleum exploration. Little archaeology has been conducted within the Pleistocene to Holocene dune field complexes just south of Teshekpuk Lake, an area of highest potential for well preserved ancient sites (Reanier, 1997). An inspection of Fig. 2 shows the concentration of sites within the dune complex just south of Teshekpuk as well as the concentration of known cultural sites within and adjacent to the Northeast Planning Area. Coincidentally, the areas that have thus far produced the greatest abundance of Quaternary mammal record commonly overlap the cultural record. This is especially true along the Colville River from Ocean Point south to Umiat and in the southern reaches of the Ikpikpuk River which forms the western boundary to the Northeast Planning Area (Fig. 2). Just as the known archaeological record speaks of the potential for abundant and significant finds, the Quaternary mammals hold great promise. The bulk of this mammal record (Table 2) is found within a complex geologic rock and sediment unit known as the Gubik Formation. The Gubik represents a history of marine and non-marine sedimentation that includes the Upper Pliocene to the beginning of the Holocene (Coulter et

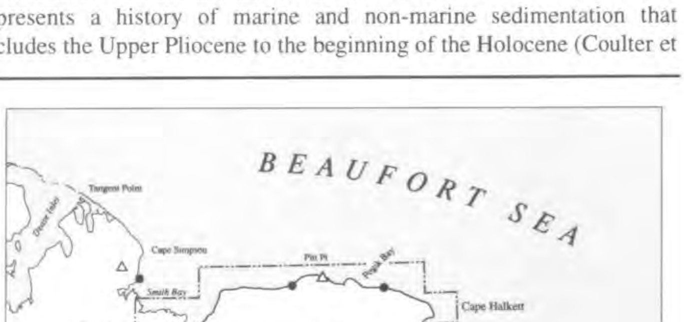

FIGURE 2 - Map of the Northeast Planning Area of the National Petroleum Reserve-Alaska with known archaeological-cultural, Quaternary mammal, and dinosaur sites indicated. Note the solid and heavier dark line that defines the boundary of the Northeast Planning Area. Modified from maps produced by the Northern District Office of the Bureau of Land Management, Alaska.

al., 1960). Bison, horse, and mammoths make up the bulk of the record, but the record of marine mammals from Teshekpuk Lake and the Colville River near Ocean Point, is of particular importance because of the presence of mammals (Table 2) with poorly known fossil histories (Repenning, 1983). Both the archaeological and fossil mammal record are critical to the history of the land connection and paleo-migrations between Eurasia and North America. Interestingly, the late Mesozoic history exemplified by the Cretaceous dinosaurs and associated vertebrates also holds crucial clues to the detailed history of migrations between the Old and New World. Therefore, the entire NPR-A appears to hold the key to a critical biologic history that spans the last 115 million years and the Northeast Planning Area represents a pivotal part of the NPR-A. For a more complete discussion of the importance of the NPR-A dinosaur and associated vertebrate record, see Gangloff (1997) and Rich et al., (1997).

The Future of Paleontological and Archaeological Research

Before 1987, the great bulk of paleontologic research within the NPR-A had been conducted by personnel of the United States Geological Survey. Exploration teams representing various oil companies have been responsible for several significant finds and collections. However, the great bulk of this work resulted in the documentation of the invertebrate and paleobotanical, rather than vertebrate fossil record. Today, most of the vertebrate and paleobotanical research is conducted by scientists from the University of Alaska, Fairbanks, and other universities. The bulk of the cultural and archaeological research was, and is now, conducted by teams of university and Bureau of Land Management personnel. Prior to 1996, there was only sporadic support of paleontological research by the Northern District of the BLM. The last two years have seen a welcome change with direct logistic support for field research and curatorial supplies being provided. Due to tighter budgets, archaeological and paleontological resource management should be run with greater efficiency and accountability. The geographic overlap of cultural and paleontological resources in the eastern third of the NPR-A allows for the integration of archaeological and paleontological research projects resulting in a symbiotic relationship between these disciplines.

Taking the present Special Areas (any area with special management designations) into account, close cooperation and overlapping logistic needs could be extended to include several of the biologic field programs that should be carried on in the Northeast Planning Area. A new Special Area should be designated for the southern half of the Ikpikpuk River. The middle stretch of the Colville River from Umiat to the Awuna should be included in an enlargement of the Colville River Special Area (Fig. 2) and integrated into the proposed symbiotic research effort over the next decade. This proposal will challenge the power and autonomy enjoyed by a few researchers and managers in the past. However, similar cooperative efforts between paleontologists and archaeologists at Olduvai Gorge and the Hadar-Afar regions of Africa have been very successful.

Two areas provide the greatest potential for a program of research and logistic symbiosis between paleontology and archaeology based on the potential for significant results for both disciplines. The first is that part of the Colville Special Area that extends from Ocean Point to Umiat

TABLE 2 - Quaternary mammal record from the eastern third of the NPR-A. Information presented based on the following sources: Harington (1978), Kurten and Anderson (1980), Repenning (1983), Lindsey (1986), Alaska Heritage Resource Survey, and University of Alaska Museum collections and records.

I. TERRESTRIAL MAMMALS

A. Proboscidea
   Mammuthus cf. *M. primigenius* (mammoth), most commonly reported and collected taxon, often represented by tusks which are highly valued
   Mammuthus sp.

B. Artiodactyla
   Bison priscus (steppe bison), second most commonly reported and collected taxon
   Ovibos sp. (muskox), most common of fossil muskox
   Symbos sp. (woodland muskox)
   Rangifer sp. (caribou)
   Alces sp. (common moose)
   Alces latifrons (broad-fronted moose)
   Saiga tartarica (saiga or saiga antelope)

C. Perissodactyla
   Equus sp. (horse)

D. Carnivora
   Canis sp. (wolf or coyote)
   Panthera sp. (lion)
   Alopex lagopus (arctic fox)
E. Rodentia
   Spermophilus sp. (ground Squirrel)

II. MARINE MAMMALS

A. Cetacea
   Unidentified whale

B. Carnivora
   Pagophilus sp. (seal)
   unidentified seal
   Enhydra sp. (sea otter)

(Fig. 2). This area includes the greatest potential for all of the disciplines presently involved in this part of the NPR-A. The second choice would be the southern Ikpikpuk River plus the Colville from Umiat to the Awuna River. It is also very important to consider the strategic potential of two settlements that are related to the two areas just defined. These two settlements are vital to future research efforts in the eastern third of the NPR-A. Nuiqsut, which is just north of the Colville River Special Area, is the largest native settlement on the Colville River and has come into special prominence with the development of the Alpine oil field in the Colville River delta. Nuiqsut has a fully operational airport and has served as an important staging and storage area for the AADP over the last four years. With the possibility of opening the Northeast Planning Area (any area involving a management plan) to further oil exploration combined with the further development of the Alpine field, Nuiqsut and its population must be further integrated into all research programs within its immediate area. Umiat, which is found near the middle of the Colville River Special Area, was once a major logistic center for oil and gas exploration on the North Slope. Umiat is strategically located so that it could serve as a key southern logistic center for the southeastern part of the NPR-A. At present, it is slowly deteriorating and valuable resources are being lost. Facilities at Umiat could be upgraded to meet the needs of existing and future research programs in this part of the NPR-A. The airstrip, which is capable of supporting the whole range of aircraft that are typically used to support research teams, could also be maintained over the next ten years at a reasonable cost. If one takes into consideration several large research initiatives such as Global Warming and Global Change which are in their early stages of development on the North Slope and in the Arctic, the revival of Umiat and the attendant costs become much more reasonable.

PRESENTLY ACTIVE RESEARCHERS

The following scientists are presently engaged in paleontological or archaeological field and/or other research pertaining to the eastern third of the NPR-A.

Paleontology

Elizabeth M. Brouwers, U. S. Geological Survey, Branch of Paleontology and Stratigraphy, Denver. Invertebrate paleontologist, paleoecologist.

Roland A. Gangloff, University of Alaska Museum and Department of Geology and Geophysics. Curator, vertebrate and invertebrate paleontologist.

Mark Goodwin, University of California Museum of Paleontology, Berkeley.

Howard Hutchison, retired, University of California Museum of Paleontology Museum, Vertebrate paleontologist.

Louis Marincovich, California Academy of Sciences. Invertebrate paleontologist.

Paul Matheus, University of Alaska, Alaska Quaternary Center. Vertebrate paleontologist and molecular paleobiologist.

Judith Totman Parrish, University of Arizona, Department of Geosciences. Paleoclimatologist and paleobotanist.

Robert A. Spicer, The Open University, Milton Keynes, U.K. Paleobotanist and paleoclimatologist.

Archaeology

Michael L. Kunz, Bureau of Land Management, Northern District Office. Archaeologist and Arctic Management Unit Team.

Richard E. Reanier, Reanier and Associates, Seattle. Archaeologist.

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USING RADIOLOGICAL SURVEYING INSTRUMENTS TO LOCATE SUBSURFACE FOSSIL VERTEBRATE REMAINS

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ABSTRACT--Radiological surveying uses a shielded gamma scintillation detector to measure gamma emissions from uranium in fossil bone. Radiological surveying was used to solve two strikingly different paleontological problems in Upper Jurassic and Pliocene rocks. At Dinosaur National Monument the problem was to find a carnivorous dinosaur skull, the rest of the skeleton having been collected several years earlier. Unsuccessful efforts were made to locate the skull at the time the skeleton was being excavated. A radiological survey of the quarry located an area with high radiation readings. Excavation at this location yielded the missing skull. At Hagerman Fossil Beds National Monument radiological surveying was used to map fossil bone locations at the Hagerman Horse Quarry. An 80 m^2 area of the Horse Quarry was laid out in 1 m^2 grids. Radiological readings were taken every one-half meter over the entire grid area. The area was excavated, and areas with higher than background readings yielded fossil bones, while those areas with normal or below background readings did not. Thus, radiological surveying provided a radiological map of the quarry indicating where to excavate. Radiological surveying is limited by burial depth, uranium concentration, and instrument sensitivity. Nevertheless, radiological surveying is the most promising method for locating subsurface bone.

INTRODUCTION

The first evidence of a fossil bone site is often fragments of fossilized bone eroding from the ground. What can not be immediately determined is: how much bone is still buried in the ground, where is the bone located, does the site contain just a few bones or a more complete skeleton, are the bones scattered over a large area or are they concentrated in one location and if the location is remote and, is it worth the time and cost to return and conduct an excavation? In the past, the only method to answer these questions was to excavate the site. Excavations are time consuming and expensive. Consequently, paleontologists have long desired a method of answering these questions without excavating.

Over the past decade, various methods of remote sensing have been tried at fossil bone sites to map bone location. The most concentrated effort was at the *Seismosaurus* quarry (Gillette 1994). Gillette called on the scientists from Los Alamo National Laboratory, Los Alamo, New Mexico, and Oak Ridge National Laboratory, Oak Ridge, Tennessee, to apply their expertise and equipment to map the buried *Seismosaurus* skeleton. A variety of ground penetrating techniques which included ground penetrating radar, proton free-precession magnetomitery, radiological scintillation counters that measure gamma radiation, and acoustic diffraction tomography, were tried but results were inconclusive; consequently up to now no promising technology has been developed.

In 1993, the first author began developing a method to detect buried

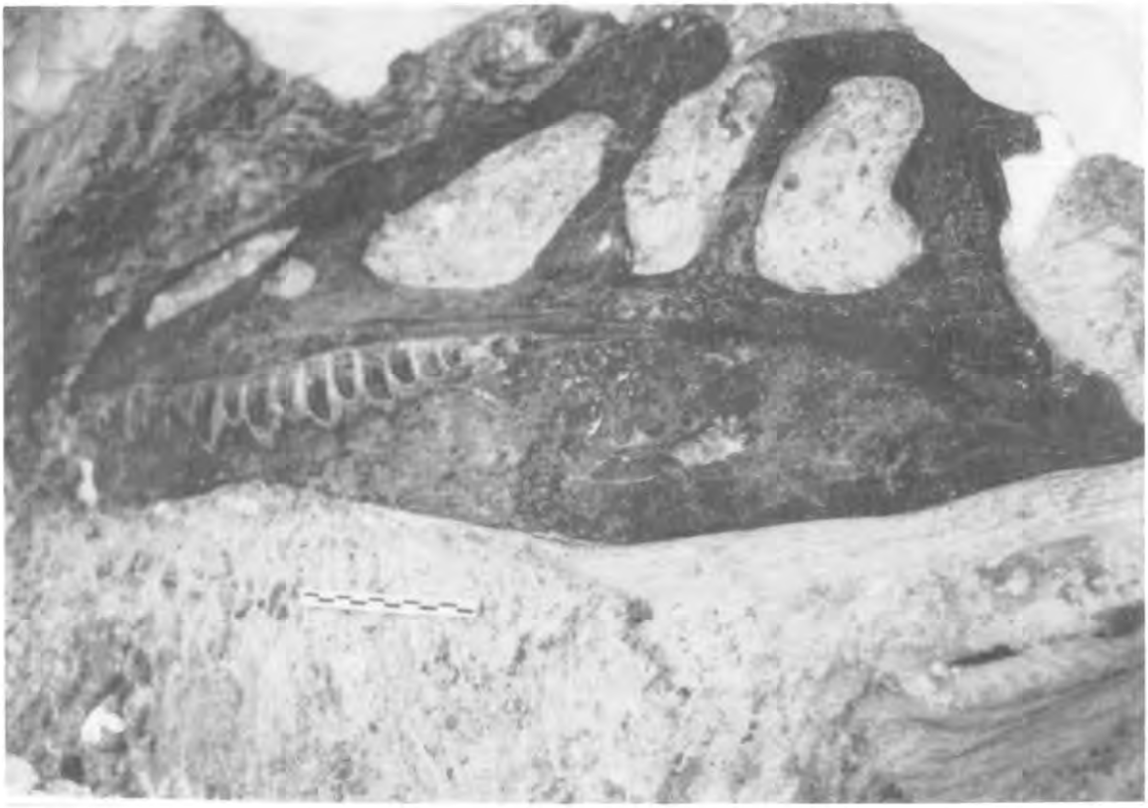

FIGURE 1 -Theropod skull found using radiological survey instruments, Dinosaur National Monument. Scale bar= 10 cm.

fossilized bone using radiation measuring instruments. Most soil and rock contain minute amounts of uranium which emits gamma radiation. It has long been known that some fossilized bone concentrate uranium during the fossilization process. After concentrating the uranium, the fossilized bone emits gamma radiation at a much higher level than the surrounding soil or rock. The instrument is designed to locate and measure these higher concentrations of uranium.

Radiation measuring instruments as purchased from the manufacturer, are usually unable to detect the buried bone because the gamma radiation emitted by the uranium is usually at very low level and in most cases is over-shadowed by the normal background radiation. The configuration of the detector and shield for the radiological surveying instrument was designed to overcome this problem.

During the past two years these radiation measuring instruments have been used with remarkable success at two National Park Service fossil bone sites. In 1996 the equipment was used to locate a theropod skull (Fig. 1) from an abandoned quarry at the Dinosaur National Monument (DNM) at Jensen, Utah. Then in 1997, the equipment was used to conduct a preliminary survey of the newly reopened Hagerman Horse Quarry at Hagerman Fossil Beds National Monument at Hagerman, Idaho.

GEOCHEMICAL CYCLE AND DISPOSITION OF URANIUM IN FOSSILIZED BONE

Geochemical Cycle of Uranium

For uranium to be deposited in fossilized bone, there must have been uranium present during the fossilization process of the animal remains. The source of that uranium is believed to be igneous rock (Trimble and Doelling 1978). The mineralization and concentration process of the uranium in the bone, starts with the geochemical cycle of uranium (Trimble and Doelling 1978). The geochemical cycle of uranium occurs at low temperatures and pressures. The uranium in igneous rocks undergoing weathering and thru leaching is oxidized from U^{+4} to U^{+6} and becomes soluble in ground water as $(UO_2)^{+2}$ ion, one of the uranyl carbonate complex ions. As long as the ground waters remain oxidizing, uranium ions remain mobile. When the uranium ions encounter a reducing environment, which could be decaying organic material, such as vegetation or animal remains, they will bond with O_2 to form the uranium-oxide mineral UO_2 uraninite.

Mechanisms For Concentration of Uranium in Fossilized Bone

Studies (Guilbert et al., 1986; Hubert et al., 1996) provide evidence that there might be two mechanisms involved in concentrating the uranium in the fossilized bone. The first mechanism is uranium ions being incorporated into crystal structure. Studies show that the crystal structure of the fossilized dinosaur bone in the Morrison Formation, is well-crystallized, stoichiometric francolite (a variety of hydroxyapatite enriched with fluorine). After burial the francolite crystals grow on pre-existing crystallite seeds and fill the space formerly occupied by collagen. As the francolite crystals grow, they incorporate other ions including uranium ions into their crystal structure and these ions become part of the bone mineralization (Hubert et al., 1996).

The second mechanism is the precipitation of crystalline uraninite and other minerals from ground water into the cracks and voids of the bone (Guilbert et al., 1986). The concentration of uranium in the bone does not result in a homogenous disposition. The disposition seems to be a result of opportunity or chance depending on the size of the cracks and voids, and their locations in the bone. Consequently, the radiation level of each bone will vary among bones even though they are from the same site. The amount of uranium contained in the bone is dependent on the number of uranium ions that are in solution in the ground water, thus the radiation level of the fossilized bone will also very between sites.

PHYSICS OF GAMMA RADIATION

The relative depth of the bone can be determined by measuring the radiation level of an excavated bone from the site. The gamma radiation is electromagnetic radiation similar to light or x-rays. As a gamma ray travels though a medium (the shielding material e.g., soil, water, etc.), it interacts or collides with atoms of that medium. Each collision results in the loss of energy; thus the gamma ray intensity is attenuated until it ceases to be detectable. The distance a gamma ray will travel is related to the original energy of the gamma ray, and the density and atomic number of the medium or shielding material. The higher the density and atomic number of the medium the shorter the distance the radiation travels. Also the inverse square law applies to gamma rays traveling though air in which as distance from the source doubles and the volume of the sphere occupied by the gamma radiation becomes four times larger. The radiation intensity at a point on the new sphere surface will be only one fourth the intensity as before. Therefore, because of the energy lost thru collisions with the medium and the inverse square law, the highest radiation readings are found at the surface of the fossilized bone, and as the distance from the radiation detector to the bone surface is increased, the readings rapidly drop off. For example the DNM theropod bone in the lab read 6.5 μR/hr (micro-R per hour) at its surface and there were readings of 6.5 μR/hr on the field survey, so it could be assumed that the bone was close to the surface.

RADIATION MEASURING INSTRUMENTS LIMITATIONS

The limiting factors in the use of radiation measuring instruments on fossilized bone sites are:

1- The amount of uranium concentrated in the bone.
2- The depth of the bone below the ground surface.
3- The sensitivity of the radiation measuring instrument.
4- The size of the bone.

These limiting factors are interdependent. If the content of uranium in the bone is high, bone can be detected at a greater depth and with less sensitive instruments. If the uranium content of the bone is low, then it takes a more sensitive instrument to detect it. If the depth of the bone is shallow, then the uranium content of the bone and the sensitivity of the instrument can be less. If the sensitivity of the instrument is increased, it will detect bone at greater depths and with a lower content of uranium. The size of the bone can also be a limiting factor due to the small diameter of the window in the shielding for the detector. This creates a small field of view for the detector, and it is easy for the operator to miss a very small bone.

RADIOLOGICAL SURVEYING EQUIPMENT AND METHODS

The radiation survey instrument (Fig. 2) used to locate the theropod skull at Dinosaur National Monument consisted of an Eberline Analog Smart Portable Micro-R survey meter model ASP-1 with a model SPA-8 sodium-iodine radiation detector. The detector is mounted inside a 0.625 cm thick lead shield. The lead shield completely encloses the detector except for a 1.25 cm opening at the top for a electronic cable and 2.5 cm diameter window at the bottom for the detector.

By enclosing the detector in a lead shield, the detector is shielded from most of the normal site background radiation of 7 to 8 μR/hr. As a result, the instrument background reading is reduced to 1.5 μR/hr to 2.0 μR/hr. The lead shield is mounted in a holder that is designed to position the detector at a 90-degree angle to the ground surface, to facilitate the handling of the shield, and to position the detector window same the distance (10 cm) from the ground surface each time a reading is taken.

The 2.5 cm diameter window collimates the gamma radiation emitted by the bone. This provides directional capability and greater transitional definition as the detector passes over the buried bone because the

FIGURE 2 - Radiological survey instrument used to conduct the radiological survey at the theropod quarry Dinosaur National Monument. The instrument is an Eberline Micro-R meter with the scintillation detector mounted inside a lead shield.

detector sees only the gamma radiation that is emitted at a zero-degree angle from the bone with respect to the face of the detector window.

The area to be surveyed is marked with a grid, then a radiological survey is conducted utilizing the radiation measuring instrument described. Each reading is recorded on the data sheet with respect to its location on the grid. At each grid location, the survey instrument will always read either background radiation or elevated radiation from fossilized bone or something else that has concentrated the uranium. After the survey is completed, the data is fed into a computer spread sheet. The next step is to delete the radiation background readings leaving only the elevated readings that may indicate bone.

RADIOLOGICAL SURVEY OF THE THEROPOD SITE DINOSAUR NATIONAL MONUMENT

In 1993 a nearly complete skeleton of a theropod was excavated from the Morrison Formation at Dinosaur National Monument. The remarkable completeness of the skeleton suggested that the skull might be present, although further excavations failed to locate it. A radiological survey was conducted in hopes of locating the missing skull. The first step was to establish if there was enough uranium concentrated in the bone to warrant a survey. Radiological measurements of the excavated theropod skeleton in the lab at Dinosaur National Monument and background readings at the theropod quarry were taken. The measurements on the excavated bone read 6.5 µR/hr which was 4.5 µR/hr higher than background radiation of 1 to 2 µR/hr at the theropod quarry. The above background reading indicated that uranium had been present during the fossilization process of the skeleton and that the bone had concentrated enough uranium to make a radiological survey feasible.

Theropod Quarry Radiological Survey

A radiological survey of the theropod quarry was conducted in June of 1995. The area surveyed measured 2 x 2 meters, which encompassed the area where the theropod skeleton was found. A grid of 10 x 10 cm squares was established using a string to mark the outside boundary of the grid (Fig. 3). A radiation reading was taken in the center of each square. Radiation readings were recorded on data sheet and later the data was entered into a computer spread sheet for analysis. The computer spread sheet (Fig. 4) shows all the radiological survey readings and their location with respect to the survey grid.

Fragments of sauropod bone are still exposed in the quarry sandstone. These bones are inside the survey grid in the lower left hand quarter and marked with the letter B on the survey data spread sheet. Readings on these bones were 2.6 µR/hr to 3.6 µR/hr, which confirmed our previous analysis that the equipment was able to detect bone at this site.

The first step in analyzing the survey data is to establish the site background readings. The background is established by taking the mean of the radiological survey data and applying a plus and minus number. Background readings indicate the normal distribution of uranium in the rock with no concentration of uranium. The radiological background reading with a shielded detector for the theropod quarry is a mean of 2.0. +/– 0.5 µR/hr.

With the background readings deleted from the radiological survey data (Fig. 5), the readings indicate that there was an area of elevated readings as shown in the enclosed box (Fig. 5). This area did not appear to be the logical location for the skull, but the elevated readings indicate that there was possible bone buried at that location. This data warranted an excavation, but because of other priorities, excavating the area was put off until the following year.

In July 1996 an excavation crew returned to the site and relocated the

FIGURE 3 - Theropod Quarry, Dinosaur National Monument showing survey grid lay out, radiological survey instrument used to conduct the radiological survey, and Dan Chure, Paleontologist at Dinosaur National Monument.

Meters

Readings are in micro-R per hour

		0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**
	0	1.8	1.8	2.0	1.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.6	1.5	2		
	0.1	1.8	2.0	2.0	2.2	2.0	2.0	2.0	2.3	2.0	2.0	2.0	2.0	2.2	2.2	2.2	2.0	2.0	1.9	1.8	2.0	
	0.2	1.8	1.8	1.8	2.0	2.0	1.9	1.9	1.9	1.8	2.3	2.0	2.2	2.3	1.9	1.3	1.2	2.0	2.0	2.0		
	0.3	1.8	1.7	1.5	1.8	2.0	2.0	2.3	2.0	2.3	2.3	2.3	2.0	2.0	2.2	2.0	2.0	1.7	1.8	2.5	2.0	
	0.4	1.8	1.6	1.8	2.0	1.8	1.7	2.2	2.1	1.8	2.0	2.0	2.1	2.2	2.2	1.9	2.1	2.2	2.0	2.8	2.0	1.8
	0.5	2.2	2.0	2.2	1.6	1.8	1.5	1.8	2.2	2.2	2.3	2.3	2.2	2.6	2.3	2.7	3.2	4.2	6.4	4.8	2.7	2.0
	0.6	2.0	1.8	2.0	1.8	1.6	1.8	1.8	2.2	2.3	2.3	2.0	2.2	2.2	2.4	2.7	3.3	4.2	4.7	3.5	2.6	2.1
	0.7	1.8	1.5	1.8	1.8	1.8	1.8	2.0	2.0	2.0	2.2	2.2	1.9	2.2	2.0	2.0	3.0	3.4	3.0	2.5	2.5	2.0
M	**0.8**	1.8	1.6	1.8	2.0	1.9	1.8	1.8	2.4	2.2	2.7	2.6	1.8	1.8	1.8	2.0	2.4	2.8	2.6	1.5	1.5	1.8
e	**0.9**	2.0	2.0	2.0	1.6	1.5	1.6	1.0	2.6	2.0	2.6	2.5	2.0	1.8	1.8	2.4	2.8	3.0	2.6	2.2	1.8	1.8
t	**1.0**	2.0	2.0	2.3	2.0	1.8	1.8	1.8	2.2	2.0	2.5	2.4	2.4	2.2	1.8	2.0	2.4	2.7	2.6	2.0		
e	**1.1**	2.2	2.2	2.2	2.3	2.0	2.0	2.2	2.2	2.4	1.9	2.3	2.0	2.2	2.3	2.3	1.9	2.3	2.0	2.1	1.8	2.3
r	**1.2**	1.8	1.9	1.9	1.9	2.3	2.3	2.4	2.3	2.1	2.1	1.6	1.8	2.0	2.0	2.2	2.0	2.5	2.0	2.0	1.9	1.6
s	**1.3**		2.0	2.0	1.9	2.0	2.8	**3.3b**	**3b**	2.6	1.9	1.8	1.8	1.6	1.9	1.9	2.2	2.3	2.1	1.9	1.6	1.6
	1.4			2.0	1.8	1.9	2.4	2.6	**2.8b**	2.4		2.2	1.8	1.9	2.0	2.0	2.0	1.8	1.8	1.8	2.0	2.0
	1.5			1.6	2.0	2.0	2.2	2.3	2.6	2.7	1.9	2.1	1.9	1.8	1.8	1.7	1.4	1.5	1.9	1.8	1.6	1.6
	1.6						1.7	2.4	2.9	**3.5b**	3.0		2.7	2.7	2.0	2.0	1.4	1.5	1.9	1.8	1.7	
	1.7								1.8	2.3	2.5	2.3	2.1	2.0	2.2	1.8	2.0	1.9	1.9	1.8	1.8	
	1.8																					
	1.9																					
	2.0																					

b=exposed bone of the sauropod

FIGURE 4 - Radiological Survey of theropod site at Dinosaur National Monument, June 24, 1995. Instrument used for the survey was a Eberline Micro-R meter with shielded detector.

Meters

Readings are in micro-R per hour

		0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**
	0																					
	0.1																					
	0.2																					
	0.3																					
	0.4															**SKULL**				**2.8**		
	0.5													2.6		**2.7**	**3.2**	**4.2**	**6.4**	**4.8**	**2.7**	
	0.6															**2.7**	**3.3**	**4.2**	**4.7**	**3.5**	**2.6**	
	0.7																**3.0**	**3.4**	**3.0**	**2.5**	**2.5**	
M	**0.8**										2.7	2.6						**2.8**	**2.6**			
e	**0.9**										2.6		2.6	2.5					**2.8**	**3**	**2.6**	
t	**1.0**										2.5							**2.7**	**2.6**			
e	**1.1**																					
r	**1.2**																	**2.5**				
s	**1.3**						2.8	**3.3b**		**3b**	2.6											
	1.4							2.6	**2.8b**													
	1.5								2.6	2.7												
	1.6								2.9	**3.5b**		3.0	2.7	2.7								
	1.7									2.5												
	1.8																					
	1.9																					
	2.0																					

b=exposed bone of the sauropod

FIGURE 5 - Radiological Survey of theropod site at Dinosaur National Monument June 24, 1995, with the background readings of 1.0 to 2.4 micro-R /hr deleted.

area of elevated readings. Excavations were started and quickly exposed bone. As the bone was uncovered it became evident that they were looking at the occipital surface of the missing theropod skull. The skull, which was laying in the conglomerate-sandstone contact was missing the palate, the right mandible, and right side of the skull. Miraculously, the braincase, the left side of the skull, the left mandible (still occluded) and the dentition were perfectly preserved. The skull had moved approximately 2 meters from the end of the neck.

HAGERMAN FOSSIL BEDS NATIONAL MONUMENT RADIOLOGICAL SURVEY

In May of 1997 Hagerman Horse Quarry at Haggerman Fossil Beds National Monument, Idaho, was opened for the first time since excavations were done by Idaho Museum of Natural History, 1968. The purpose was to gain additional paleontological information on the Hagerman horse and to apply the latest excavation, and analytical techniques to the excavations. Because the Hagerman bones are radioactive, it was decided to include a radiological survey. A radiological survey of the Quarry (Fig. 6) was conducted before excavations were started.

The quarry is located high up on the side of a bluff overlooking the Snake River and the Hagerman Valley. The National Park Service had used a backhoe to dig into the hillside and expose a 40 meter long by 5 meter wide surface of the bone bed. The area for the radiological survey was laid out and marked off with a 20 X 4 meter grid. The instrument used for the survey was a Eberline Micro-R survey meter mounted on a wheeled cart (Fig. 7). Radiological readings were taken every half meter and recorded on a data sheet. Fossilized bone was exposed in two areas and in each of these areas the survey readings were higher than the normal site background. This exposed bone gave a good reference reading as to the radioactivity of the bone.

When the radiological survey was completed, the data was put on a computer spread sheet (Fig. 8) for analysis. The normal radiation background level for the Hagerman Horse Quarry was determined to be 1 to 1.5 μR/hr. The survey data with the normal background (Fig. 9) readings deleted shows a number of areas with elevated readings. Because two areas of elevated readings have exposed bone, it is very likely that the instrument is also reading buried fossilized bone in the other areas of elevated readings.

During the summer the excavation crew excavated most of the 20 X 4 meter square area surveyed in the spring. When the location of the bones showed on the radiological survey were compared to the actual bone locations as revealed by excavation, the radiological survey was accurate. The results demonstrated that radiological surveying can be used on relatively young mammal bone sites as well as much older dinosaur bone sites. The excavations uncovered twenty-five horse skulls.

DISCUSSION

The use of radiological survey instruments clearly has many applications in vertebrate paleontology. It could be especially useful when field time is limited and the location is remote. A radiological survey can quickly give information on the extent of a bone deposit and help evaluate whether or not to return to the site in the future. Radiation survey instruments are valuable in locating single bones or concentration of bones, defining bone boundaries when trenching around bone, minimizing bone damage, and minimizing unproductive digging in nonfossiliferous ground.

Notice: The radiological survey equipment configuration and radiological survey technic, are protected by a pending patent.

FIGURE 6 - Ramal and Carole Jones conducting the radiological survey at Hagerman Horse Quarry using the Eberline Micro-R meter with scintillation detector in a lead shield mounted on a cart. Carole Jones is recording survey data.

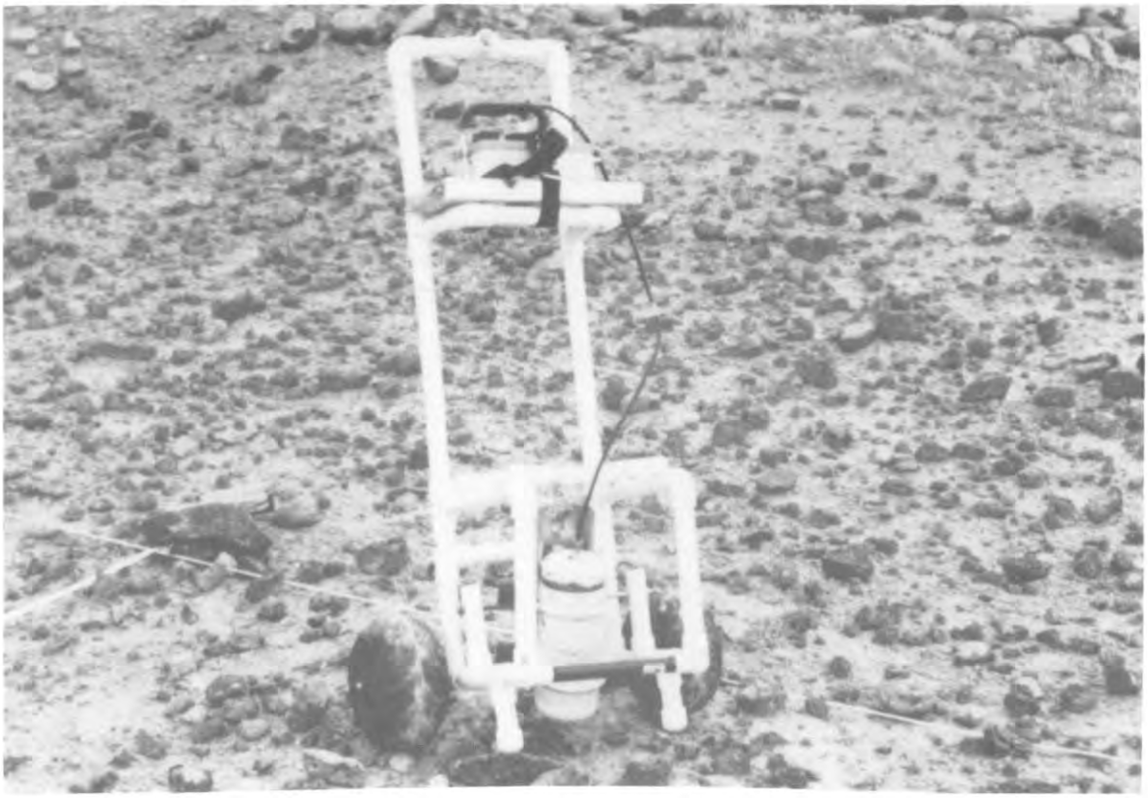

FIGURE 7 - Radiological survey instrument used to conduct the radiological survey at Hagerman Horse Quarry, Hagerman Fossil Beds National Monument. Instrument is an Eberline Micro-R meter with scintillation in a lead shield which is mounted on a cart.

METERS

Readings are in Micro-R per hour

METERS 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
4	2.6	2.2	1.8	1.4	2.0	1.4	1.4	1.4	1.4	2.0	1.4	1.2	1.5	1.3	1.4	2.0	1.6	1.6	1.9	1.4
3.5	2.0	2.0	2.0	2.5	1.8	1.6	1.6	2.4	1.6	2.4	2.6	1.2	1.2	1.1	1.4	2.0	1.8	1.4	1.3	1.3
3	1.5	1.8	1.7	2.7	1.6	2.5	1.5	1.5	1.2	1.5	2.0	1.4	2.0	1.6	1.5	4.0	2.2	1.7	1.2	1.5
2.5	1.4	1.4	1.7	2.0	1.5	1.6	1.8	1.4	1.5	3.0	1.8	1.6	1.7	1.4	1.3	1.8	2.4	1.5	1.3	1.4
2	1.3	1.5	1.2	2.4	1.3	1.5	1.2	1.4	1.0	1.2	1.4	1.5	1.3	1.5	1.5	1.3	1.8	1.4	1.2	1.5
1.5	1.5	1.2	1.1	1.7	1.3	1.7	1.2	1.2	1.3	1.4	1.2	1.2	1.4	1.4	1.3	1.4	1.3	1.4	1.2	1.3
1	1.6	1.4	1.3	1.4	1.3	1.6	1.2	1.6	1.4	1.7	1.2	1.3	1.3	1.3	1.2	1.2	1.4	1.7	1.4	1.3
0.5	1.7	1.4	1.2	1.7	1.3	1.2	1.6	1.6	1.5	1.4	1.2	1.3	1.2	1.2	1.2	1.4	1.6	1.4	1.3	1.4
0	1.3	1.2	1.2	1.4	1.2	1.0	1.6	1.1	1.2	1.4	1.2	1.2	1.0	1.2	1.2	1.4	1.6	1.4	1.3	1.2

FIGURE 8 - Radiological Survey of Hagerman Fossil Horse Quarry, May 5, 1997 Instrument used for the survey was a Eberline Micro-R meter with a Shielded detector mounted on a cart.

METERS

Readings in Micro-R per hour

METERS 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
4	2.6	2.2	1.8		2.0					2.0						2.0	1.6	1.6	1.9	
3.5	2.0	2.0	2.0	2.5	1.8	1.6	1.6	2.4	1.6	2.4	2.6					2.0	1.8			
3		1.8	1.7	2.7	1.6	2.5					2.0		2.0	1.6		4.0	2.2	1.7		
2.5			1.7	2.0		1.6	1.8			3.0	1.8	1.6	1.7			1.8	2.4			
2				2.4												1.8				
1.5				1.7		1.7														
1	1.6					1.6		1.6		1.7								1.7		
0.5	1.7			1.7			1.6	1.6									1.6			
0							1.6										1.6			

FIGURE 9 - Radiological Survey of Hagerman Fossil Horse Quarry, May 8, 1997, with the background readings of 1.0 to 1.5 micro-R deleted.

ACKNOWLEDGMENTS

We thank Jim Madsen who first suggested that (RJ, DC) get together to discuss using the radiation survey instruments at the theropod quarry. Carole Jones recorded the data for the radiological surveys. Scott Madsen, Ann Elder of Dinosaur National Monument, and volunteers Rod Joblove and Ron Hopwood for excavating the skull, Ann Elder and Scott Madsen prepared the skull. Marcus Schmidt (Dinosaur National Monument) provided the helicopter to carry the skull back to the laboratory. Angell Britt and Merlin Mott skillfully used their forklift to move the skull jacket from the helicopter drop to the laboratory. We also thank Eberline Instrument Corporation for the donation of the micro-R rate meter used in radiological survey. Canon USA, funded the Hagerman Horse Quarry Excavations.

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THE TOADSTOOL PARK TRACKWAY SITE, OGLALA NATIONAL GRASSLAND, NEBRASKA

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ABSTRACT--During the University of Nebraska State Museum's 1992 vertebrate fossil resource inventory of the Oglala National Grassland, an extensive vertebrate trackway site was documented within basal sandstones of the Orella Member of the Brule Formation (Oligocene) prominently exposed at Toadstool Geologic Park in northern Sioux County, Nebraska. Because of these trackways, Toadstool Geologic Park was designated as Oglala National Grassland Sensitive Site # 55, or the Toadstool Park Trackway Site. The Toadstool Park Trackway Site is the only area on the Oglala National Grassland designated for the protection of vertebrate trackways. The trackways are preserved on the upper surface of the "Toadstool Park channel complex," which is the exhumed paleoshoreline of an ancient river system that was at least 175 m wide and 2 m deep. We have identified 75 sandstone slabs bearing extensive trackways of at least 11 contemporary track morphologies along more than a kilometer of paleoshoreline. Fifteen slabs were cast in latex for future study. To date, invertebrate burrows and tracks of tadpole shrimp (notostracans), birds, perissodactyls (likely small and large rhinoceroses), artiodactyls (likely small antelope, camels, and entelodonts), and carnivores or oreodonts (four-toed tracks of various sizes) have been recognized. Our observations indicated that natural erosion, unrestricted foot traffic, vandalism, and theft are destroying the site. This work was funded by USDA Forest Service Challenge Cost-Share Agreements 02-07-92-025, 02-07-93-01, 02-07-94-015, and 11020795-28 (University of Nebraska-Lincoln/Nebraska National Forest). Latex peels and trackway slabs collected during this study are housed in the University of Nebraska State Museum.

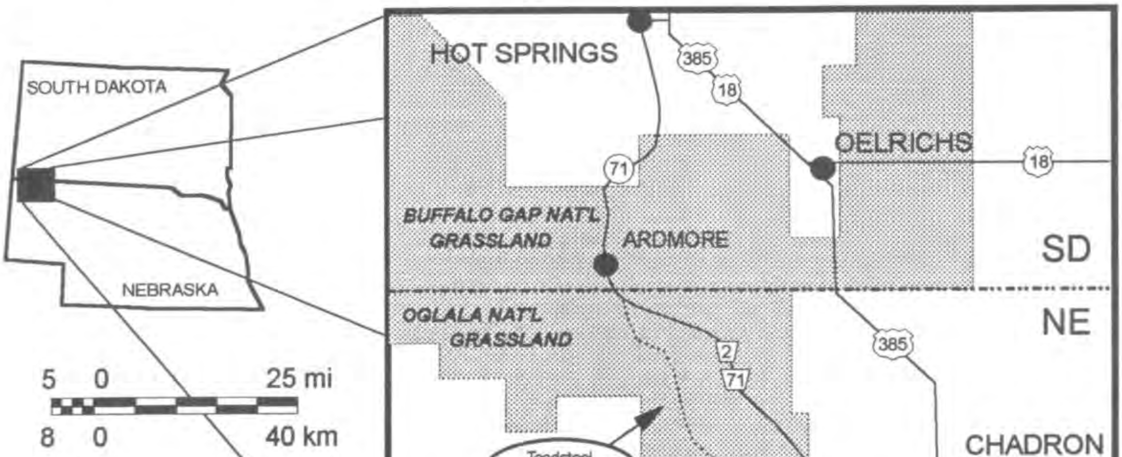
INTRODUCTION

During the 1992 paleontological resource inventory of the Oglala National Grassland by the University of Nebraska State Museum (UNSM), an extensive fossil vertebrate trackway site was documented within sandstones prominently exposed at Toadstool Geologic Park (Fig. 1) in northern Sioux County, Nebraska (see LaGarry, 1997; LaGarry and Hunt, 1996a, b). Because of these trackways, Toadstool Geologic Park was designated as Oglala National Grassland Sensitive Site # 55, or the Toadstool Park Trackway Site, in UNSM reports to the Nebraska National Forest (LaGarry and Hunt, 1996b). Toadstool Geologic Park is the only area site on the Oglala National Grassland designated for the identification and protection of vertebrate trackways. Once the importance of these trackways was recognized, the Nebraska National Forest provided funding specifically for documenting this site. This report describes our 1992-1995 research at Toadstool Geologic Park, along with our general recommendations to the Nebraska National Forest for management of the site.

GEOLOGIC SETTING

Many visitors to Toadstool Geologic Park are drawn by the unusual geologic features, or "toadstools," that are the Park's namesake. These features are erosional remnants of a sandstone bed that have been isolated on pedestals of a more easily erodable siltstone. In addition to their scenic qualities, these sandstones contain extensive vertebrate trackways. The trackway-bearing sandstones occur within the White River Group, which was deposited during the Eocene and Oligocene epochs of the Tertiary Period (between about 38 and 30 million years ago). These rocks are widely recognized for their abundant vertebrate fossils (Emry et al., 1987). The rocks and vertebrate fossils of the White River Group have been most widely studied in exposures in Badlands National Park in southwestern South Dakota (Meek and Hayden, 1857, 1861; Matthew, 1899, 1909; Wanless, 1922, 1923; Osborn, 1929; Scott and Jepsen, 1936; Clark, 1937, 1954; Wood, 1940; Scott, 1940, 1941; Clark et al., 1967), but White River Group rocks and fossils are also found in Nebraska, Colorado, Wyoming, and North Dakota (Schultz and Stout, 1955; Evanoff et al., 1992; Murphy et al., 1993; Terry et al., 1995).

FIGURE 1 - Location of Toadstool Geologic Park and the Oglala and Buffalo Gap National Grasslands.



Rocks of the White River Group, which includes (from oldest to youngest) the Chamberlain Pass, Chadron, and Brule formations (see LaGarry, in press; Terry, in press; Terry and LaGarry, in press), are primarily the product of volcanic activity in the western United States. Fine volcanic ash was transported from the west by prevailing winds to blanket much of the central Great Plains, mixing with other sediments to form the fine silt and clay layers of the White River Group (Evanoff et al., 1992; Tedford et al., 1996). These volcaniclastic siltstones and claystones show varied degrees of paleosol development, which gives the White River Group its characteristic color banding (Retallack, 1983). After the volcanic ash settled on the land surface, local streams not only reworked some of the volcanically derived sediment, but also deposited locally derived sands and gravels in their channels, such as those at Toadstool Geologic Park, as they meandered across the terrain.

The prominent trackway-bearing sandstones at Toadstool Geologic Park occur within Schultz and Stout's (1955) "Toadstool Park channel complex," which is a fluvial sandstone at the base of the Orella Member of the Brule Formation. The type section (rocks used as a formal standard of reference) of the White River Group is in the Big Badlands of South Dakota (Meek and Hayden, 1857, 1861). However, the type sections of the Brule Formation (see Darton, 1899) and its two oldest subdivisions, the Orella and Whitney members (Schultz and Stout, 1955), are located at Toadstool Geologic Park (Fig. 2). This places the trackway-bearing sandstones within Schultz and Stout's (1955) type section of the Orella Member (as revised by LaGarry, in press). Most outcrops of the Orella Member consist of vertical cliffs of interbedded siltstone and sandstone (Fig. 3A). The Orella Member overlies the Chadron Formation (Fig. 3B) and underlies the Whitney Member of the Brule Formation (Fig. 3C). However, the most prominent feature of the Orella Member are the trackway-bearing, toadstool-forming "Toadstool Park channel complex" sandstones at its base (Fig. 3D, E).

THE ORELLAN VERTEBRATE FAUNA

Each of the rock units within the White River Group contains a discrete fossil vertebrate fauna dominated by mammals but also yielding occasional fish, reptiles, birds, and snails (see Savage and Russell, 1983; Emry et al., 1987). Three major stages of mammalian evolution (called "North American land mammal ages," or NALMAs) are defined by these faunas (i.e., the Chadronian, Orellan, and Whitneyan NALMAs). The Orella Member is generally considered to be the most fossiliferous rock unit within the White River Group (LaGarry and Hunt, 1996a), and fossil vertebrates recovered from the Orella Member at Toadstool Geologic Park were used to define the Orellan NALMA (Wood et al., 1941; Savage and Russell, 1983; Emry et al., 1987). The Orellan NALMA includes *Leptomeryx* (a small antelope), *Daphoenus* (an amphicyonid), *Leptictis* (an insectivore), *Paleaolagus* (a rabbit), *Mesohippus* (a small horse), *Merycoidodon* and *Merychoerus* (oreodonts), *Metamynodon*, *Hyracodon*, and *Subhyracodon* (rhinoceroses), *Poebrotherium* (a camel), and *Dinictis* and *Hoplophoneus* (cat-like carnivores), among others (Emry et al., 1987). Fossilized teeth and bones of these mammals have been described, but very little is known about their ecology and behavior.

VERTEBRATE TRACE FOSSILS AND THEIR PRESERVATION

Vertebrate fossils often consist of mineralized bones and teeth, and are often termed "body" fossils in order to distinguish them from "trace" fossils. Trace fossils are indirect evidence of an animal's activities, such as burrows, tunnels, nests or egg chambers, footprints, tooth marks, and coprolites. Trace fossils are common in ancient marine deposits because invertebrates (e.g., clams, snails, worms, brachiopods) that live in or on the sea floor leave abundant traces as they burrow or crawl after food. These traces become preserved, or "fossilized," when they are buried by additional sediments (Häntzschel, 1975). In contrast, trace fossils of terrestrial animals are less common because environments that preserve them (e.g., streams, ponds, lakes) are less extensive. When preserved, such traces of an animal are often obscure and consist of isolated tracks, rather than trackways. The discovery and study of tracks and trackway sites depends on other factors as well. Large animals, such as dinosaurs, leave bigger and more easily recognized tracks (Langston, 1983), and the popularity of dinosaurs and dinosaur-related studies increases the number of people looking for such tracks.

Sites preserving the tracks of Cenozoic mammals are uncommon, and few are well studied. Such trackway sites have been reported from the late Eocene of Trans-Pecos Texas (Sarjeant and Wilson, 1988; Sarjeant and Langston, 1994) and Utah (Moussa, 1968), the Oligocene of Spain (Raaf et al., 1965) and South Dakota (see below), the Miocene of Kansas (Robertson and Sternberg, 1942), Louisiana (Wetmore, 1956), and India (West et al., 1983), and the Pliocene of Death Valley, California (Scrivner and Bottjer, 1986) and Japan (Yoshida, 1967), among others. Vertebrate trackways were reported from the White River Group in the Big Badlands of South Dakota (Chaffee, 1943; Bjork, 1976). Vertebrate trackways at Toadstool Geologic Park were first noted by Harvey (1960), who attributed these features to either track-making animals or sedimentary processes. Trackways at Toadstool Geologic Park were rediscovered by Nixon (1991), who recognized distinctive bird tracks (see also Terry et al., 1995).

MATERIALS AND METHODS

During our 1992-1995 research at Toadstool Geologic Park, University of Nebraska State Museum field parties consisted of two to six paid assistants and two to 10 volunteers annually. Our field seasons averaged six weeks in duration from 1 June to 31 August of each year. We 1) measured sections to document details of the geology of the Orella Member of the Brule Formation and its trackway-bearing sandstones; 2) collected nonvertebrate fossils (e.g., plants, limb casts, insect nests and tunnels, coprolites, etc.) to better reconstruct the local paleoenvironment; 3) mapped the positions of the trackways in relation to the visitor's trail; 4) mapped the orientations and positions of tracks on individual sandstone slabs; 5) documented evidence of the erosion of trackway-bearing slabs; 6) documented vandalism and accidental destruction of geologic and paleontologic resources within the park; and 7) recorded evidence of theft of vertebrate fossils in and near the Park.

Measured Sections

The standard geological method for describing, classifying, and interpreting rocks is the measured section. A measured section is a symbolic vertical cross section of a rock exposure (Freeman, 1992). Once described in this manner, rock exposures are commonly compared, contrasted, and correlated based on their lithic composition (lithostratigraphy) and fossils (biostratigraphy). The lithic composition of a rock unit is a direct result of the environments in which the rocks were deposited (see Pettijohn, 1975; Friedman and Sanders, 1978). For this reason we recorded several measured sections at Toadstool Geologic Park to characterize the depositional environment in which the trackways were preserved (Fig. 4).

Trackway Site Mapping

Detailed maps of trackway-bearing sandstone slabs were produced using the pace and Brunton compass method, and by triangulation of new trackway slabs from the positions of previously mapped trackway slabs and prominent landmarks (see Freeman, 1992). Using these methods, we could add newly recognized trackway slabs to the map as they were discovered using only a Brunton compass for surveying equipment (Fig. 5A, B). This approach minimized our visual impact on the surrounding scenery while mapping the trackway site. Detailed maps of the orientations and distributions of tracks on individual slabs were constructed using measuring tapes (Fig. 5C, D). Trackway-bearing slabs were drawn in the field, and the positions of individual tracks were determined by

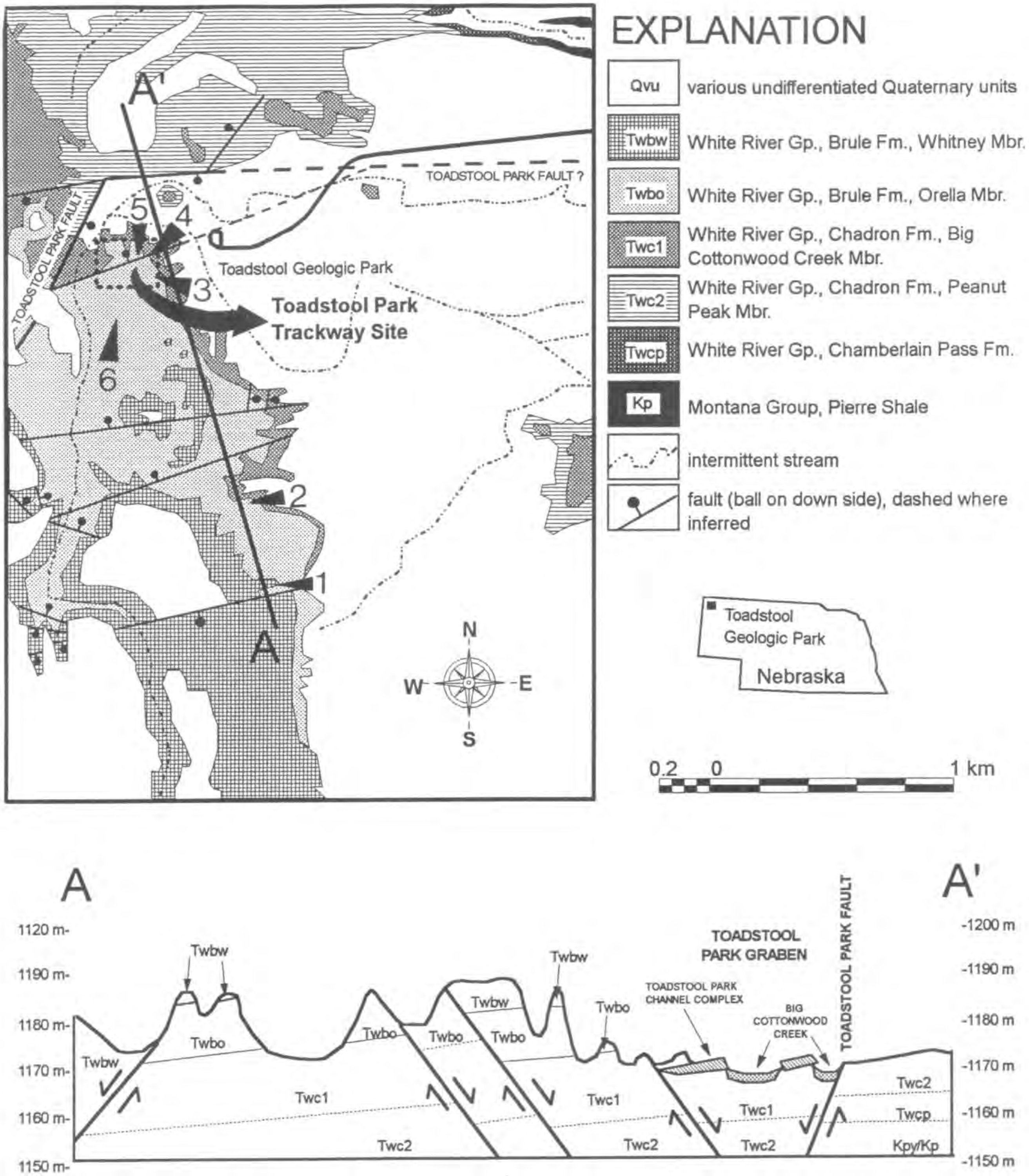


FIGURE 2 - Geologic map (top) and cross section (bottom) of Toadstool Geologic Park showing the locations of measured sections (numbered arrows), the Toadstool Park Trackway Site, the Toadstool Park Fault, and the Toadstool Park Graben. After Terry and LaGarry (in press).

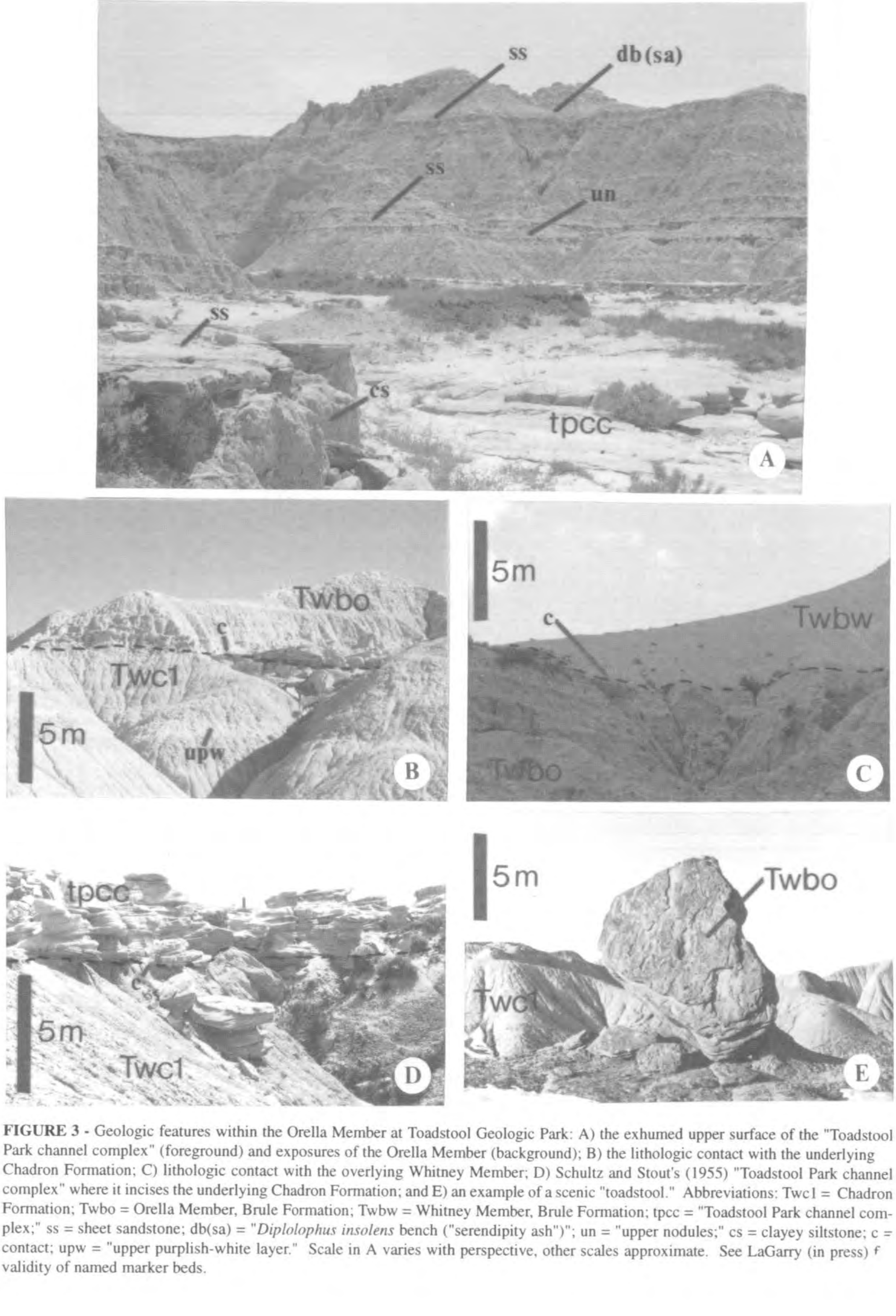


FIGURE 3 - Geologic features within the Orella Member at Toadstool Geologic Park: A) the exhumed upper surface of the "Toadstool Park channel complex" (foreground) and exposures of the Orella Member (background); B) the lithologic contact with the underlying Chadron Formation; C) lithologic contact with the overlying Whitney Member; D) Schultz and Stout's (1955) "Toadstool Park channel complex" where it incises the underlying Chadron Formation; and E) an example of a scenic "toadstool." Abbreviations: Twc1 = Chadron Formation; Twbo = Orella Member, Brule Formation; Twbw = Whitney Member, Brule Formation; tpcc = "Toadstool Park channel complex;" ss = sheet sandstone; db(sa) = "*Diplolophus insolens* bench ("serendipity ash")"; un = "upper nodules;" cs = clayey siltstone; c = contact; upw = "upper purplish-white layer." Scale in A varies with perspective, other scales approximate. See LaGarry (in press) f validity of named marker beds.

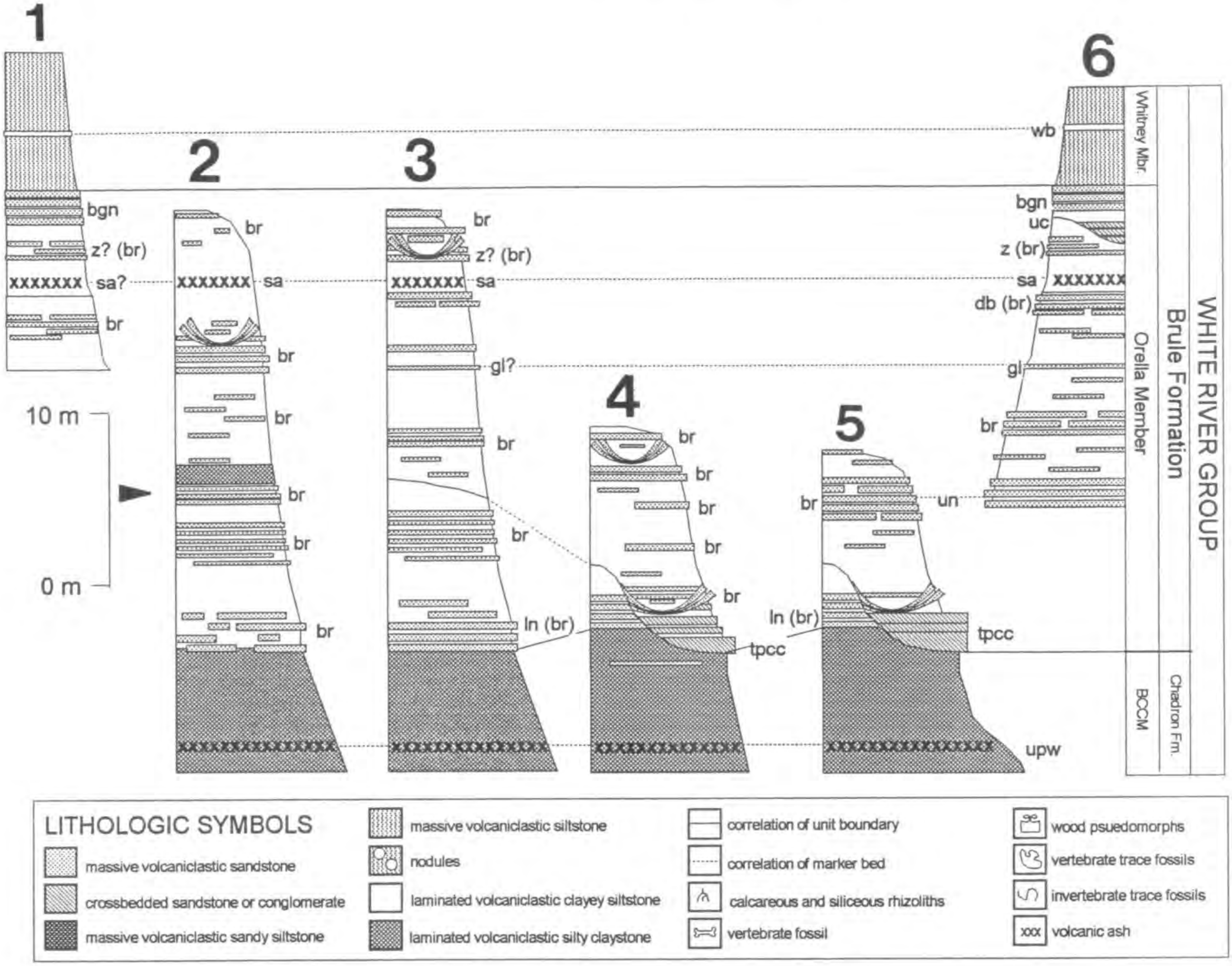


FIGURE 4 - Measured sections of the Orella Member of the Brule Formation at Toadstool Geologic Park. Abbreviations: wb = "white bed;" bgn = "bluish-green nodules;" z = "Z nodules;" uc = "upper channels;" db = "*Diplolophus insolens* bench;" br = brown sheet sandstone; gl = "green ledge;" un = "upper nodules;" ln = "lower nodules;" tpcc = "Toadstool Park channel complex;" and upw = "upper purplish-white layer." Terminology of Schultz and Stout (1955) except "serendipity ash" and brown sheet sandstone. See LaGarry (in press) for validity of named marker beds. Modified from LaGarry (in press).

measurement with the tape.

Latex Peels

We selected particular trackway-bearing slabs for replication with latex peels based on 1) the degree of preservation of recognizable trackways; 2) the rarity of the trackways (unique examples were given highest priority); 3) the size of the slab; 4) the position of the slab in relation to the visitor's trail; 5) the amount of vandalism evident on the slab; 6) our observations of visitor behavior in the vicinity; 7) the available personnel; 8) the available latex; 9) the physical condition of the slab; and 10) weather constraints (large slabs take longer to dry, up to two weeks, and wet slabs cannot be peeled). Using the above criteria, scientifically important slabs in imminent danger of destruction by visitor foot and bicycle traffic or erosion were assigned highest priority. Slabs selected for latex peel preparation were thoroughly cleaned of sediment and debris using soft-bristled brushes. Three thick coats of #800 latex (80% solids) were applied also using soft-bristled brushes. Each coat of latex was allowed to dry prior to the next application (Fig. 5E, F). The third coat was backed with cheese cloth to add additional support. Once dried, the peels were carefully removed, and the remaining latex debris was cleaned from the site.

Track-making Animals and Trace Fossil Nomenclature

Identification of a trackway-making animal is difficult because only exceptionally well-preserved examples are likely to be identified. Several guides to tracks and trackways of extant vertebrates are available (e.g., Seton, 1958; Murie, 1974; Brown and Morgan, 1983; Arnosky, 1989), but few references are available for tracks of extinct taxa (Sarjeant, 1975). This difficulty is compounded by our poor understanding of the morphology and contours of the feet of most vertebrates. Furthermore, small or juvenile members of one species may leave tracks the size and shape of a smaller, unrelated species. Thus, identification of a trackway-making animal is tenuous at best. Because of these ambiguities, trace fossil studies typically recognize groupings based solely on the shape of the track (e.g., Vialov, 1972), rather than Linnean groupings (i.e., Class, Order, Family, Genus, Species) based on the evolutionary relatedness of track-making animals (for additional discussion see Sarjeant and Kennedy, 1973; Sarjeant, 1975, 1990; Scrivner and Bottjer, 1986). However, some workers prefer to retain the zoological affinities of trackways, and have adopted a combined system in which morpholog-

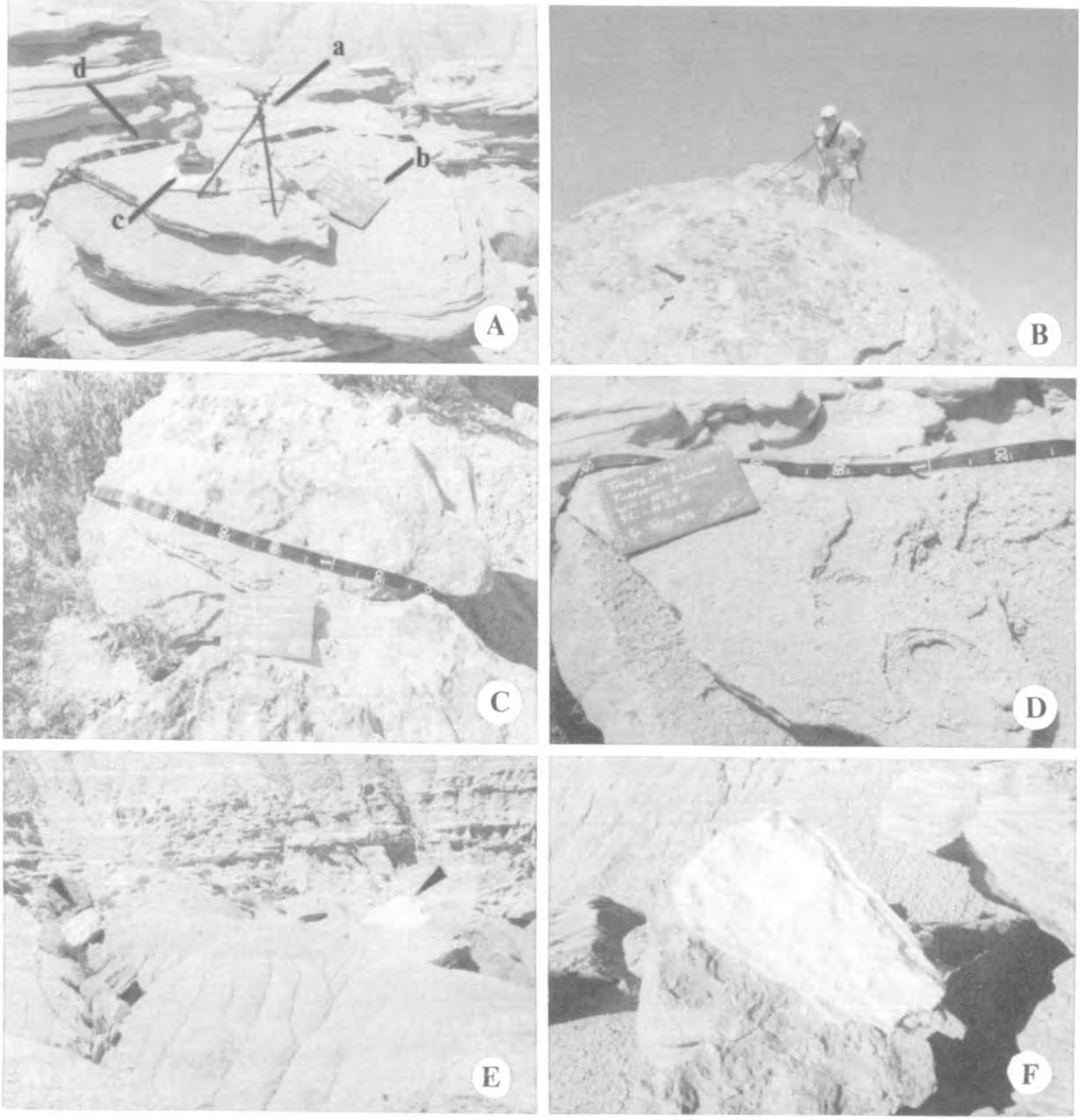


FIGURE 5 - Documenting trackways at the Toadstool Park Trackway Site: A) equipment used included a Brunton compass and tripod (a), a chalkboard for labeling field photographs (b), and measuring tapes (c, d); B) using triangulation to plot additional trackway slabs; C, and D) using measuring tapes to record features of the slab; E) latex peels of trackway slabs (arrows); and F) a labeled and cured latex peel just before removal.

ically defined ichnogenera and ichnospecies are assigned to Linnean families and orders (see Sarjeant and Langston, 1994, for an example).

Fossil vertebrates recovered from the White River Group are relatively well known (see Savage and Russell, 1983; Emry et al., 1987), allowing comparisons to the manus and pes of similarly shaped animals in modern faunas. Based on these comparisons, we identified track-making animals at the Toadstool Park Trackway Site to order (e.g., carnivore, perissodactyl, artiodactyl), and sometimes to family (e.g., felid, oreodont, camelid, amphycyonid). We use Linnean orders and families to categorize the tracks and trackways discussed herein pending a formal, systematic description of the invertebrate and vertebrate ichnotaxa at the Toadstool Park Trackway Site (Wells, unpublished data).

Assessment of Site Condition

Toadstool Geologic Park is a multiple-use area. In addition to its scientific value, it also has scenic, natural, educational, and recreational values, and attracts as many as 100 visitors per day (observations of 2-5 July, 1995). Many of these visitors walk or bicycle the mile long visitor's trail through the park to observe the "toadstools," while others wander over the landscape looking for fossils, wildlife, scenic solitude, or physical challenges. The small campground attracts visitors seeking solitude, artistic inspiration, or opportunities for wildlife or landscape photography. Some visitors, however, seek to collect vertebrate fossils for personal use or scientific study, which is illegal without a permit from the Nebraska National Forest, or commercial gain, which is not permitted. Beginning in 1992, we recorded detailed observations about visitor-use behaviors at Toadstool Geologic Park in order to understand their impact on our research activities, the condition of the site, and nearby vertebrate fossil resources. These observations assisted us in documenting damage to the site, monitoring illegal activity, planning our research program, and in offering management recommendations for the preservation and conservation of the trackways at Toadstool Geologic Park.

RESULTS AND DISCUSSION

Some preliminary results of our geological studies of Toadstool Park have been reported elsewhere (see Terry et al., 1995), and a complete review of these is beyond the scope of this report. The stratigraphic revisions and redescriptions of LaGarry (in press) and Terry and LaGarry (in press), and the detailed geologic mapping of the region by LaGarry and LaGarry (1997), have improved our understanding of the distribution and depositional history of the Orella Member. Terry et al. (1995) briefly described the depositional environments of the Orella Member and some of the first trackways recognized at Toadstool Geologic Park. Following is a brief review of the geology of the site, along with previously unpublished descriptions of invertebrate and vertebrate trackways and the impact of visitors to the site.

Geology

LaGarry and LaGarry (1997) mapped several major and many minor faults at Toadstool Geologic Park. Where these faults intersect Schultz and Stout's (1955) "Toadstool Park channel complex," the sandstones are broken into isolated slabs that subsequently weather into the scenic toadstools. Much of Toadstool Geologic Park occurs on a block (the Toadstool Park Graben: Fig. 2) that has moved downward relative to rocks around it. If there is no additional movement along these faults, or no movement along new faults, the current set of fault-displaced sandstone slabs will eventually erode away and the larger toadstools will eventually disappear.

LaGarry's (in press) reexamination of the lithologic characteristics of the Orella Member resulted in a reinterpretation of its depositional environments. Based on more than 60 measured sections across northwestern Nebraska, LaGarry (in press) redescribed the Orella Member as consisting of two lithotopes, or bodies of rock produced by particular depositional environments (Fig. 4). The first lithotope consists of fluvial overbank deposits composed of interbedded sheet sandstones and tan, light brown, brown, and brownish orange laminated volcaniclastic clayey siltstones. The second lithotope consists of single and multistoried channel sandstones. The best developed and most widespread of these channel sandstones is the "Toadstool Park channel complex." This sandstone was deposited during the Oligocene by a river system occupying a steep-walled valley (Schultz and Stout, 1955). According to Terry et al. (1995), the vertical and lateral arrangement of sedimentary structures within the "Toadstool Park channel complex" indicates a mixed-load river system that was ephemeral or seasonal in nature and likely fluctuated between braided (e.g., Platte River) and meandering (e.g., Missouri River). They further suggested that during periods when the river was braided, sediments were deposited very quickly, possibly by seasonal or episodic flash floods. Subaerially exposed mudflats then recorded the tracks of passing animals. The tracks dried, were filled with sediment, and preserved by subsequent deposition. Based on the geometries of surrounding strata, the trackway-bearing upper surface of the "Toadstool Park channel complex" likely represents the exhumed paleotopography of a braided stream channel at least 175 m across and 2 m deep. When the river system was meandering, maximum (bank to bank) flow periodically receded to a shallow, central channel about 2 m wide. A detailed study of the facies architecture of these deposits is in progress (LaGarry and Wells, unpublished data).

Invertebrate Trace Fossils

At Toadstool Geologic Park, invertebrate trails and feeding structures are more common within the "Toadstool Park channel complex" than vertebrate trackways (Table 1). These burrows were likely made by worms or insects, and are common within dark gray or dark brown fine-grained sandstones (Fig. 6A,B). In contrast, similarly shaped root and limb casts are typically filled with chalcedony (Wells, unpublished data). The abundance of burrows may indicate that the invertebrate fauna fed on abundant plant detritus (humus) intermixed with the silt and sand, and that the shorelines of the ancient river were vegetated for an extended period.

In 1993, a large crawling trace (Häntzschel, 1975) was discovered in the "Toadstool Park channel complex" (Fig. 6C). In 1995, this unique trace was recovered by latex peel and curated into the vertebrate fossil collections of the University of Nebraska State Museum (UNSM 88532) for further study. Based on its morphology, LaGarry et al. (1996) suggested that this trace was made by an undescribed tadpole shrimp (Arthropoda: Crustacea: Eubranchiopoda: Notostraca). Detailed studies of these trace fossils are in progress (Wells and LaGarry, unpublished data).

Vertebrate Trace Fossils

Fossil trackways are preserved along 1 km of exposures of the upper surface of the "Toadstool Park channel complex." Tracks have also been observed on at least one other ancient surface about 1 m lower in the section (Wells, unpublished data). We have identified 75 sandstone slabs bearing several extensive trackways and hundreds of individual tracks representing at least 11 contemporary track morphologies (Table 1). Fifteen of these slabs were cast in latex for future study (Wells, unpublished data). Following are brief descriptions of the trackways documented to date.

Reptiles--Reptile tracks and traces, while relatively common in some Tertiary trace fossils assemblages (Sarjeant and Langston, 1994), have not been recognized at the Toadstool Park Trackway Site. However, there are paired sets of concentric, semicircular scratches about 0.5 m long at several locations throughout the site. Once studied, these features may be attributable to a clawed reptile (Nixon, unpublished data).

Birds--Tracks of birds, while present on several slabs, are relatively rare (Table 1). These three-toed footprints are commonly associated with invertebrate burrows (see also Terry et al., 1995). On several slabs, there

TABLE 1. Trackway-bearing slabs recognized at Toadstool Geologic Park (Oglala National Grassland Sensitive Site #55) through 1995.

SLAB	CONTENTS	LOCATION[1]	CONDITION[2]	COMMENTS
1	bird tracks & probe holes (?) invertebrate burrows	near visitor's trail	damaged (FT)[3]	latex peel 1994
2	birds invertebrate burrows	near visitor's trail	destroyed 1993 (FT)	latex peel 1992
3	very large artiodactyl small artiodactyl	near visitor's trail	damaged (FT)	—
4	small artiodactyl	near visitor's trail	damaged (FT, V)	carved ΛΚΠ
5	carnivore or oreodont	near visitor's trail	damaged (FT)	four-toed tracks
6	carnivore or oreodont	near visitor's trail	damaged (FT)	four-toed tracks
7	birds invertebrate burrows	near visitor's trail	destroyed 1994 (FT)	—
8	mammal	near visitor's trail	damaged (FT)	—
9	mammal	near visitor's trail	damaged (FT)	—
10	very large artiodactyl invertebrate crawling trace	off trail to southeast	damaged (ER)	latex peel 1995
11	mammal	off trail to southeast	damaged (ER)	—
12	carnivore or oreodont	near visitor's trail	good	collected 1992
13	large rhinoceros small rhinoceros entelodont carnivore or oreodont	near visitor's trail	damaged (ER)	latex peel 1994
14	large perissodactyl very large artiodactyl	near visitor's trail	damaged (ER)	latex peel 1995
15	large rhinoceros small rhinoceros entelodont carnivore or oreodont	near visitor's trail	good (tilted)	latex peel 1995
16	large perissodactyl	near visitor's trail	good (tilted)	latex peel 1995
17	large perissodactyl very large artiodactyl	near visitor's trail	good (tilted)	latex peel 1995
18	mammal	near visitor's trail	damaged (FT)	—
19	mammal	near visitor's trail	damaged (ER)	—
20	mammal	near visitor's trail	damaged (ER)	—
21	mammal	near visitor's trail	damaged (FT, ER)	—
22	mammal	near visitor's trail	damaged (FT)	—
23	bird tracks & probe holes (?) invertebrate burrows	near visitor's trail	good	—
24	mammal	off trail to north	damaged (ER)	badly weathered
25	mammal	off trail to north	damaged (ER)	badly weathered
26	mammal	off trail to north	damaged (ER)	badly weathered
27	mammal	off trail to north	damaged (ER)	badly weathered

TABLE 1. Continued.

SLAB	CONTENTS	LOCATION[1]	CONDITION[2]	COMMENTS
28	mammal	off trail to north	damaged (ER)[3]	badly weathered
29	bird tracks & probe holes (?) invertebrate burrows	near visitor's trail	good	latex peel 1995
30	bird tracks & probe holes (?) invertebrate burrows	near visitor's trail	good	—
31	bird tracks & probe holes (?) invertebrate burrows	near visitor's trail	damaged (FT)	—
32	bird tracks & probe holes (?)	near visitor's trail	damaged (FT)	—
33	tortoise (?)	near visitor's trail	damaged (FT)	—
34	mammal	near visitor's trail	damaged (FT)	—
35	invertebrate burrows	near visitor's trail	good	collected 1993
36	mammal	near visitor's trail	damaged (FT)	—
37	mammal	near visitor's trail	damaged (FT)	—
38	mammal	off trail to northwest	good	—
39	mammal	off trail to northwest	good	—
40	mammal	off trail to northwest	good	—
41	carnivore or oreodont	near visitor's trail	damaged (ER)	latex peel 1994
42	bird invertebrate burrows	near visitor's trail	destroyed 1994 (FT)	—
43	invertebrate burrows	near visitor's trail	good	—
44	large perissodactyl small perissodactyl small artiodactyl	near visitor's trail	good	latex peel 1995
45	mammal	near visitor's trail	damaged (FT)	—
46	mammal	near visitor's trail	damaged (FT)	—
47	very large artiodactyl	near visitor's trail	damaged (FT, V)[2]	—
48	bird	on visitor's trail	damaged (FT, V)	theft (?) 1995
49	mammal	near visitor's trail	good	—
50	mammal	near visitor's trail	good	—
51	mammal	near visitor's trail	damaged (FT, ER)	—
52	small artiodactyl	off trail to southeast	good	latex peel 1995
53	large perissodactyl	off trail to southeast	good	latex peel 1995
54	large perissodactyl	off trail to southeast	good	latex peel 1995
55	mammal	off trail to southeast	good	—
56	mammal	off trail to southeast	good	latex peel 1995
57	mammal	off trail to southeast	good	—
58	mammal	near visitor's trail	good	—
59	invertebrate burrows	near visitor's trail	good	—
60	invertebrate burrows	near visitor's trail	good	—

TABLE 1. Continued.

SLAB	CONTENTS	LOCATION[1]	CONDITION[2]	COMMENTS
61	invertebrate burrows	near visitor's trail	good	----
62	invertebrate burrows	near visitor's trail	good	----
63	invertebrate burrows	near visitor's trail	good	----
64	invertebrate burrows	near visitor's trail	good	----
65	invertebrate burrows	near visitor's trail	good	----
66	invertebrate burrows	near visitor's trail	good	----
67	invertebrate burrows	off trail to southwest	good	----
68	invertebrate burrows	off trail to southwest	good	----
69	invertebrate burrows	off trail to southwest	good	----
70	mammal	off trail to southwest	good	----
71	invertebrate burrows	off trail to southeast	good	----
72	invertebrate burrows	off trail to southeast	good	----
73	invertebrate burrows	off trail to southeast	good	----
74	invertebrate burrows	off trail to southeast	good	----
75	invertebrate burrows	off trail to southeast	good	----

1. "Near trail" indicates slabs located within 5 m of visitor's trail. "Off trail" indicates slabs > 5 m from visitor's trail.
2. Slabs in good condition are unabraded, tracks show clearly. Damaged slabs are abraded, tracks are indistinct.
3. Abbreviations: FT = foot traffic; ER = erosion; V = vandalism

are regularly spaced holes between the bird tracks that we have interpreted as bill probe holes (Fig. 6D). Ostensibly, the birds were feeding on the burrowing invertebrates. Bird tracks were visible near the visitor trail until 1993, when erosion destroyed the slab (Table 1). Prior to its loss, a latex peel of this slab was recovered by the Trailside Museum. This peel was used to construct a plaster duplicate of the original slab. During 1995, another slab containing bird tracks (Fig. 6E) was vandalized and several sets of tracks were destroyed. Fortunately, this slab was also partially cast in latex prior to its destruction.

Mammals--Based on comparisons to tracks of extant mammals, we have recognized two-toed tracks (artiodactyls), three-toed tracks (perissodactyls), and four-toed tracks (see below). The artiodactyl tracks are of several sizes, and may have been produced by small antelope (small), camels (medium), and entelodonts (large). The perissodactyl tracks are of generally two sizes and have been attributed to a small and large rhinoceros, respectively (Fig. 7, Table 1). The four-toed tracks have been attributed to either oreodonts or carnivores. These two groups of mammals contain several genera and many species of sizes sufficient to produce these tracks.

One of the most spectacular of the trackways occurs on a set of sandstone slabs that record the passage of several large rhinoceroses along the eastern paleoshoreline (the "rhinoceros runway" slab of LaGarry and Hunt, 1996b: Figs. 7A, 8). These tracks are overprinted by a set of smaller rhinoceros tracks oriented perpendicular to the paleoshoreline (Fig. 7B), and large artiodactyl and carvivore or oreodont tracks parallel to the paleoshoreline. Another extensive rhinoceros trackway (Fig. 7C, E, F) was preserved in both sandy and muddy substrates, allowing us to observe a wide range of track morphologies (Wells, unpublished data). Also, many tracks are preserved in cross section (Fig. 7D).

Impact of Tourist Visitation

Toadstool Geologic Park is a multiple use area that attracts visitors who come to view the scenery, or to experience the solitude, wildlife, violent weather, or dry, hot climate (Fig. 9A). Others come to conduct scientific research or collect fossils legally or illegally. These latter visitors are few. During our early paleontological resource inventories (see LaGarry and Hunt, 1994), our research parties spent an average of five weeks at Toadstool Geologic Park annually. In 1994 and 1995, after the trackway research received separate funding, some members of our research party remained at Toadstool Geologic Park for up to three months (LaGarry and Hunt, 1996a, b). Because we were at Toadstool Geologic Park for such extended periods, we were able to observe visitor behavior daily, and paid particular attention to visitors who damaged the site.

Erosion--The semiarid climate in this area is such that rains are infrequent, but often torrential. Flash floods are common and usually destructive. Under normal conditions, weathering erodes from 10-20 cm of rock annually from steeply sloping surfaces. This process is slowly, but continually, eroding away old trackway slabs and exposing new ones. However, visitation is accelerating the erosion of some areas. In 1993, we began observing the damaging of trackway-bearing slabs by erosion from unrestricted foot and bicycle traffic through the Park (Fig. 9B, C). This erosion is heaviest and has the greatest impact on trackway slabs nearest the visitor trail. As many as 80% of the trackway slabs are eroding faster than counterparts off the trail due to erosion by foot traffic (Table 1). Foot traffic alone may be responsible for as much as 10 feet of downward erosion of the visitor trail since the park opened in the mid-1960's. Since we began monitoring the condition of the Toadstool Park Trackway Site in 1993, five trackway slabs containing the best examples of bird tracks have been destroyed by foot-traffic erosion (Table 1). To date, the only solution to this problem has been to obtain a latex peel of the most important trackway slabs before they are entirely destroyed.

Vandalism--Vandalism within the park ranges from the carving of names or initials into trackway slabs (Fig. 9D, E) to random acts of destruction (Table 1). Most vandalism occurs within the Park or within a brief walk from the Park. Because foot traffic in Toadstool Geologic Park is unrestricted, individuals can climb the outcrops at will. Often this leads to the accidental damaging of an unstable sandstone slab or ledge. Based on our discussions with visitors to the Park, we believe these to be

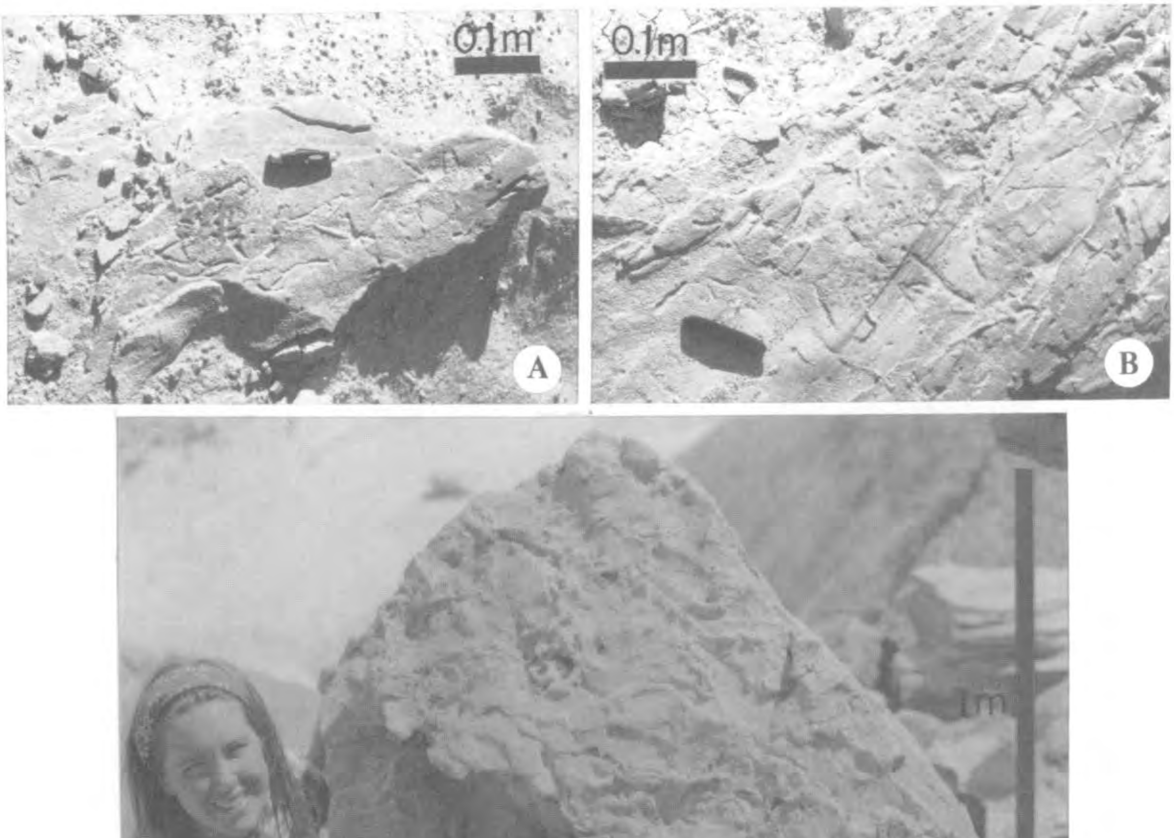


FIGURE 6 - Trackway slabs along the Toadstool Geologic Park visitor's trail: A, and B) invertebrate feeding trails; C) tadpole shrimp trace fossil (arrows); D) invertebrate feeding burrows, bird tracks, and bill probe holes (knives show trend of trackways); E) bird tracks (arrow).

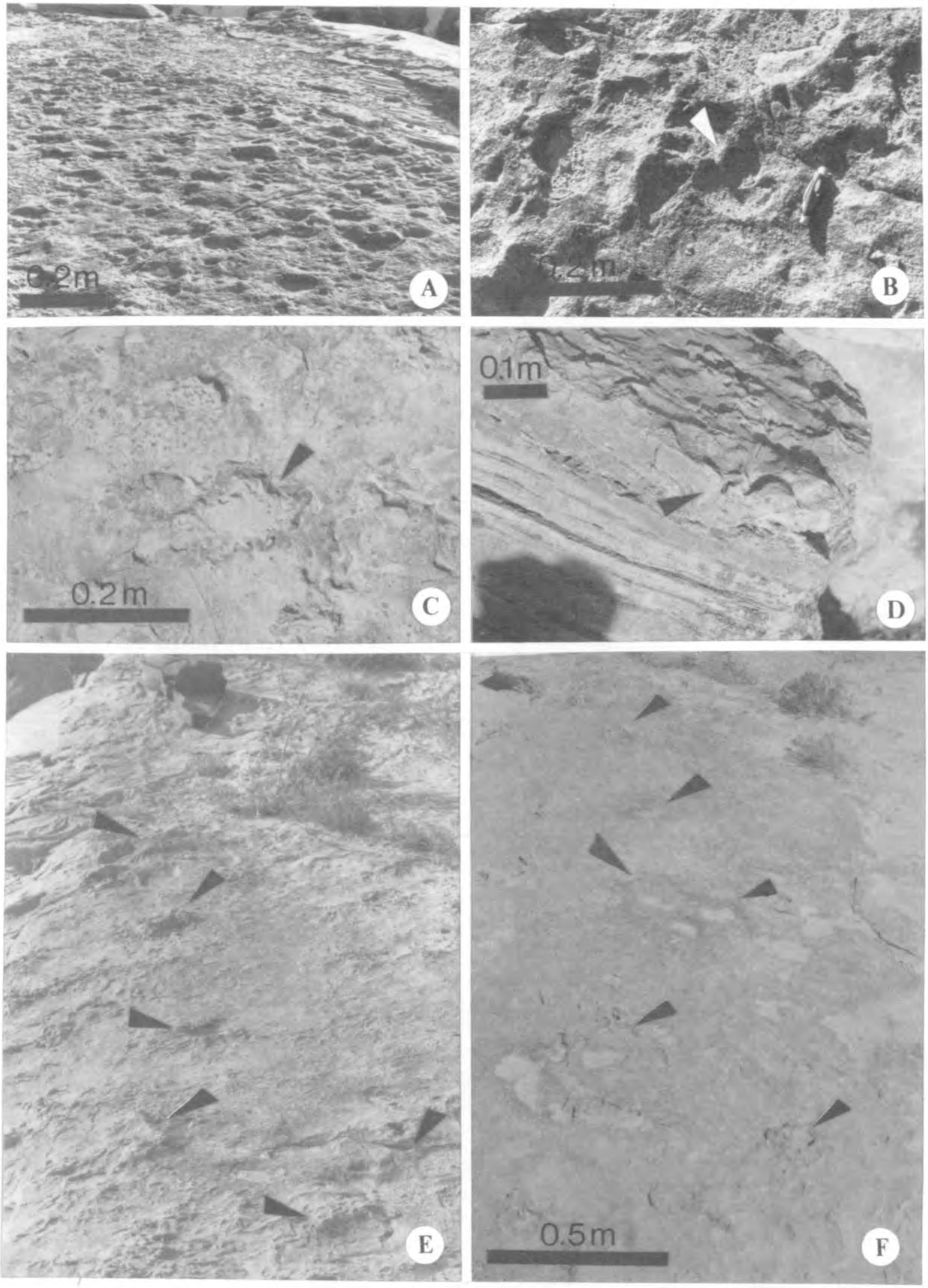


FIGURE 7 - Trackway slabs along the Toadstool Geologic Park visitor's trail: A) slab showing the passage of several perissodactyls (likely large and small rhinoceroses), a very large artiodactyl (likely an entelodont), and a four-toed mammal (likely a carnivore or oreodont); B) isolated small perissodactyl track from slab in A; C) isolated example of large perissodactyl from slab in E and F; D) cross section through track of a very large artiodactyl; and E, F) two views of a slab showing tracks of the large perissodactyl (arrows) with the animals moving toward (E) and away (F) from reader.

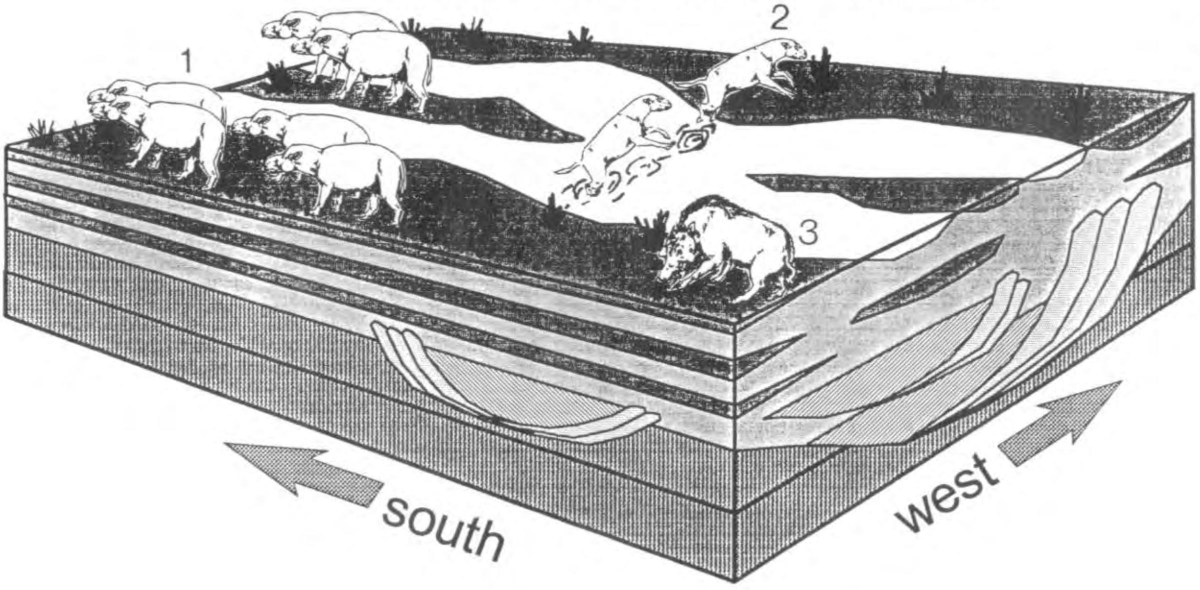


FIGURE 8 - Cartoon reconstruction of the trackway-making animals and underlying sediments of the "rhinoceros runway" slab (Fig. 7A): 1) large rhinoceros; 2) small rhinoceros; 3) entelodont. Plants reconstructed based on chalcedony limb and root casts (Wells, unpublished data).

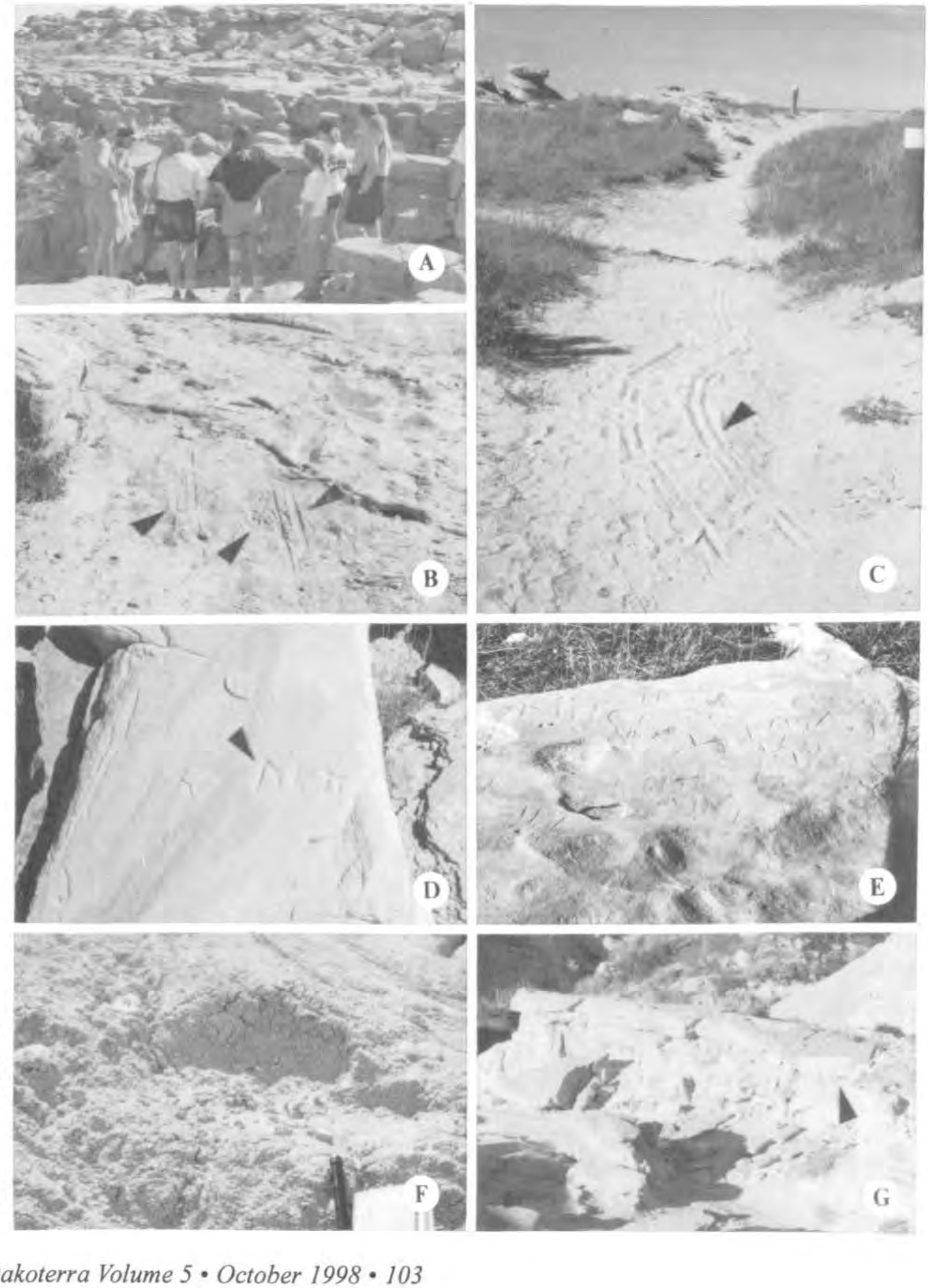


FIGURE 9 - Visitor impact on the Toadstool Park Trackway Site: A) guided tour of visitors looking at a slab containing bird tracks; B, C) foot traffic (arrows) deeply incises the visitor's trail as it winds through the "toadstools;" D, E) various initials carved into sandstone slabs (the one pictured in C has tracks); F) 0.5 m wide shallow excavation left after the illegal removal of a vertebrate fossil; and G) the bird track slab shown in A after tracks were illegally removed (arrows).

isolated instances. However, we have witnessed deliberate acts of destruction by visitors (Table 1). Such acts are damaging to all recognized values of the site, but especially to the vertebrate trackways. In 1992, we observed visitors topple an enormous slab situated on the ridge near the start of the visitor's trail to a position 5 m down the adjacent slope. Visitors also contribute a large amount of garbage to parts of the landscape. The remoteness of the Park contributes to these events.

Theft of Vertebrate Fossils--During the 1991 UNSM paleontological resource survey of the Oglala National Grassland, we salvaged vertebrate fossils from within Toadstool Geologic Park (see LaGarry and Hunt, 1996a). However, after designating the Park as Sensitive Site # 55, we ceased salvaging vertebrate fossils there. In our view, such activity would attract the undesired attention of hundreds of visitors to the fossil resources within the Park, and alert unscrupulous individuals to the presence of potentially sensitive sites. We had previously documented 32 sensitive sites within a 2 km radius of the park that were vulnerable to illegal collecting by visitors to Toadstool Geologic Park (LaGarry and Hunt, 1994). Monitoring of these sites from 1992 to 1995 indicated that many are revisited annually by collectors and fossils are removed illegally (see LaGarry and Hunt, 1996a: Fig. 9E). Because of the prevalence of this activity, we have not included maps of trackway locations herein.

Most of the trackway-bearing sandstone slabs at Toadstool Park are far too large and heavy to move. In 1993, we collected the few trackway slabs that could be easily carried (see LaGarry and Hunt, 1996b: Table 1). In contrast, vertebrate fossils are usually carried away by tourists as fast as they weather from the rock. In 1995, we witnessed the result of the first (and to our knowledge only) deliberate theft of vertebrate trackways. A prominent slab having bird tracks was vandalized and several of the best examples of tracks were removed (Fig. 9F). We are confident that this was not accidental damage that coincidentally damaged the tracks, because only the parts of the slab that had tracks were damaged, and the only tracks remaining were those that could not be conveniently removed.

RECOMMENDATIONS

A complete listing of UNSM recommendations to the Nebraska National Forest pertaining to the Oglala National Grassland and Toadstool Geologic Park are in LaGarry-Guyon (1994) and LaGarry (1997). Rather than repeat those recommendations here, we focus on three general themes regarding the Toadstool Park Trackway Site.

Continued Documentation of the Resource

The Toadstool Park Trackway Site is one of only a few such sites in North America and the world, and is important for its potential to increase our knowledge of mammalian behavior and evolution. The rocks in which the Toadstool Park Trackway Site occurs contain important clues about the Earth's past changes in climate (see Prothero, 1994 for review). As such, it should be investigated scientifically in the most efficient manner possible prior to its loss by erosion. It has been our experience that cooperative agreements between the University of Nebraska-Lincoln and the Nebraska National Forest are a cost-effective means of accomplishing this goal and serve the continued interests of both parties.

Interpretation and Education

It is fortunate for the people of the United States that this site occurs on Federal lands where its protection is mandated. The educational and interpretive opportunities are vast. To our knowledge, the Toadstool Park Trackway Site is the only Cenozoic mammalian trackway site on Federal lands in the Midcontinent that is easily accessible to the interested visitor. By educating the visiting public about the scientific value of the site, much of the incidental damage to the site can be reduced or eliminated. This site is also an excellent vehicle for promoting the USDA Forest Service and its land management values. Recently added interpretive displays and a new visitor's trail serve to summarize the new information obtained about the trackways and reduce the impact of visitation to the site, respectively.

Conservation of the Resource

Because the Toadstool Park Trackway Site is unique and important, it is our view that every reasonable effort should be made to conserve or preserve the scientific resources at the site. There are many ways to achieve this goal. Currently, the Nebraska National Forest is improving the trail, campground, and restrooms at Toadstool Geologic Park. Also, a campground host is present on site during the summer when visitation is highest. These steps, along with improved interpretive markers and displays, will hopefully create a sense of stewardship within visitors to the site, and slow the natural and visitor induced damage to the site. Using latex peels to create durable duplicates of the most important trackway-bearing slabs may allow the display and study of these trackways without compromising the nonscientific values of the site.

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FOSSIL VERTEBRATE TRACKS IN NATIONAL PARK SERVICE AREAS

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ABSTRACT--Fossilized tracks of ancient vertebrates are widespread and are known from at least 19 National Park Service areas. The ichnostratigraphic record of vertebrates preserved in national parks ranges from the late Paleozoic through the Quaternary. The earliest tracks are known from the Pennsylvanian Wescogame Formation at Grand Canyon National Park, Arizona. The largest concentration of vertebrate ichnofossils occurs in the national parks on the Colorado Plateau. Glen Canyon National Recreation Area contains the greatest diversity and stratigraphic range of fossil tracks in any National Park Service unit. More than three dozen tracksites, representing eight different formations, have been identified at Glen Canyon. Dinosaur tracksites are most common, but tracks from non-dinosaurian reptiles, birds and mammals are also known from the national parks. The Copper Canyon tracksite at Death Valley National Park preserves one of the most abundant and diverse Tertiary track localities in North America. Nineteen fossil vertebrate track types have been identified including birds, artiodactyls, perissodactyls, carnivores, and rare proboscideans.

INTRODUCTION

Scientific and public interest in fossil vertebrate tracks has grown rapidly during the past decade. Large numbers of new tracksites have been discovered and numerous publications have been produced reporting on vertebrate ichnofossils (Gillette & Lockley, 1989; Thulborn, 1990; Lockley, 1991a; Lockley & Hunt, 1995). Fossil vertebrate tracks are widespread and are known from a number of National Park Service (NPS) units. Hundreds of fossil tracksites are known from parks on the Colorado Plateau.

Fossil vertebrate tracks preserved within National Park Service areas provide important opportunities for public education and interpretation of *in situ* fossils. Fossil tracks differ from fossil bones in that they provide different types of information about ancient organisms. Fossil bones preserve data on the environment in which the animal died or where it was buried, whereas fossil tracks provide data related to the environment in which the animal lived. Tracks represent an interface between the organism and its environment. Environments that promote good preservation of tracks and footprints do not typically promote the fossilization of bone.

Vertebrate ichnofossils have been reported from 19 National Park Service areas (Fig. 1). This record ranges from Pennsylvanian trackways in Grand Canyon National Park through Quaternary tracks at Zion National Park. Glen Canyon National Recreation Area contains the greatest diversity and stratrigraphic range of fossil tracks. Although tracks associated with dinosaurs are documented in the highest frequency, tracks from other reptiles, birds and mammals are known from National Park units.

PALEOZOIC TRACKSITES

Grand Canyon National Park, Arizona

The first discovery of vertebrate tracks in the Grand Canyon was made by Charles Schuchert in 1915. These tracks were collected from the Permian Coconino Sandstone on the South Rim (Schuchert, 1918). Richard Lull described the Paleozoic tracks collected by Schuchert, identified the trackmakers as an amphibian and named them *Laoporus* (Lull, 1918).

In 1924, the National Park Service invited Charles Gilmore to visit Schuchert's locality. Gilmore surveyed and discovered new track localities in the Grand Canyon. Between 1926 and 1928 Gilmore collected large numbers of fossil tracks from the Coconino Sandstone (Permian), Hermit Shale (Permian), and Wescogame Formation of the Supai Group (Pennsylvanian) for the Smithsonian Institution. He also developed an outdoor interpretive exhibit of Paleozoic tracks alongside Hermit Trail and published a series of classic papers about the late Paleozoic tracks from the Grand Canyon (Gilmore, 1926, 1927, 1928).

A reinterpretation of Permian vertebrate tracks occurred through the study of the extensive ichnofaunas from the redbeds of southern New Mexico (Haubold et al., 1995; Hunt et al., 1995; Haubold, 1996). A reexamination of the Grand Canyon tetrapod tracks based upon the revised ichnotaxonomy was undertaken by Hunt and Santucci (1998) (Fig. 2A).

Coconino Sandstone Tetrapod Ichnofauna:
Chelichnus duncani (Owen, 1842) (=*Baropezia arizonae, B. eakini, Allopus? arizonae, Agostopus matheri, A. medius, Palaeopus regularis, Nanopus maximus, Barypodus metszeri, Laoporus noblei*)
Chelichnus gigas (Jardine, 1850) (=*Barypodus palmatus, Amblypous pachypodus, Baropus coconinoensis*)
Chelichnus bucklandi (Jardine, 1850) (=*Laoporus noblei, L. coloradensis, L. schucherti, Nanopus merriami, Dolichopodus tetradactylus*)

Hermit Shale Tetrapod Ichnofauna:
Batrachichnus delicatulus (Lull, 1918) (=*Exocampe? delicatula, Batrachichnus delicatula, B. obscurus, Dromillopus parvus*)
Parabaropus coloradensis (Lull, 1918) (=*Megapezia? coloradensis*)
Hyloidichnus bifurcatus (Gilmore, 1927) (=*Hyloidichnus whitei*)
Gilmoreichnus hermitanus (Gilmore, 1927) (=*Cursipes* sp., *Palaeosauropus hermitanus, Hylopus hermitanus, Collettosaurus pentadactylus*)
Limnopus sp. (Gilmore, 1927) (=*Parabaropus coloradensis*)
Ichniotherium sp. (Gilmore, 1928) (=*Parabaropus coloradensis*)

Wescogame Formation Tetrapod Ichnofauna:
Batrachichnus delicatulus (Lull, 1918) (=*Stenichnus yakiensis*)
Limnopus sp. (Gilmore, 1927) (=*Ammobatrachus turbatans, Tridentichnus supaiensis, Anomalopus sturdevanti*)

Glen Canyon National Recreation Area, Utah

Three Permian tracksites are known from the Cedar Mesa Sandstone in Glen Canyon National Recreation Area. One of the tracksites apparently preserves evidence of a predator attacking a prey. However, only photographs and replicas of this trackway are available for study since the original site is now underwater after the construction of the Glen Canyon Dam in 1963. The Glen Canyon Permian tracksites include:

- "Dirty Devil Tracksite" contains *Anomalopus*-like tracks converging with a small *Stenichus*-like trackway (Lockley and Madsen, 1993). The point of convergence for the tracks shows the small tracks ending abruptly and may represent evidence of a predation event. Hunt and Lucas (1998) have recently reevaluated the converging tracks interpretation and have concluded that the evidence does not unequivocally support the predation scenario.

- "Steer Gulch Tracksite" contains tracks resembling those of *Anomalopus*.
- "Grand Gulch Tracksite" has 6 track-bearing slabs.

MESOZOIC TRACKSITES

Arches National Park, Utah

A high-density, dinosaur megatracksite exists in the lowest member of the Jurassic Morrison Formation in and around Arches National Park. The track-bearing sediments represent a vast basin where the water table was at or near the land surface level (Duffy, 1993). This highly dinoturbated surface yields *Allosaurus*-like tracks. The portion of the megatracksite within the boundary of Arches National Park represents a coastal plain environment (Lockley, 1986, 1991b; Lockley and Hunt, 1995).

Several iguanodontid tracks are known from the Cedar Mountain Formation near Thompson Ranch just north of Arches National Park. Three specimens of these tracks are in the collections of the College of Eastern Utah.

Big Bend National Park, Texas

Anthony Fiorillo (in press) reported possible large vertebrate footprints observed in cross-section within the Upper Cretaceous Javelina Formation at Big Bend National Park. Based upon the size and morphology of the sedimentary structures, these were interpreted as possible sauropod impressions.

Canyonlands National Park, Utah

A single tracksite of a well-preserved impression of a tridactyl dinosaur was found in the Rock Point Formation of the Chinle Group near Upheaval Dome in Canyonlands National Park. This specimen was identified as the ichnogenus *Grallator* (Hunt et al., 1993; Lucas et al., 1995).

A Chinle Group tracksite in Canyonlands National Park contains tracks of a tetrapod with a four-toed manus and five-toed pes identified as *Brachychirotherium*. The toes are blunt and lack well developed claw impressions. These tracks likely represent prints of an aetosaur-like reptile. The tracks of a large five-toed herbivore are also reported from Canyonlands. These have been identified as *Pentasauropus* and are probably attributed to a dicynodont reptile.

Fossil vertebrate tracks are also known from the upper part of the Kayenta Formation just below the overlying Navajo Sandstone in Canyonlands. There may also be some tracks from the Permian Cedar Mesa Formation in Canyonlands that are accessible by river trip. Loope (1984) reported four tracksites within Canyonlands National Park. Stokes (1986) reported a tracksite in Labyrinth Canyon just outside the park boundary. An additional tracksite is known from the Kayenta-Navajo transition from the Horseshoe Canyon area of Canyonlands.

Capitol Reef National Park, Utah

Fossil tracks were first reported from Capitol Reef National Park by Peabody (1956) and Lammers (1964). Numerous fossil vertebrate trackways are preserved in the Triassic Moenkopi Formation. The tracks include footprints and swimming traces of *Chirotherium*. Invertebrate

FIGURE 1 - Distribution of fossil vertebrate tracks in National Park Service areas. 1, John Day Fossil Beds National Monument, Oregon; 2, Death Valley National Park, California; 3, Mojave National Preserve, California; 4, Zion National Park, Utah; 5, Pipe Spring National Monument, Arizona; 6, Grand Canyon National Park, Arizona; 7, Rainbow Bridge National Monument, Utah; 8, Glen Canyon National Recreation Area; 9, Capitol Reef National Park, Utah; 10, Canyonlands National Park, Utah; 11, Arches National Park, Utah; 12, Dinosaur National Monument, Colorado and Utah; 13, Montezuma's Castle National Monument, Arizona; 14, Petrified Forest National Park, Arizona; 15, Colorado National Monument; 16, Badlands National Park, South Dakota; 17, Scott's Bluff National Monument; 18, Big Bend National Park, Texas; 19, Gettysburg National Military Park, Pennsylvania.

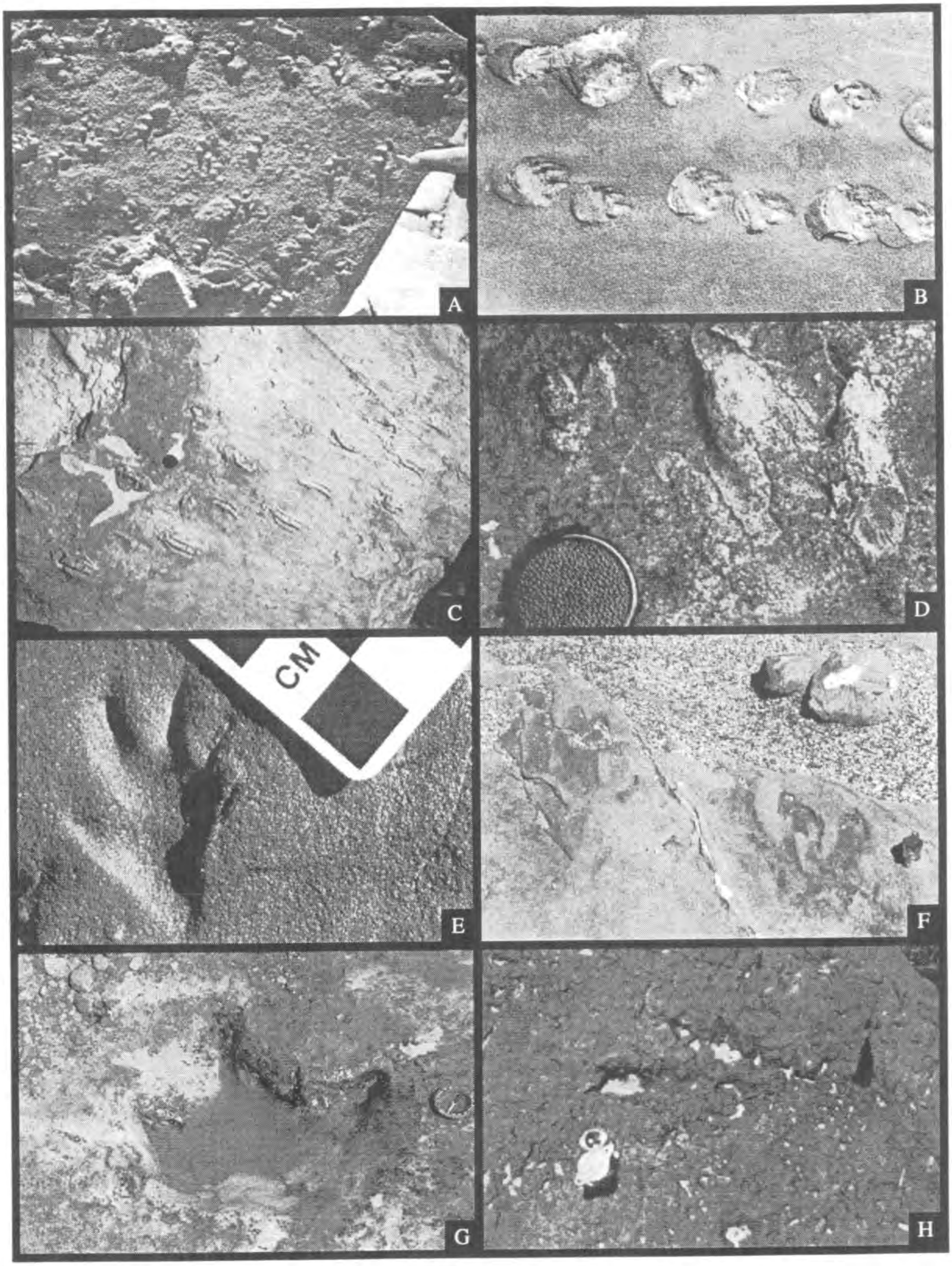

FIGURE 2 - A, *Chelichnus* tracks in Permian Coconino Sandstone at Grand Canyon National Park; B, *Chelichnus* tracks in Permian Coconino Sandstone at Grand Canyon National Park; C, Tetrapod swimming traces in Triassic Moenkopi at Capitol Reef National Park; D, *Atreipus milfordensis* tracks in Triassic Newark Supergroup at Gettysburg National Military park; E, *Rhynchosauroides* track in Triassic Chinle Group at Petrified Forest National Park; F, *Eubrontes* tracks in Jurassic Navajo Sandstone at Pipe Spring National Monument; G, Ornithopod-like tridactyl track in the Jurassic Moenave Formation at Zion National Park; H, *Grallator* track in Jurassic Kayenta Formation at Zion National Park.

traces including *Palaeophycus* and *Diplidnites* are reported from the Torrey Member of the Moenkopi.

Recent work by McAllister and Kirby (in press) indicated that the tracks show paddling activity in shallow water and movement onto emergent, subaerial surfaces. There appears to be some impressions that preserve evidence of tetrapods fighting a lateral current that carried them sideways (Fig. 2C).

A few tridactyl tracks are reportedly preserved in the Chinle Group and dinosaur and tritylodont tracks in the Kayenta Formation from Capitol Reef National Park.

Colorado National Monument, Colorado

A tracksite found near the top of the Chinle in "transitional" beds below the overlying Wingate Sandstone is not far from the east entrance of Colorado National Monument. The tracks consist of a number of subcircular to oval depressions, some of which show partial impressions of a tridactyl foot of a theropod dinosaur (Hunt et al., 1993).

Dinosaur National Monument, Colorado and Utah

Dinosaur National Monument area contains many important fossil vertebrate track localities. Frank Peabody found unusual Triassic Moenkopi tracks in the vicinity of the monument. This material includes some swim tracks that are in the collection of the Utah Field House Museum of Natural History in Vernal, Utah.

About two dozen tracksites occur within the boundaries of Dinosaur National Monument. Among these is a swimming trackway of *Gwyneddichnium* that shows webbing between the toes. There are specimens preserving both walking and swimming behavior for this track type (Lockley et al., 1992A, B, C; Lockley and Hunt, 1993).

Numerous tracksites have been discovered in the Upper Triassic Popo Agie Formation of the Chinle Group. Fossil tracks recorded from the monument are diverse and include track types assigned to dinosaurs, mammal-like reptiles, phytosaurs, aetosaurs, lepidosaurs, trilophosaurs, and tanystropheids. An *Otozoum* tracksite is known from the Navajo Formation within the monument.

Gettysburg National Military Park, Pennsylvania

A Late Triassic dinosaur track was reported within a building stone used in the construction of a stone bridge at Gettysburg National Military Park. Dinosaur tracks are preserved in mudstones that were quarried during the 1930s in an area outside of the park. The track-bearing deposits were laid down in a gradually deepening trough of sediments.

The Gettysburg track has been identified as *Atreipus milfordensis* and is preserved with manus and pes impressions (Santucci and Hunt, 1995). *Atreipus milfordensis* represents, as of yet, an undescribed dinosaur that exhibits a theropod-like pes in combination with a short-clawed and functionally tridactyl manus. The tracks are preserved in a block of the Gettysburg Shale, which is part of the Newark Supergroup (Fig. 2D).

Glen Canyon National Recreation Area, Utah

More than three dozen tracksites from eight formations have been reported from Glen Canyon National Recreation Area (Lockley et al., 1992d). Large theropod tracks (*Eubrontes*) were collected from Explorer Canyon and are on display at the Page Visitor Center (Fig. 3A, B). The stratigraphic breakdown of Glen Canyon tracksites was reported by Lockley et al. (in press).

Moenkopi Formation:

- "Trachyte Point Tracksite" contains irregular traces of several different size tetrapod swim traces. Horseshoe-shaped xiphosurid traces are also preserved at the site.
- "Mouth of Farley Canyon Tracksite" includes three track types (Schultz et al., 1995). The limulids are the most abundant. There are also elongate vertebrate swim tracks and lacertilian traces similar to *Rhynchosauroides*.

Chinle Group:

- "Four Mile Canyon Tracksite" preserves the first reported occurrence of *Atreipus* tracks from the western United States (Lockley et al., 1992d). There are also numerous well preserved lizard-like tracks of morphotypes assigned to be *Rhynchosauroides*. Collections of tracks were made in 1992.

Wingate Sandstone:

- "Lee's Ferry Tracksite" was first reported by Riggs (1904), and specimens were collected for the Field Museum of Natural History. These specimens represent the first fossil tracks collected and illustrated from this geographic area. The specimens are best assigned to *Grallator*.
- "North Wash Tracksite" was reported by Hunt et.al. (1953). The site includes two sets of reptilian footprints in the North Wash below the mouth of Marinas Canyon. The site is just outside the recreation area boundary. All specimens are identified as grallatoroid.
- "Rincon Tracksite" is also referred to as the "Secor" site in the NPS files. This is one of the best known fossil tracksites within Glen Canyon and is illustrated in a popular boaters' guide. The tracks represent a bipedal trackmaker producing tridactyl prints.

Kayenta Formation:

- "Explorer's Canyon Tracksite" is now submerged. A number of specimens were collected in the 1960s, and one is on display at the visitor center that was featured in a *National Geographic* article (Edwards, 1967). These tracks are best assigned to *Eubrontes*.
- "Mike's Mesa Tracksite" includes large fallen blocks of bioturbated gray-green sandstone. The blocks with *Eubrontes* tracks appear to have come from the overlying Kayenta.
- "Slick Rock Canyon Tracksite" consists of two track-bearing exposures. There is a single *in situ Eubrontes* track and a large fallen block with more than 30 medium-sized *Grallator* tracks.
- "Cedar Canyon Tracksite" consists of a series of trail-bearing slabs from the Kayenta/Navajo transition. These include *Grallator* and broad-toed tridactyl tracks that resemble *Moyenisauropus*. These tracks resemble *Anomoepus*, which has traditionally been attributed to an ornithopod dinosaur.
- "Long Canyon Tracksite" preserves 20 consecutive, deeply impressed, elongate tracks of a bipedal theropod, which reveal toe impressions.

Navajo Sandstone:

- "Dam Tracksite" is the first tracksite reported from within Glen Canyon (Stokes, 1978). These tracks are best assigned to *Eubrontes*.
- "Crossing of the Fathers Tracksite" is the largest mapped *in situ* exposure in the Navajo Sandstone. Tracks include at least 28 trackways of prosauropods (*Otozoum*) and the small tridactyl *Grallator*.
- "West Canyon Tracksite" was submerged for years below lake level. Four *Otozoum* and a *Grallator* trackway were visible on emerged strata in 1991.
- "Last Chance Bay Tracksite" has *Eubrontes* trackways preserved as casts on the underside of an inaccessible overhang.
- "Driftwood Canyon Tracksite" contains *Eubrontes* tracks within an interdunal deposit.
- "Hole in the Rock Tracksite" preserves *Grallator* footprints.
- "Slick Rock Canyon Tracksite" includes a *Grallator*-dominated track assemblage. *Eubrontes*, *Brasilichnium* and an *Anomeopus*-like tridactyl biped track are also preserved at the site.
- "Annie's Canyon Tracksite" preserves *Eubrontes*, *Grallator* and *Otozoum* tracks on the eastern shore of Lake Powell.
- "Tapestry Wall Tracksite" contains at least 14 large theropod tracks

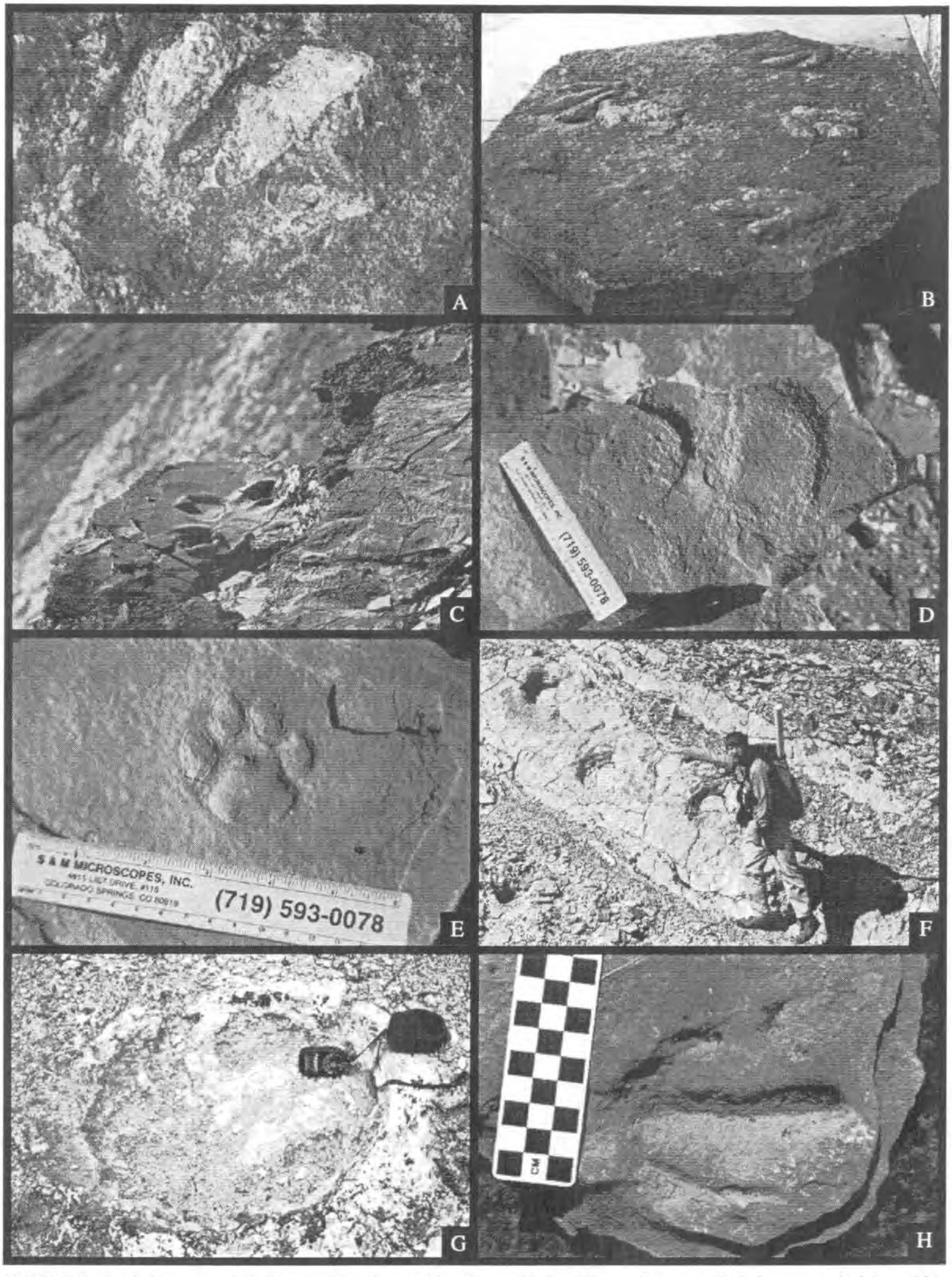

FIGURE 3 - A, *Eubrontes* track in Kayenta Formation at Glen Canyon National Recreation Area; B, *Eubrontes* track slab outside of visitor center at Glen Canyon National Recreation Area; C, Camelid tracks in Miocene Copper Canyon Formation at Death Valley National Park; D, Equid tracks in Miocene Copper Canyon Formation at Death Valley National Park; E, Carnivore track in Miocene Copper Canyon Formation at Death Valley National Park; F, Proboscidean tracks in Miocene Copper Canyon Formation at Death Valley National Park; G, Proboscidean track in Mio-Pliocene Verde Formation at Montezuma Castle National Monument; H, Large bird track in Pleistocene Coalpits sediments at Zion National Park.

(*Eubrontes*) on the underside of a long overhang.

- "Orange Cliff Tracksite" is a tracksite located at the northernmost portion of Glen Canyon National Recreation Area. Tracks are preserved near the base of the Navajo Sandstone.

Summerville Formation: A number of tracksites from this unit occur on the north side of Lake Powell. One site outside the boundaries of Glen Canyon contains possible pterosaur tracks.

- "Bullfrog Sauropod Tracksite" preserves several sauropod footprint casts showing skin impressions. They occur near the contact between the Tidwell Member of the Summerville Formation and the Salt Wash Member of the Morrison Formation. This tracksite is located near Bullfrog, on the northern side of Lake Powell.

Morrison Formation: The only known Morrison tracksite within Glen Canyon is just outside the boundary of national recreation area. The tracksite is in the Lost Spring Wash area and yields sauropod tracks.

Petrified Forest National Park, Arizona

The first fossil vertebrate tracks were discovered at Petrified Forest National Park in 1993. Two different track types were identified in channel sandstone unit within the Upper Triassic Chinle Group. Tiny, five-toed tracks called *Rhynchosauroides*, produced by a small, lizard-like animal, were the first vertebrate tracks discovered (Fig. 2E). A swimming trace of a larger reptile, possibly a phytosaur, was located during a secondary survey. This trace preserves scrape marks where the reptile claws scratched the substrate (Santucci and Hunt, 1993; Santucci et al., 1995).

Most of the Late Triassic tracksites in the western part of the United States are in the uppermost (youngest) strata of this age (i.e., Dinosaur National Monument, Canyonlands National Park). The vertebrate tracks at Petrified Forest National Park are several million years older than the other known sites.

Pipe Spring National Monument, Arizona

Three tridactyl dinosaur footprints, tentatively identified as *Eubrontes*, have been reported from Pipe Spring National Monument (Fig. 2F). The tracks occur in an orange-red cross-bedded sandstone that may lie stratigraphically within the base of the Early Jurassic Navajo Sandstone. These tracks were first reported by Stokes (1988) and have been recently studied by Cuffey (Cuffey et al., 1997; Cuffey et al., in press).

Rainbow Bridge National Monument, Utah

A small number of typical *Eubrontes* tracks are preserved in the Kayenta Formation at Rainbow Bridge National Monument. The badly weathered tracks have been known to exist at Rainbow Bridge for many years. Hall (1934) identified some tracks in the area in his University of California Rainbow Bridge Expedition Report.

Zion National Park, Utah

At least two fossil dinosaur tracksites occur in the early Jurassic Kayenta Formation at Zion National Park (Stokes and Bruhn, 1960). These sites were recently mapped as part of the Zion Paleontological Survey and were located near the Kayenta - Navajo transition (Santucci, et al., 1998). The tracks are principally tridactyl theropod footprints including one set identified as *Grallator* (Fig. 2H).

A tracksite in the Springdale Member of the Moenave Formation was discovered in 1992. This site preserves at least 18 ornithopod-like tridactyl tracks (Fig. 2G). These tracks have not yet been identified and may represent a new ichnotaxon.

CENOZOIC TRACKSITES

Badlands National Park, South Dakota

A trackway of four camelid tracks were reported from the Poleslide Member of the Brule Formation from the south unit of Badlands National Park (Bjork, 1976). Two poorly preserved carnivore tracks were also found in association with the camelid tracks. The carnivore tracks preserve claw marks. These tracks were preserved in a fluvial sandstone unit above the *Leptauchenia* clays.

Death Valley National Park, California

The earliest report of fossil vertebrate tracks from Death Valley was published by Donald Curry (1941). Curry recognized the importance and rarity of the fossil tracks in Copper Canyon. He collected a number of track specimens and assigned names to specific sites (e.g., Carnivore Ridge, Barnyard). During the 1950s and early 1960s, Raymond Alf collected fossil cat, camel and bird tracks from unknown locations in Death Valley (Alf, 1959).

The Copper Canyon fossil track locality in Death Valley National Park contains a rich and diverse assemblage of fossil vertebrate tracks from the Late Miocene Copper Canyon Formation. Tracks from this locality include impressions of birds, camels, horses, cats, bear-dogs, and proboscidians. Scrivner and Bottjer (1986) interpreted the Copper Canyon sediments to represent a thick sequence of lake deposits (Figs. 3C, D, E, F). The geochemistry of the sediments exhibits a "freshening-upward" trend. The geologic evidence indicates the lake was originally a shallow saline playa that slowly became more freshwater over time. The diversity and abundance of fossil tracks in Copper Canyon support this interpretation. Fewer numbers and types of tracks are associated with the more saline lake conditions, whereas many more groups and track types are found in the freshwater sequences.

The significance of the Copper Canyon tracksite includes: 1) the fossil tracks and trackways, including both impressions and casts, exhibit excellent morphological detail due to their preservation in fine-grained sediments; 2) the site represents one of the most diverse and abundant Tertiary vertebrate tracksites in North America; 3) 19 fossil vertebrate track types have been identified, including birds, artiodactyls, perissodactyls, carnivores and proboscideans; and, 4) rare proboscidean tracks (*Proboscipeda*) record one of the earliest occurrences of proboscideans in North America (Santucci, 1998).

John Day Fossil Beds National Monument, Oregon

Fossil vertebrate tracks were discovered in the Eocene Clarno Formation within the boundaries of John Day Fossil Beds National Monument. The four-toed tracks were discovered by Bruce Hansen and probably represent a small cat-like carnivore (Theodore Fremd, personal communication, 1998).

Mojave National Preserve, California

Pliocene tracks are known from the Tecopa Formation in Mojave National Preserve. Camel and carnivore tracks from this unit are on display at the Raymond Alf Museum. At one locality in this formation, the remains of camel limbs were found preserved in an upright position. The area is nicknamed "Standing Camel Basin" (Lockley and Hunt, 1995).

Montezuma Castle National Monument, Arizona

"Elephant Hill" is a mammoth tracksite at Montezuma Castle National Monument (Fig. 3G). The tracks occur in a limestone unit of the Mio-Pliocene Verde Formation. There are also tracks of camels and carnivores from this unit. At least two track localities are known in the area around the National Monument. A few of the tracks from these sites are in the collections at the American Museum of Natural History. The mammoth tracks are 40-45 cm in diameter with a single stride of about 2 meters. The tracks appear to be bipedal, but actually represent a quadruped that overstepped its front footprints with its hind feet (Brady and Seff, 1959).

Scotts Bluff National Monument, Nebraska

Fossil vertebrate tracks are reported from the late Oligocene Gering Formation at Scott's Bluff National Monument (Swinehart and Loope, 1987). These alleged tracks are located along the Saddle Rock Trail in horizontally stratified fine-grained volcanic clastic sands and ash deposits. The tracks appear in cross-section as concave-up deformation structures. These have been interpreted as vertebrate tracks. The size and bilobed morphology of some of these structures suggest that the track-makers were possibly large ungulates such as entelodonts.

Zion National Park, Utah

The Coalpits Lake deposits preserve Quaternary tracks. The lacustrine mudstones preserve camel, bird and insect tracks. The unit has not been formally mapped or described (Fig. 3H).

CONCLUSION

The increased scientific interest in vertebrate inchnofossils has a parallel trend in new tracksite discoveries within national parks. The number of tracksites recognized within national parks is likely to expand in the future. Likewise, the demands of park staff in management and protection of these non-renewable resources will also increase. Park management should seek to understand the significance of fossil tracksites and identify the variety of human and non-human threats that may adversely impact these paleontological resources.

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BRIDGER FORMATION (MIDDLE EOCENE) OF SOUTHWEST WYOMING: WIDESPREAD MARKER UNITS AND SUBDIVISIONS OF BRIDGER B THROUGH D.

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ABSTRACT--Nine widespread marker units in the middle Eocene Bridger Formation in the southern Green River Basin subdivide the informal Bridger B-D submembers. The marker units include ash-fall tuffs, limestones, a widespread fossiliferous sequence of green mudstones, and the base of a pumice-rich, blue sheet sandstone. Two of these marker units, the Sage Creek and Lone Tree limestones, have been previously named and described. The newly described markers include the Church Butte and Henrys Fork tuffs, the Lyman, Soap Holes, and Promintory limestones, and the Black Mountain turtle layer. These marker units divide each of the Bridger B-D submembers into lower, middle, and upper subdivisions. These subdivisions allow for scattered vertebrate localities to be positioned vertically into a detailed stratigraphic sequence. They will also aid in the recognition of paleoenvironmental variation in time and space, and the tectonic development of the basin.

INTRODUCTION

The Bridger Formation of the southern Green River Basin in southwest Wyoming contains the most abundant mammal fossils of any middle Eocene rocks in North America. Bridger fossils have been collected since before the Civil War (Leidy, 1869; West, 1976) and the formation is the type section for the Bridgerian Land Mammal Age (Wood et al., 1941; Krishtalka et al., 1987). The formation is a sequence of predominant green and brown mudstones and claystones, scattered ribbon and sheet sandstones, widespread micritic and silicified limestones, and rare, thin but widespread ash-fall tuffs. Matthew (1909) provided the most detailed subdivisions of the Bridger, dividing the entire formation into five informal units (Bridger A-E). Of these informal units, the most abundant mammal assemblages occur in Bridger B through D. Rocks of the Bridger B through D are best exposed in tributaries south of the Blacks Fork River (Fig. 1). This region has traditionally been called the Bridger Basin (Hayden, 1871; 55), which is a physiographic, not structural, basin. In the exposures just east and southeast of the town of Lyman, Wyoming, the Bridger B through D is 547.5 m thick (Fig. 2). This paper refines the stratigraphy of the Bridger Formation in the Bridger Basin, using widespread marker units as boundaries between subdivisions within Matthew's (1909) informal units.

We have recognized 25 stratigraphic marker beds in the Bridger B through D as a result of seven years of mapping and stratigraphic descriptions in the Bridger Basin. Of these 25 markers, nine are sufficiently widespread and occur in the appropriate stratigraphic position to divide each of Matthew's informal units into a lower, middle, and upper subdivision. Many of the marker beds were traced across the entire basin, a distance of 63 km (Fig. 1). These marker units allow for detailed positioning of fossil localities across the entire basin and provide the potential for reconstructing the tectonic and paleoenvironmental development of the basin.

History of Stratigraphic Nomenclature

The Bridger "group" was named by Hayden (1869) for the rocks above the Green River lake shales in the vicinity of Fort Bridger in southwest Wyoming. Hayden (1869) did not designate a type section, but the badlands extending from Church Butte to Sage Creek and Hickey mountains (Figs. 1, 2) represent the classic area of study of the early workers.

The first detailed subdivision of the Bridger was made by Matthew and Granger from their field work extending from 1902 to 1906. Matthew (1909) divided the Bridger formation (sic) into five informal units, separated in part by widespread marker beds (Fig. 3). The marker beds tended to be widespread lacustrine limestones, which he called "white layers." The most widespread of Matthew's marker beds was the Sage Creek White Layer, a thick limestone sequence that divided units B and C. The Lone Tree White Layer divided the Bridger C and D beds in the vicinity of Sage Creek, Hickey, and Cedar mountains. The boundary between the Bridger A and B was not well defined by Matthew, but the base of the Bridger E was marked by the first banded bed, the base of the lowest red bed. The divisions of most fossiliferous units of the Bridger, Matthew's units B through D, were arbitrarily divided into five subunits, corresponding to basal, lower, middle, upper, and top levels (Matthew, 1909: 297). Matthew did not define additional marker beds as boundaries for these subdivisions. Osborn (1929) used the major stratigraphic divisions of Matthew (1909), but curiously attempted to rename the Sage Creek White Layer the Cottonwood Creek White Layer. Matthew (1909) named one of the persistent limestones in the middle Bridger B the Cottonwood White Layer (Fig. 3), superceding Osborn's (1929) usage of the term for the Sage Creek White Layer. Most workers, such as Bradley (1964), have retained Matthew's name for this widespread marker.

Citing problems in correlating Matthew's white layers beyond the historic type area of the Bridger, Wood (1934) named Bridger A and B the Blacks Fork Member, and Bridger C and D the Twin Buttes Member. The two members are separated by the Sage Creek White Layer, and Wood (1934: 241) cited evidence for a change in the mammalian faunas across the boundary. West and Hutchison (1981) added a third member to the Bridger Formation, naming the Bridger E the Cedar Mountain Member. However, this name was previously used for a sequence of Cretaceous rocks in Utah, and we propose a new name in the following discussion. The nomenclature proposed herein maintains much of the previous terminology, and subdivides Matthew's units using widespread marker beds as subunit boundaries.

WIDESPREAD MARKER UNITS IN THE BRIDGER FORMATION

Four kinds of lithologies comprise the Bridger Formation marker units (Table 1). These include ash-fall tuffs, lacustrine limestones, green calcareous mudstones associated with lacustrine limestones, and a series of pumiceous sheet sandstones. Table 1 lists the features and Table 2 the type localities of eight of the marker units with the most regional extent. These eight markers have either been named by Matthew (1909) or are herein named as informal stratigraphic units.

The most distinctive marker beds in the Bridger B-D are two ashfall tuffs, named the Church Butte tuff and the Henrys Fork tuff. The tuffs are altered volcanic ashes characterized by highly smectitic claystones with euhedral crystals of biotite, hornblende, and other accessory minerals, such as plagioclase, zircon, pyroxene, apatite, and allanite. The tuffs are light green to white in fresh exposures, but weather into dark (medium gray) bands on the outcrop surfaces. They are distinguished by their stratigraphic position and the composition of their heavy mineral suites (Table 1). The Church Butte tuff is named for exposures near Church Butte (Fig. 1) and the Henrys Fork tuff is named for exposures along the Henrys Fork of the Green River (Fig. 4; Murphey, 1995). Both are found throughout the area and are distinctive beds that cross major facies

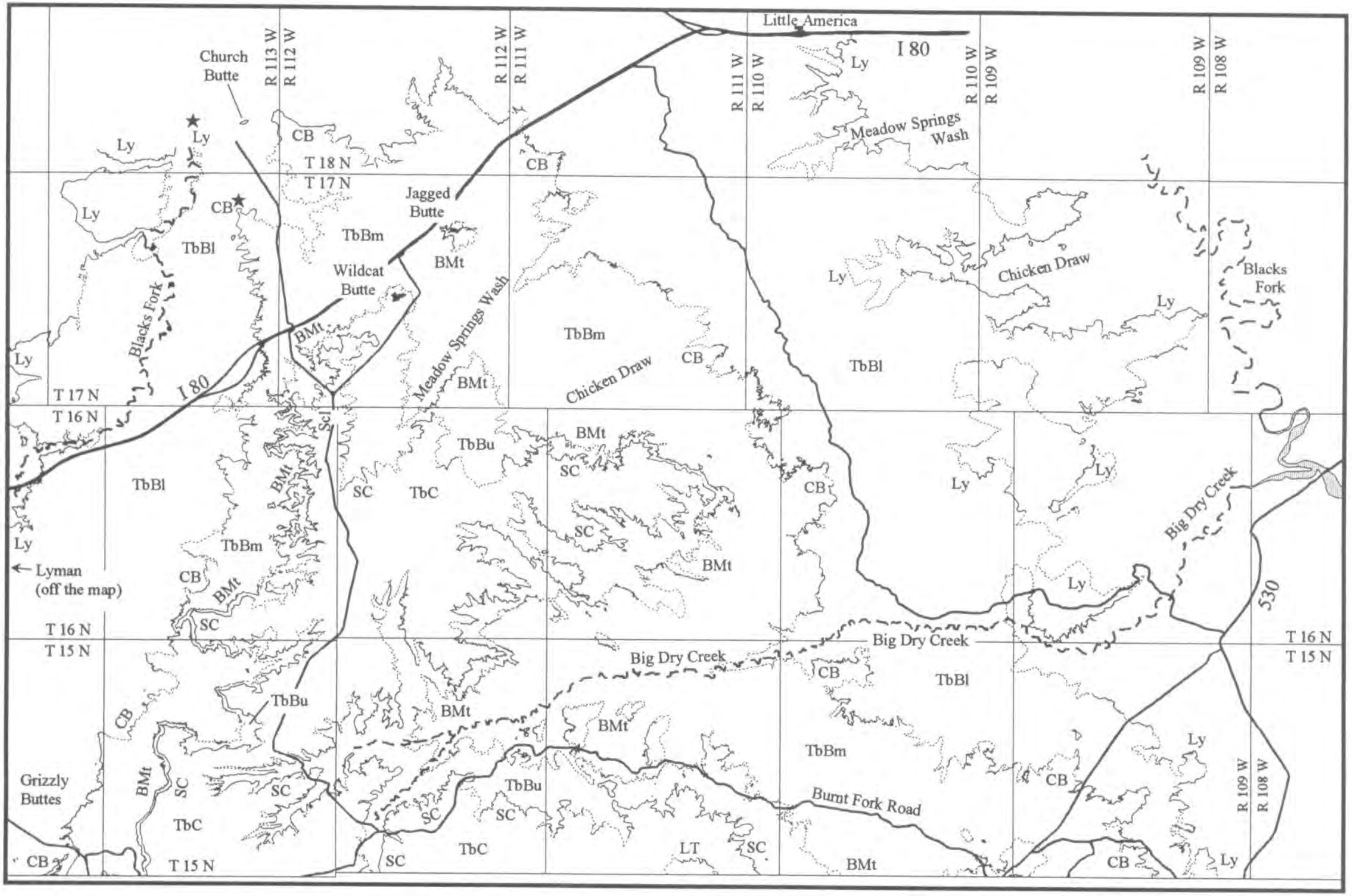

FIGURE 1 - The Bridger Basin showing the marker units in Bridger B-E. The Bridger B marker beds and subdivisions are labeled. The type localities of the marker units are marked with stars.

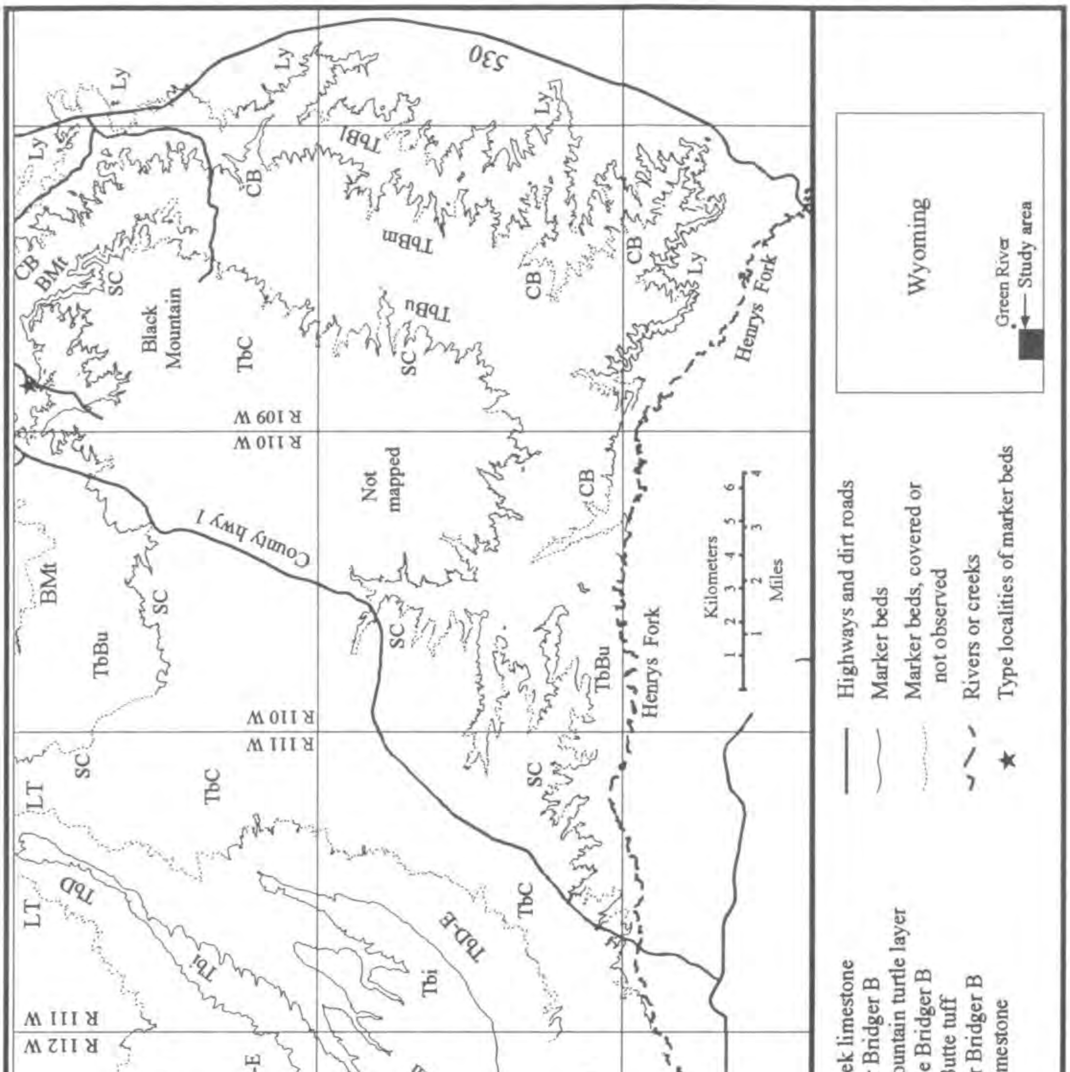

FIGURE 1 - Continued

changes. For example, the Henrys Fork tuff is recognizable from the lacustrine and fluvial facies of the western side of the basin (Murphey, 1995) to the entirely fluvial facies of the Bridger C in the eastern side of the basin. Because volcanic ashes are deposited over a time span of a few days to a few weeks (Schmincke and van den Bogaard, 1991), the two tuffs essentially represent time lines. Most of the sediment in the Bridger Formation has long been known to be volcaniclastic (Sinclair, 1906) with the source being the intermediate to mafic volcanics of the Absaroka Mountains (Love, 1939; Bradley, 1964). However, the two ash-fall tuffs have mineral suites that indicate source volcanics that are more silicic than those in the Absaroka volcanic field and suggest a source from the Challis volcanic field in Idaho (Evanoff and Rossetti, 1992; Evanoff et al., 1996).

The traditional marker units in the Bridger Formation are the "white layers" (Matthew, 1909) that are relatively thin but widespread limestone beds. These include the Cottonwood, Sage Creek, Lone Tree, and Upper

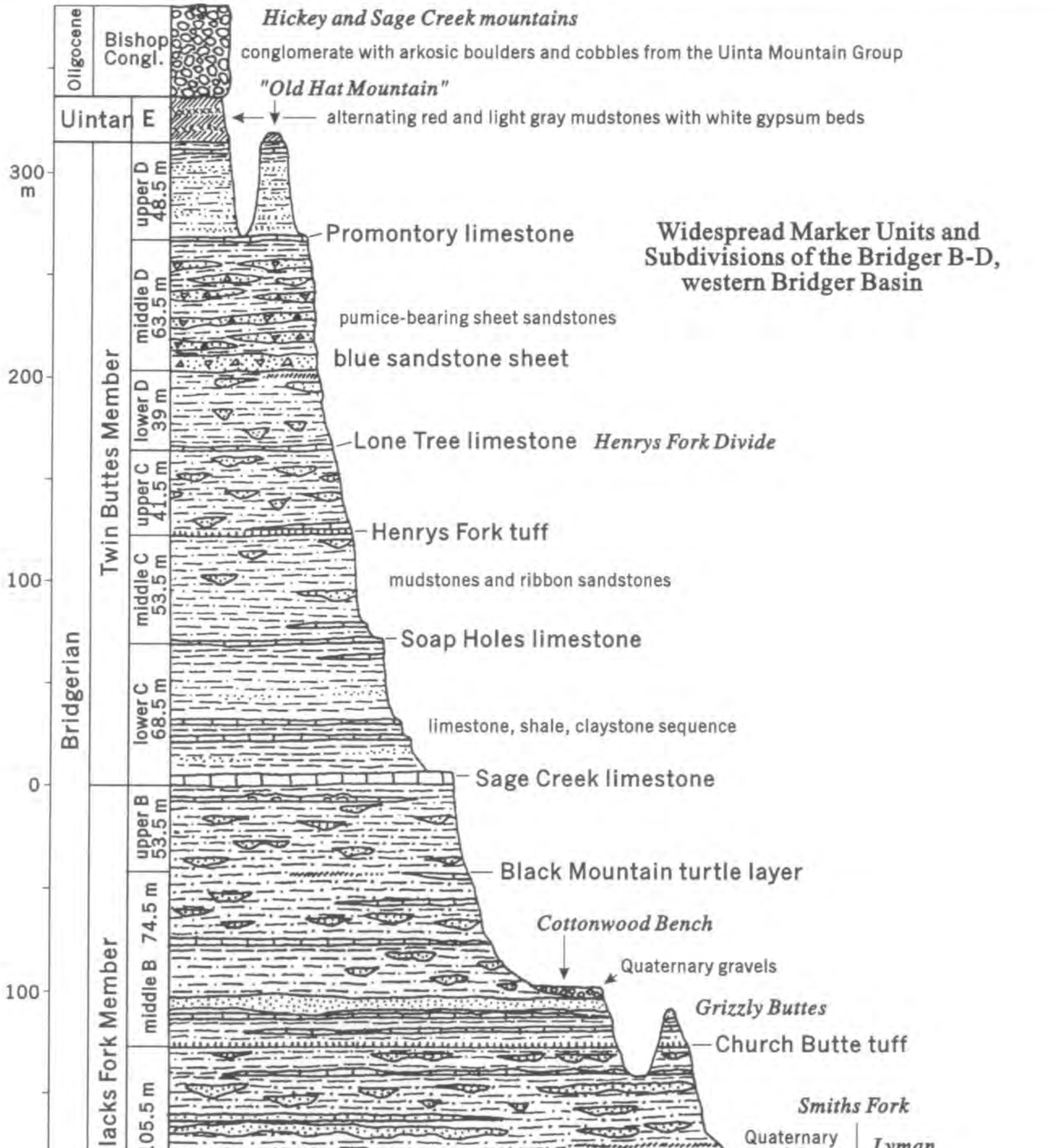

FIGURE 2 - A generalized stratigraphic section showing the sequence of rocks in the Bridger Formation from the type area, extending from Lyman, Wyoming, to the summits of Sage Creek and Hickey mountains. The widespread markers of the Bridger B-D are shown, as well as the subdivisions of Matthew's informal submembers of the Bridger Formation. The thicknesses are from a series of stratigraphic sections starting south of Church Butte and ending on "Old Hat Mountain" on the east side of Hickey Mountain.

<table>
<tr><th>Hayden, 1869</th><th colspan="2">Matthew, 1909</th><th>Osborn, 1929</th><th>Wood, 1934
West & Hutchison, 1981</th><th colspan="4">This Paper</th></tr>
<tr><td rowspan="11">Bridger group</td><td rowspan="11">Bridger formation</td><td>E</td><td>Bridger E</td><td>Cedar Mountain Member</td><td rowspan="11">Bridger Formation</td><td colspan="3">Turtle Bluff Member (E)</td></tr>
<tr><td rowspan="3">5
Upper White Layer 4
D 3
2
1
Lone Tree White Layer</td><td rowspan="3">Bridger D
Lone Tree White Layer</td><td rowspan="6">Twin Buttes Member</td><td rowspan="6">Twin Buttes Member</td><td rowspan="3">D</td><td>upper
Promontory limestone</td></tr>
<tr><td>middle
blue sheet sandstones</td></tr>
<tr><td>lower
Lone Tree limestone</td></tr>
<tr><td rowspan="3">5
4
C 3
2
1
Sage Creek White Layer</td><td rowspan="3">Bridger C
Cottonwood Creek White Layer</td><td rowspan="3">C</td><td>upper
Henrys Fork tuff</td></tr>
<tr><td>middle
Soap Holes limestone</td></tr>
<tr><td>lower
Sage Creek limestone</td></tr>
<tr><td rowspan="3">5
4
B 3
Cottonwood White Layer
2
1</td><td rowspan="3">Bridger B</td><td rowspan="4">Blacks Fork Member</td><td rowspan="4">Blacks Fork Member</td><td rowspan="3">B</td><td>upper
Black Mountain turtle layer</td></tr>
<tr><td>middle
Church Butte tuff</td></tr>
<tr><td>lower
Lyman limestone</td></tr>
<tr><td>A</td><td>Bridger A</td><td colspan="2">A</td></tr>
</table>

FIGURE 3 - A history of stratigraphic nomenclature of the Bridger Formation, showing the origin of the current named subdivisions. The usage of "group" by Hayden (1869) and the formal "White Layers" by Matthew (1909) and Osborn (1929) are the original designations and do not follow modern usages. Correlations between Matthew's subdivisions (1-5) and the lower, middle, and upper subdivisions of the current study are uncertain.

white layers of Matthew (1909; see Fig. 3). The limestones are typically micritic and fossiliferous, and some are silicified. Fossils in these limestones include ostracodes, freshwater gastropods, and stromatolites. Many of the limestones are white, but some, such as the Lyman limestone at the base of the Bridger B and the Soap Holes limestone at the base of the middle Bridger C, are brown to medium gray in both weathered and fresh exposures. We have opted to use the term "limestone" to replace the term "white layer" where the lithologies of the marker is a limestone. We limit the term "white layer" to other marker beds that are very white, tuffaceous, but crystal-poor beds, such as the "sugar white layer" of Gazin (1941). None of the most widespread marker units that bound the Bridger subdivisions are true "white layers" by our definition. We have retained Matthew's (1909) original names for most of the limestones, except for the Upper White Layer. On Hickey, Sage Creek, and Cedar mountains, the lowest red beds of the Bridger E overlie a sequence of limestones that are above the Upper White Layer (or "upper limestone" if we stay consistent with Matthew's terminology). Because the Upper White Layer is not the uppermost limestone of the Bridger D, we have renamed this marker the Promontory limestone. The Lyman limestone is named for the town of Lyman, for this limestone outcrops in the bluffs just below and north of the town. The Soap Holes limestone is best exposed in the center of the Soap Holes Reservoir, Wyoming, 7½ minute Quadrangle. The Soap Holes limestone is very similar to the Burntfork White Layer of Matthew (1909), which is exposed within the middle Bridger C along the Henrys Fork south of Cedar Mountain. However, the Soap Holes limestone is at a position 28 m below the Burntfork limestone on the south side of Cedar Mountain. Therefore, the two brown siliceous limestones are not equivalent (Murphey, 1995).

One very widespread marker unit is a sequence of green claystones and siltstones in the upper Bridger B that contains a large number of turtle fossils. This is the Black Mountain turtle layer (Table 1) that is one of the most fossiliferous horizons in the Bridger B. This marker unit is best exposed along the north side of Black Mountain in the eastern part of the area (Fig. 1). In the southern part of the basin, the Black Mountain turtle layer overlies a light gray to brown micritic limestone that is replaced to the north by a whitish calcareous mudstone.

In the vicinity of Hickey Mountain, Sage Creek Mountain, and Cedar Mountain, the base of the middle Bridger D is marked by a series of widespread, light bluish gray sheet sandstones containing abundant pumice fragments. The sandstones are composed of fine to very fine sand-sized grains with medium sand-sized biotite grains and scattered pumice granules. Locally the base of these sandstones is a distinct marker. Future investigations will determine how persistent the sandstones are to the east along the south end of Cedar Mountain and if they occur in the upper slopes of Black Mountain and Twin Buttes. These sandstones are not included with the other named marker units in Tables 1 and 2 because of the uncertainty of their regional significance. However, these sandstones are important paleontologically, for the 1902 field notes of W. D. Matthew (Frick Museum archives, American Museum of Natural History) indicates that most of the early *Uintatherium* fossils came from these blue sandstones.

STRATIGRAPHIC SUBDIVISIONS

Our stratigraphic subdivisions of the Bridger Formation retain almost all of the previously named stratigraphic units (Fig. 3). Matthew's (1909) subdivisions are widely used by stratigraphers and vertebrate paleontologists and should be retained as informal submembers of the Blacks Fork and the Twin Buttes members. The Bridger E of Matthew (1909) is equivalent to the Cedar Mountain Member of West and Hutchison (1981), but the name was previously used. Prior to West's and Hutchison's paper, the name Cedar Mountain was given to a series of lower Cretaceous rocks in Utah, the Cedar Mountain Formation (Stokes, 1944). The Bridger E is herein renamed the Turtle Bluff Member, with its boundaries and type section identical to those given in West and Hutchison (1981). Turtle Bluff was the name given to Cedar Mountain by geologists of the King Survey (King, 1878) and on the west end of Cedar Mountain is the Turtle Bluff triangulation station (Burntfork, Wyoming, 7½ minute Quadrangle). The base of the Turtle Bluff Member is marked by the lowest red bed in the sequence which typically caps a widespread sequence of limestones at the top of the Bridger D in the Hickey Mountain, Sage Creek Mountain, and the western end of Cedar Mountain. Future mapping will determine if the lowest red beds or if the top of the upper Bridger D limestone sequence are the best criteria for the

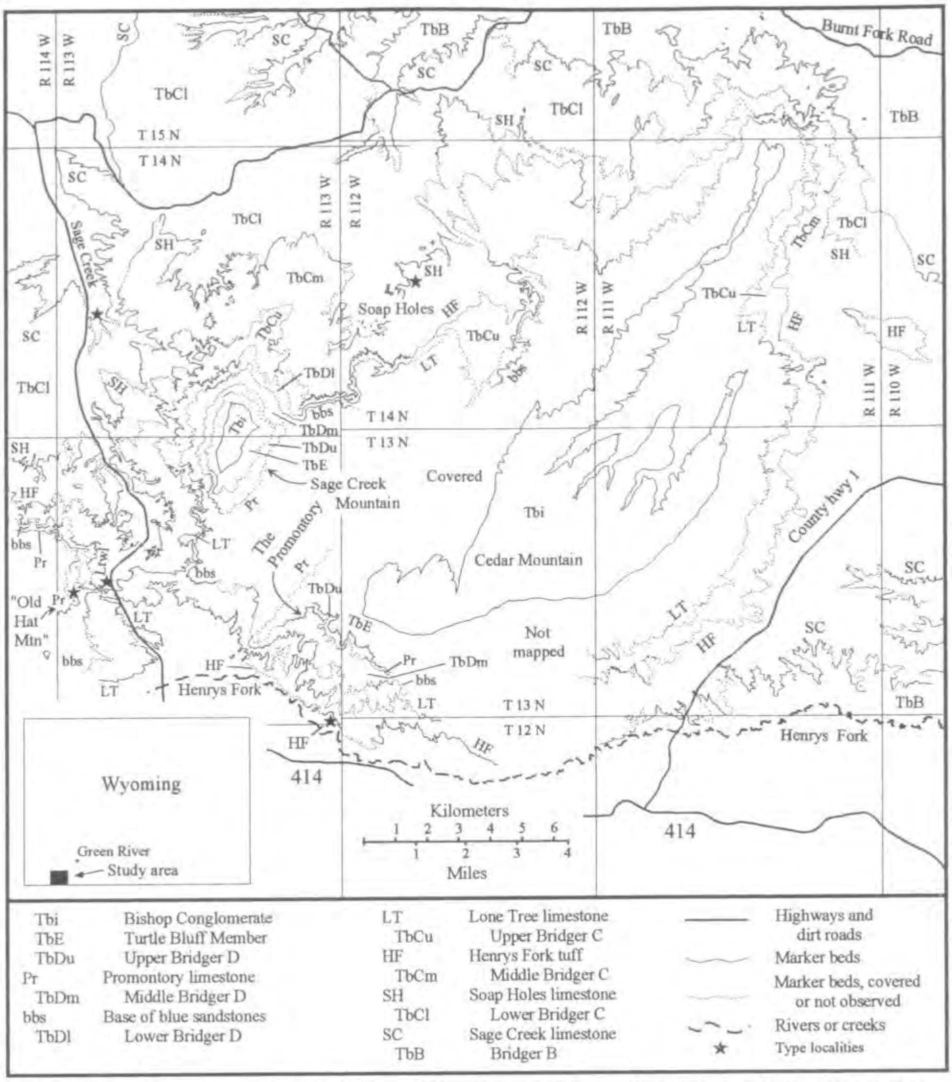

FIGURE 4 - The marker units of the Bridger C-D in the southern part of the Bridger Basin, not including the Black Mountain - Twin Buttes area, which remains to be mapped. The type localities of the marker units are designated with stars.

base of the Turtle Bluff Member in other areas where the Bridger E beds are exposed.

The Bridger B through D are subdivided into lower, middle, and upper subdivisions (Figs. 1, 3, and 4) with the boundaries placed at the base of the nine widespread marker units described in Table 1. These subdivisions allow for the scattered fossil localities to be grouped in smaller stratigraphic intervals, a goal that Matthew (1909) attempted to do with his five arbitrary subdivisions of his informal "members" (Fig. 3). Because Matthew (1909) did not define the boundaries of his five subdivisions within each submember (B-D), correlation of his subdivisions with the lower, middle, and upper subdivisions of this study cannot be made with confidence. The marker units clearly define the subdivisions and should allow for greater precision in identifying the stratigraphic intervals in which past and future collections will be made.

DISCUSSION

The stratigraphy of the Bridger B through D using the nine marker beds provides a general stratigraphic framework. The remaining 16 marker units can be placed into this framework. The thickness variations between the 25 markers across the basin will reflect shifting basin subsidence and depositional loci. Scattered fossil localities can be vertically positioned into a much more detailed stratigraphy to produce a high resolution biostratigraphy for the Bridger vertebrates and mollusks. The sedimentology and fauna of intervals between the marker units reflect the depositional environments and paleocommunities across the basin. Finally, as the sedimentology and fauna of each interval is studied and compared with those above and below it, changes in middle Eocene paleoclimates in the region can be determined.

Problems still exist with the proposed stratigraphic framework. The extent of the blue pumiceous sandstones in the Bridger D, and the detailed definition of the Bridger D-E contact remain as stratigraphic problems. The Black Mountain turtle layer and most marker beds in the Bridger C-D remain to be mapped in the southeastern part of the Basin, south of the Henrys Fork. Finally, facies changes in the Bridger C and D from the west side of the area to the east make correlations across the basin uncertain. However, the stratigraphy given in this paper refines our understanding of the Bridger Formation and its fauna.

ACKNOWLEDGMENTS

Our work on the Bridger Formation has been greatly helped by discussions with Dr. Peter Robinson, University of Colorado Museum, Dr. Paul Bucheim, Loma Linda University, and Dr. Howard H. Hutchison, University of California, Berkeley. We were helped in the field by many students over the years, especially Mr. Benjamin Burger, currently at the State University of New York at Stony Brook. Dr. Laurie Bryant, Bureau of Land Management, Casper, Wyoming, has provided great support for

TABLE 1 - Features of the named widespread marker units of the Bridger B-D.

Marker Unit Name	Description
Promontory limestone	White, typically blocky, micritic limestones supporting a prominent ledge. Locally has brown to gray chert nodules in the middle. Fossils are abundant, including freshwater snail shells (*Biomphalaria* sp.) and aquatic vertebrates throughout, and land snail shells and land vertebrates in the upper half. Capped by calcareous mudstones containing locally abundant vertebrates. Named for "The Promontory," a prominent ledge on the west side of Cedar Mountain (PLS, Burntfork 7½' Quadrangle Map) that is 7.5 km east of the type locality. Originally called the "Upper White Layer" by Matthew (1909) but there are additional white limestones in the Bridger D above this unit. 2.5 m thick at the type locality.
Lone Tree limestone	Alternating sequence of gray to white blocky micritic limestones, light green mudstones, and brown claystones that weather into a prominent light green band. The limestones support ledges and weather rusty brown and locally contain light gray chert nodules. Fossils are locally abundant and include freshwater snail shells, rare unionid clams, and scattered aquatic vertebrates. Land vertebrates occur in the upper half and in the overlying mudstones. Named the "Lone Tree White Layer" by Matthew (1909) for the town of Lonetree, Wyoming, 4.5 km southeast of the type locality. 2.5 m thick at the type locality.
Henrys Fork tuff	Widespread, yellowish gray to white biotitic claystone that weathers to a dark gray band. Contains euhedral biotite, zircon, allanite, and apatite crystals. Hornblende is present but the crystals are highly etched and are much less abundant than biotite. Biotite crystals are up to 1.3 mm in diameter near the base of the unit. Plagioclase is by far the most abundant feldspar. Bottom contact is distinct, the top contact is diffuse, and in the south half of its distribution is overlain by a white, highly fossiliferous marly limestone. Named for the Henrys Fork River which is near the type locality. 0.95 m thick at the type locality.
Soap Holes limestone	Medium gray, well indurated, cherty limestone that weathers to a blocky reddish brown ledge. Very sparry as observed in thin section, almost no micrite. Cherts are dark gray. Fossils are rare, and limited to poorly preserved fish bones, snails, and trionychid turtles. Locally stromatolitic. Named for the Soap Holes Reservoir area, a broad expanse of badlands east of Sage Creek Mountain. 1.2 m thick at the type locality.
Sage Creek Limestone	The most widespread and prominent sequence of limestones in the region. Composed of lower massive micritic limestones containing freshwater snails shells and rare turtles; middle ledgy stromatolitic limestones with black to dark gray chert bands; and upper ledgy to platy marly limestones with scattered plant fragments. Locally includes interbedded green to brown claystones and shales. The massive micritic limestones support a very widespread bench. Named by Matthew (1909) as the "Sage Creek White Layer" for outcrops along Sage Creek and first mapped by Bradley (1964). 4.1 m thick at the type locality.
Black Mountain turtle layer	Widespread gray-green claystone, 1.5 to 3.0 m thick, with thin interbedded siltstones and sandstones. Contains abundant fossil turtles and fragmentary mammal, crocodilian, and gar pike fossils. Bottom contact is distinct, underlain in southern part of the basin by a resistant limestone that usually supports a narrow bench. Farther north the limestone is replaced by a whitish calcareous mudstone. Upper contact is diffuse, and generally defined by 2 to 10 m thick sandstones. 2.5 m thick at the type locality.
Church Butte tuff	Widespread, olive green claystone with abundant euhedral crystals of hornblende, biotite, zircon, pyroxene, and apatite. Weathers to a dark gray band. Hornblende crystals are unetched and outnumber biotite crystals. Pink plagioclase is by far the most abundant feldspar. Named for Church Butte which is 3.1 km northeast of the type locality. 0.7 m thick at the type locality.
Lyman limestone	Light gray ledgy limestone that weathers brown and contains abundant ostracodes in the west and freshwater gastropods (*Goniobasis* sp.) in the east. Can be interbedded with light brown shales. Prominent bench supporter. The unit is named for the town of Lyman, Wyoming, where the limestone is exposed in the slope north of the town. Described as marker bed G by McGrew and Sullivan (1970). The unit is 1.5 m thick at the type locality, 23.8 km northeast of Lyman.

TABLE 2 - Type localities of the named widespread marker units of the Bridger B-D.

Marker Bed Name	Location and Comments
Promontory Limestone	PLS: NE¼ NE¼ SE¼ SW¼ sec. 19, T. 13 N., R. 113 W. Map UTM: 567,820mE; 4,549,380mN. Elevation: 7940 ft. 7½' Quadrangle Map: Lonetree (pr 1980). On the northeast point of the "brim" of a butte the early workers called "Old Hat Mountain," west of the Henrys Fork divide.
Lone Tree limestone	PLS: SW¼ NW¼ NW¼ NW¼ sec. 20, T. 13 N., R. 113 W. Map UTM: 568,660mE; 4,549,640mN. Elevation: 7580 ft. 7½' Quadrangle Map: Lonetree (pr 1980).
Henrys Fork tuff	PLS: SW¼ NE¼ SE¼ SE¼ sec. 36, T. 13 N., R. 113 W. Map UTM: 576,520mE; 4,545,320mN. Elevation: 7360 ft. 7½' Quadrangle Map: Burntfork (pr 1980).

TABLE 2 - Continued

Marker Bed Name	**Location and Comments**
Soap Holes limestone	PLS: SE¼ NE¼ SE¼ SE¼ sec. 17, T. 14 N., R. 112 W. UTM: 578,950mE; 4,560,025mN. Elevation: 7030 ft. 7½' Quadrangle Map: Soap Holes Reservoir (pr 1980).
Sage Creek limestone	PLS: SE¼ NE¼ NE¼ SE¼ sec. 19, T. 14 N., R. 113 W. Map UTM: 568,580mE; 4,558,560mN. Elevation: 7060 ft. 7½' Quadrangle Map: Reed Reservoir (pr 1980). At the old Sage Creek stage station, at "Sage Creek Spring" (Sinclair, 1906; Matthew, 1909) both of which are no longer present. Plate 38 in Sinclair (1906) is a photograph of the type locality.
Black Mountain turtle layer	PLS: NE¼ NW¼ NW¼ SW¼ sec. 5, T. 14 N., R. 109 W. Map UTM: 606,340mE; 4,564,060mN. Elevation: 6505 ft. 7½' Quadrangle Map: Devils Playground (1987).
Church Butte tuff	PLS: center, SE¼ SE¼ SE¼ sec. 2, T. 17 N., R. 113 W. Map UTM: 572,190mE; 4,591,880mN. Elevation: 6640 ft. 7½' Quadrangle Map: Millersville (1980).
Lyman limestone	PLS: SE¼ NE¼ SW¼ NW¼ sec. 26, T. 18 N., R. 113 W. Map UTM: 571,080mE; 4,596,060mN. Elevation: 6365 ft. 7½' Quadrangle Map: Church Butte (1969).

PLS - public land survey, 6th Principal Meridian; UTM - universal transverse mercator, Zone 12; pr - photorevised map date

the field work of this study. Dr. Edwin E. Larson, University of Colorado, has determine the mineralogy of the tuffs and helped to determine the sources of the ash. Drs. James E. Martin, Howard H. Hutchison, and Robert M. West reviewed the paper and their comments have improved the content of this discussion. Funding for this project was provided by the University of Colorado Museum, Loma Linda University, and BP Petroleum. We thank all these people and organizations for their support.

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GEOLOGIC AND PALEONTOLOGIC INVESTIGATION OF THE CIMARRON NATIONAL GRASSLAND, MORTON COUNTY, KANSAS

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ABSTRACT--A geologic and paleontologic survey was completed on parts of the Cimarron National Grassland in Morton County, extreme southwestern Kansas. Six geologic units were mapped: 1) ?Triassic Dockum Group; 2) Miocene Ogallala Group; 3) undifferentiated Ogallala Group and Quaternary sediments; 4) Quaternary loess; 5) Quaternary dune sands; and 6) Quaternary alluvium. The geologic contacts often were inferred because of the extensive soil cover. Fossils were found only in the Ogallala Group. These were recovered from the Fullerton Gravel Pit and include the horse *Protohippus*, the dog *Osteoborus*, and the camels *Megatylopus*? and *Hemiauchenia*. These taxa co-occurred during the early Hemphillian Land Mammal Age, and are the first vertebrate fossils reported from Morton County, Kansas. Only two other reported Miocene fossil assemblages are located in the southwestern quarter of Kansas; therefore, this fauna represents a significant addition to our knowledge of Kansas Tertiary paleontology.

INTRODUCTION

Drought conditions during the 1930's and the prevailing farming practices of that time caused decimation of land on the Great Plains. Winds swept across the landscape, picked up a great amount of topsoil, stripped the land of its value, and caused the era to become popularly known as the "Dust Bowl." In 1938, the United States government began purchasing land in southwestern Kansas from local farmers in order to provide economic relief. In 1960, the federally owned lands were renamed the Cimarron National Grassland. Today, the grassland in extreme southwestern Kansas contains 108,175 acres within Morton and Stevens counties. The area is managed for wildlife, water conservation, livestock grazing, recreation, and mineral production.

In an on-going effort to characterize the resources of the grassland, the United States Department of Agriculture's (USDA) Forest Service and Fort Hays State University (FHSU) entered into a mutually beneficial agreement in 1994 to explore the paleontologic resources on parts of Cimarron National Grassland in Morton County. This agreement called for the production of a surficial geologic map in both hard copy and digital formats, collection and curation of fossil specimens, and assessment of the fossil resources. The study area consisted of all lands of the Cimarron National Grassland within the Midway Southeast and Elkhart North 7.5 minute topographic quadrangles.

PREVIOUS WORK

McLaughlin (1942) constructed the initial geologic map of Morton County and investigated the area with regard to ground water resources. He did not mention fossils from Morton County. Smith (1938, 1940) provided a regional geologic study for all of southwestern Kansas. Hibbard, a paleontologist from the University of Michigan, worked extensively in southwestern Kansas (e.g., Hibbard, 1938, 1940, 1941a, b, 1944a, b; Frye and Hibbard, 1941); however, his work primarily dealt with the Plio-Pleistocene sections of Meade County. In 1995, Donna Porter organized a Friends of the Pleistocene field trip in the area (Porter, 1995). Porter's work in the area involves dune development in southwestern Kansas.

METHODS

After additional background research, a team from the Department of Geosciences and the Sternberg Museum of Natural History at FHSU traveled to the study area to map the geology. Due to the extensive vegetation and low relief, the contacts very often had to be inferred and are represented on our map by dashed lines (Fig. 1). Few fossils were found during the mapping stage. Machine operators at the Fullerton Gravel Pit found the majority of the fossils and donated them for this study. Without their generosity, very little would be known about the fossil vertebrates in the county.

After completion of fieldwork, the data were placed digitally into a Geographic Information System (GIS). Besides the geological and paleontological data collected through fieldwork, other pre-existing digital data layers were compiled including roads, public land survey system, railroad, pipelines, soil types, streams, contours, land use/land cover, Cimarron National Grassland boundary, and digital orthophoto quadrangles. These data are now available for use by Forest Service personnel to better manage the resources on the grassland.

RESULTS

Six geologic units were mapped in the study area: 1) ?Triassic Dockum Group; 2) Miocene Ogallala Group; 3) undifferentiated Ogallala Group and Quaternary sediments; 4) Quaternary loess; 5) Quaternary dune sands; and 6) Quaternary alluvium. The geologic contacts often had to be inferred because of the extensive soil cover over most of the study area. Fossils were found only in the Ogallala Group.

?Triassic Dockum Group

The oldest rocks within the study area present the greatest enigma as to their age and correlation. These rocks are exposed at the base of a well-known geologic landmark called Point of Rocks (SE 1/4 Sec. 12, T. 34 S., R. 43 W.). This bluff was a landmark for travelers along the Cimarron Cutoff of the Santa Fe Trail, and wagon paths can still be seen in the area. This area was also important to travelers because of the nearby Middle Spring, a valued water supply in the arid region.

Point of Rocks is capped with a resistant Ogallala calcrete, which disconformably overlies a 12 m section of unfossiliferous buff, yellow, brown, and white sandstone, red to maroon siltstone, and red shale, which has been called ?Triassic Dockum Group. This assignment is based on correlation with lithologically similar redbeds in Oklahoma. A brief review of the history and rationale for this correlation is offered here.

In an early work, Gould (1900:135) referred "Point of Rocks, in Morton county, a line of bluffs on Bear creek, in Stanton county, and several exposures between these, on the North Fork of the Cimarron" to the Cretaceous Dakota. Subsequently, Gould and Lonsdale (1926) examined outcrops in Texas County, Oklahoma, south of Point of Rocks. In that county, they identified three exposures of redbeds: 1) along Beaver Creek in the southeastern part of Texas County near Palodura Creek (T. 1 N., R. 18 and 19 E.); 2) beds west of Guymon near the old Red Point post office (near NW 1/4 Sec. 25, T. 3 N., R. 13 E.); and 3) rocks along Tepee Creek farther to the west (T. 3 N., R. 12 E). Gould and Lonsdale believed the first two redbed localities represented the Permian Cloud Chief Formation. They suggested that the third site at Red Point could be Triassic, stating that some work "suggests that these beds are not of Permian age" (Gould and Lonsdale, 1926:25). However, they end their discussion by saying "the Texas and Cimarron County red beds do not

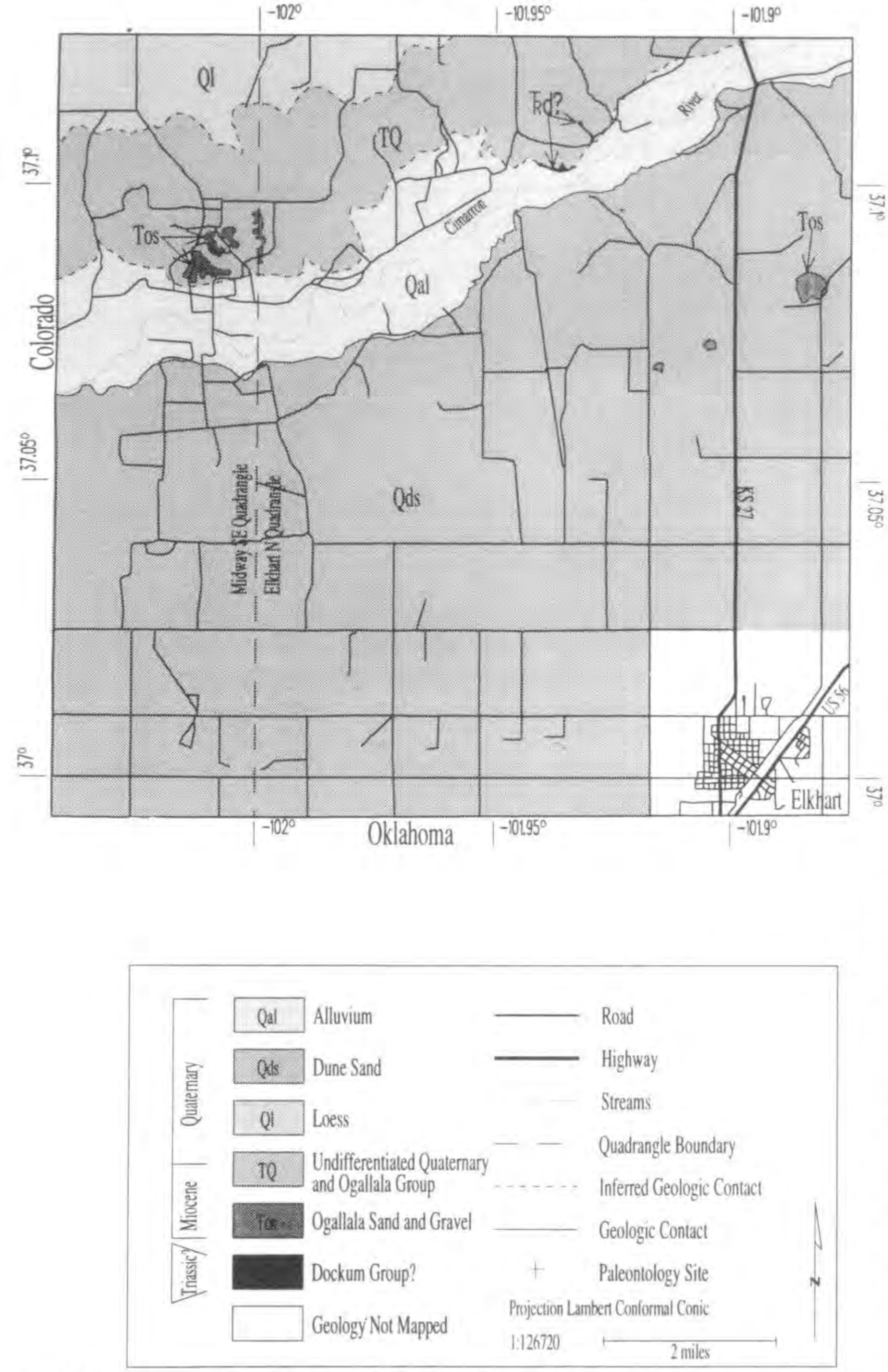

FIGURE 1 - Geologic map of the study area in Morton County, Kansas, extreme southwestern Kansas.

resemble the Texas Triassic rocks and do have the facies of the Oklahoma and Kansas Permian red beds" (Gould and Lonsdale, 1926:26).

Schoff (1939) reviewed the geology of Texas County, Oklahoma, discussed the same three redbed outcrops, and limited the Permian Cloud Chief Formation to the first area, along Beaver Creek. Schoff considered the other two outcrops to be Mesozoic in age, and he tentatively referred to them as Triassic and Jurassic, respectively. This new assertion was based primarily on an unpublished report of Lower Cretaceous invertebrate fossils being found in a sandstone bed at the Red Point locality in 1925, suggesting to Schoff that between the Permian Cloud Chief and the Lower Cretaceous fossil beds there would be Triassic and Jurassic beds. However, on his map of the area, he refers to both of these outcrops as Triassic(?) "because of the incomplete field data, and the tentative character of the conclusions, and because some of the outcrops are too small to be shown individually" (Schoff, 1939:49).

The Kansas Geological Survey first mapped the Point of Rocks, Kansas, redbeds as Triassic on the state map of 1937 (Merriam, 1963). McLaughlin stated that the redbeds at Point of Rocks are similar to those in the Red Point area in Oklahoma which "Schoff (1939: 49-51) and others have called Triassic(?)" (McLaughlin, 1942:71). However, as stated above, Schoff suggested that those rocks could be either Triassic or Jurassic and had evidence of Cretaceous invertebrates.

These rocks have been questionably assigned to the Triassic in several more recent publications (Moore et al., 1944, 1951; Merriam, 1963), and Buchanan and McCauley (1987) placed them in the Jurassic. But in no case was any additional evidence presented to support the assignment. Unfortunately, the present study did not uncover any evidence that would help to resolve this issue. However, we plan continued study seeking positive evidence for the age of this unit. Such evidence might come in the form of microfossils, especially pollen. In the confirmed Dockum sequence of Texas, Dunay and Traverse (1971) have found spores and pollen. However, the red clay and sand do not present an optimum environment for the preservation of pollen.

Miocene Ogallala

The Ogallala Group is comprised of late Tertiary sediments and rocks that crop out across parts of Texas, Oklahoma, Kansas, Colorado, New Mexico, Nebraska, South Dakota and Wyoming. Vertebrate fossils have been collected throughout the region. Sediments were spread across this vast area by fluvial systems running generally west to east. The sediment is a mixture of clay, silt, sand, and gravel, with localized cement of opal or calcium carbonate. In northern areas of the distribution, the clastics are often derived from the Front Range in Colorado and have a silicic composition. In southern regions, the clastics are often derived from basaltic sources in New Mexico. Additional clastics are often derived from local bedrock. Because of its complex depositional regime across such a large area, individual beds are rarely traceable over long distances. In many places, a veneer of younger silt, sand, and gravel further complicates the physical stratigraphy, making it difficult or impossible to differentiate the older beds from the younger.

In Kansas, the Ogallala Group can be readily identified by the presence of resistant calcrete beds and generally fine-grained sediments. It is now known that the calcrete beds are not useful for defining the top of the Ogallala (Diffendal, 1982) as was once thought (Frye et al., 1956).

The age of the Ogallala Group has also been revised. Older literature refers to the Ogallala Group in Kansas as Pliocene (e.g., Frye et al., 1956). However, with the acceptance of the Miocene/Pliocene boundary at 5 ma, placement in the late Miocene is necessitated. Based on biostratigraphy the Ogallala Group in Kansas ranges in age from early Clarendonian (~12 ma) (e.g., Gretna, Hamburg, and Keller local faunas) to the late Hemphillian (~6 ma) (e.g., Edson, Lost, and Rhinoceros Hill local faunas).

Fullerton Gravel Pit--The sediment at the Fullerton Gravel Pit is fluvial in origin and contains thinly bedded to cross-bedded fine to

TABLE 1 - Faunal list from the Fullerton Gravel Pit, Morton County, Kansas. Specimens are listed at the lowest taxonomic level that they were identified to. All specimens are housed at the Sternberg Museum of Natural History, Hays, Kansas.

CLASS	ORDER	FAMILY	GENUS	SPECIMEN # FHSM VP
Reptilia	Chelonia			13315, 13350, 13562, 13397
Mammalia				13307, 13308, 13309, 13310, 13311, 13312, 13314, 13407, 13408, 13409, 13410, 13411, 13412, 13413, 13571, 13572
Mammalia	Perissodactyla	Equidae		13294, 13295, 13296, 13297, 13416, 13417, 13563, 13564, 13565
Mammalia	Perissodactyla	Equidae	*Protohippus*	13292, 13293, 13345
Mammalia	Artiodactyla			13304, 13321
Mammalia	Artiodactyla	Camelidae		13298, 13299, 13302, 13305, 13317, 13318, 13319, 13320, 13346, 13347, 13348, 13349, 13399, 13400, 13406, 13414, 13415, 13569
Mammalia	Artiodactyla	Camelidae	*Megatylopus*	13300, 13570
Mammalia	Artiodactyla	Camelidae	*Hemiauchenia*	13301, 13303, 13398, 13401, 13402, 13403, 13404, 13405, 13567, 13568
Mammalia	Artiodactyla	Cervidae		13306
Mammalia	Carnivora	Canidae		13316
Mammalia	Carnivora	Canidae	*Osteoborus*	13344
Mammalia	Proboscidea			13313, 13566

coarse-grained sands with well-rounded cobbles of calcrete, sandstone, and igneous rocks up to 20 cm in diameter.

It has been stated many times by past workers that in southwestern Kansas it is very difficult to distinguish Ogallala sand and gravel from younger sediments (Smith, 1938; McLaughlin, 1942). It has been the general opinion, however, that Ogallala sediment is finer-grained than sediments deposited in younger and presumably more competent fluvial systems. McLaughlin (1942:83) specifically mentioned the Fullerton Pit by legal locality and stated that "these gravels are probably post-Ogallala in age." Frye et al. (1956:50-51) stated "The earliest post-Ogallala sediments of the central Great Plains are coarser than those of the upper Ogallala, and Pleistocene materials subsequently transported eastward from the Rocky Mountains to western Kansas are considerably coarser than any of the Ogallala materials."

It is not true, however, that Ogallala sediment is finer than post-Ogallala sediment. The fossil vertebrates recovered from the Fullerton Gravel Pit are consistent with vertebrates found at other Hemphillian sites across the state (see biostratigraphy section). It seems unlikely that the fossils were re-worked into younger sediment. It would be unlikely to have such a concentration of Hemphillian-aged material in a reworked site and no younger taxa are present in the fauna which would be expected with reworking. Thus it is likely that the deposit is of the same age as the fossils and the coarse grain size at the Fullerton Gravel Pit clearly shows that Ogallala fluvial systems could be just as competent, if not more so, then their younger counterparts. Grain size alone does not indicate the age of sediments in southwestern Kansas.

Systematic Paleontology--A complete list of specimens from the Fullerton Gravel Pit is presented in Table 1, but the specimens identified to genus are reviewed below. All specimens are in the collections of the Sternberg Museum of Natural History, Hays, Kansas.

Class Mammalia
Order Perissodactyla
Family Equidae
Genus *Protohippus*

Specimens - VP-13292 right maxillary with P3-M3; VP-13293 right m3; VP-13345 distal end of left humerus.

Order Artiodactyla
Family Camelidae

An unusual feature about the Fullerton fauna is the number of camel specimens that have come from the locality. The exact taphonomic filter working to preserve camels is not known, but camels continue to be recovered with greater frequency then other identifiable mammal remains.

Genus *Megatylopus*?

Specimen - VP-13300 1st phalange; VP-13570 cervical vertebra centrum.

Genus *Hemiauchenia*

Specimens - VP-13301 1st phalange; VP-13303 partial right metatarsal; VP-13398 partial distal end of radius; VP-13400 proximal end of left metacarpal; VP-13401 proximal end of left metacarpal; VP-13402 partial right metatarsal; VP-13403 proximal end of right metatarsal; VP-13404 proximal end of left metatarsal; VP-13405 partial metapodial; VP-13567 partial distal metapodial; VP-13568 partial proximal metapodial.

Order Carnivora
Family Canidae
Genus *Osteoborus*

Specimen - VP-13344 posterior end of left dentary with m2.

Biostratigraphy--The horse *Protohippus* ranged from the late Hemingfordian to the end of the late early Hemphillian about 6 ma (MacFadden, 1998). The camels *Megatylopus*? and *Hemiauchenia* ranged from late Barstovian into the Blancan (Honey et al., 1998), and the dog *Osteoborus* ranged through the Hemphillian (Munthe, 1998). All these taxa co-occur during the early Hemphillian (8.8-6.0 ma), thus suggesting this age for the fauna at the Fullerton Gravel Pit.

Quaternary Deposits

Quaternary deposits dominate the surface area within the study area. Dune sand prevails in the southern portion and loess in the north. No fossils were found in either of these two units, but these sediment types are known to occasionally yield fossils. Frye and Leonard (1951) presented a listing of many loess sites across the western two thirds of Kansas that produce mollusks. Likewise, our team recovered *Bison* remains from loess just outside the study area.

Dune sands are extensively deposited on the south side of the Cimarron River (Fig. 1). Most of the dunes have a vegetative cover, but their characteristic dune shape is very evident. The age of the dunes varies throughout the southwestern quarter of the state (Smith, 1938). According to Smith (1940), the dunes in the area could be contemporaneous with the loess deposits, but in at least a few cases are younger, as the sand occasionally overlies the loess. Lastly, Quaternary alluvium covers the meandering river valley of the Cimarron River.

DISCUSSION

Future work on the enigmatic Mesozoic rocks in the Point of Rocks area may yield clues as to their ages and stratigraphic correlations. The Fullerton Gravel Pit local fauna is the first fossil vertebrate fauna from Morton County and adds significantly to only two other Miocene localities in the entire southwestern quarter of Kansas. The local fauna seems to be typical of other Hemphillian assemblages, with the exception that camels are highly concentrated. This concentration may be real or artificial. To date, no fossil seeds have been found in the Ogallala Group of Morton County, although they are prevalent elsewhere in the state. This absence is likely due to the coarse-grained nature of the sediments, which would not preserve the fragile reproductive structures.

ACKNOWLEDGMENTS

Many people contributed to the success of this project. Mr. Joseph Hartman, Elkhart Office of the Cimarron National Grassland, was instrumental in initiating this project, and he provided the field crew with creature comforts during the fieldwork. Al Kane, "Rusty" Dersch, Cathleen May, and Deb Dandridge, as well as others at the USDA Forest Service have all played a role in the project. Several departments at Fort Hays State University provided support, including the Department of Geosciences, Computing Center, Center for Teaching Excellence and Learning Technology (CTELT), and Business office. University students who worked on various phases of this project were Susan E. Fishman-Armstrong, H. Robins Richards III, Steven C. Wallace, and Patricia Duffey; all of their work is greatly valued. We thank the Morton County Data Processing Department for the loan of a GPS unit. No research gets done without access to library materials and the staff at Forsyth Library, especially those in inter-library loan, deserve a special thanks. A special thanks goes to Dale and Norma Lee Smith, and Cameron Liggett for their support. Michael R. Voorhies, University of Nebraska, Lincoln, and Richard C. Hulbert Jr., Georgia Southern University, Landrum, shared their knowledge regarding Miocene horses.

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STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS, AND FOSSIL RESOURCES OF THE CHADRON FORMATION IN THE SOUTH UNIT OF BADLANDS NATIONAL PARK, SOUTH DAKOTA

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ABSTRACT-- In 1995 the National Park Service and the University of Nebraska-Lincoln entered into a cooperative agreement to study the geological and paleontological resources in the South Unit of Badlands National Park. The project was divided into three main parts: 1) geological mapping of the late Eocene Chadron Formation and interpretation of depositional environments; 2) documentation of fossil resources and fossil theft with respect to the various members of the Chadron Formation; 3) production of a geologic map relating members and depositional environments of the Chadron Formation to the regional distribution of fossil resources. These data are intended to serve as a guide for the protection of known fossil resources, delineate areas of active fossil theft, and serve as a predictive tool for the exploration and monitoring of potentially fossiliferous areas. Preliminary results indicate that: 1) the Ahearn, Crazy Johnson, and Peanut Peak Members of the Chadron Formation can be recognized and mapped throughout the study area; 2) fossils are most abundant within the Crazy Johnson Member, although this is likely related to the greater proportion of this member in the map area; 3) no evidence of fossil theft was observed at any fossil sites. This is likely due to problems of accessibility, and the presence of well known, easily reached fossil beds just outside of the present study area.

INTRODUCTION

The South Unit of Badlands National Park has been the focus of paleontological and geological research for over 150 years, beginning with the brontothere jaw described by Prout (1846) and the expeditions of Evans (1852). Subsequent research has shown these deposits to be the richest fossil beds in the world for Eocene and Oligocene mammals. These fossils were deemed of such importance by earlier paleontologists and geologists that they became the standards for defining particular periods of geologic time in North America: the Chadronian, Orellan, Whitneyan, and Arikareean "North American land mammal ages" (Wood et al., 1941).

Strata within the South Unit are unique both for their historical importance to the science of paleontology and geology in North America and for the potential that still remains for research and important scientific discoveries (Terry et al., in press). Current research covers such diverse areas as paleoclimatology, vertebrate and invertebrate paleontology, sedimentology, and stratigraphy. A history of paleontological and geological research in the Badlands is provided by Macdonald (1951) and Bjork (1996).

Regional Geologic Setting

Deposition of the White River Group in southwestern South Dakota was the result of the interaction of tectonics and climatic change. The Black Hills were uplifted during the latter phases of the Laramide Orogeny (early Tertiary) resulting in the exposure, weathering, and erosion of Paleozoic and Mesozoic sedimentary rocks (Lisenbee and Dewitt, 1993). Consequently, faults radiating away from the Black Hills created a slightly northwest-southeast trending asymmetric basin (Fig. 1) hinged on the north along the Sage Fault (SFZ) and on the south along the Sandoz Ranch, White Clay, and Pine Ridge faults (PWSFZ) (Clark et al., 1967: figs. 6, 7). This basin was filled with sediments deposited by fluvial systems originating in the Black Hills (Fig. 2), and by eolian processes, including rare volcanic airfall events (Ritter and Wolff, 1958; Seefeldt and Glerup, 1958; Nicknish and Macdonald, 1962; Clark et al., 1967; Clark, 1975).

Revisions in lithostratigraphic nomenclature for the White River Group have recently been proposed (LaGarry, in press; Terry, in press; Terry and LaGarry, in press), and are discussed throughout the text where appropriate (Fig. 2). Other recent studies include a new interpretation of lacustrine limestones within the upper part of the Chadron Formation (Evans and Welzenbach, in press), a detailed description of tuffs of the White River Group and suggested regional correlations (Larson and Evanoff, in press), and a current assessment of the Chadronian, Orellan, Whitneyan, and Arikareean NALMAs in relation to newly proposed magnetostratigraphic zonations, revised radiometric dates, and lithostratigraphic units (Prothero, 1996; Tedford et al., 1996; Prothero and Whittlesey, in press).

The Eocene-Oligocene White River Group in this area contains the Chamberlain Pass, Chadron, and Brule Formations. It is underlain by the Cretaceous Pierre Shale and Fox Hills Formation (Stoffer and Chamberlain, 1996), and is overlain by the Arikaree Group (Fig. 2). The Pierre Shale and Fox Hills Formation were severely altered by pedogenesis to form the Yellow Mounds Paleosol Series of Retallack (1983), the lower of the two paleosols within the Interior Zone (Fig. 3A). This episode of pedogenesis is recognized as a zone of bright yellow, orange, and lavender, up to 26 m thick (Retallack, 1983), that underlies the White River Group throughout the region (Pettyjohn, 1966).

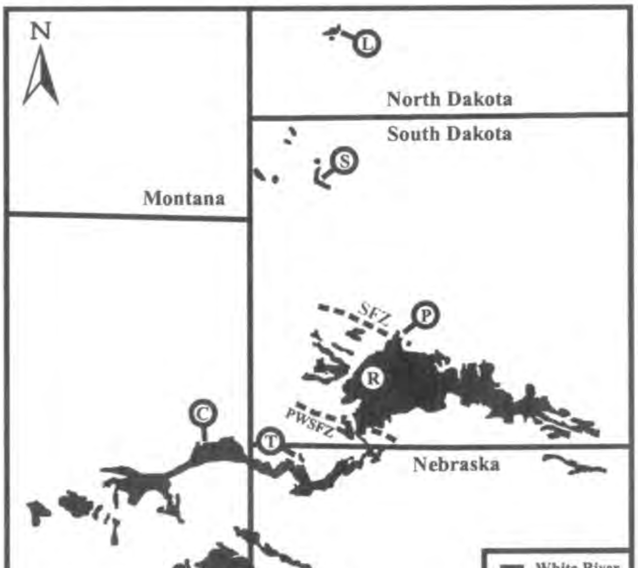


FIGURE 1 - Regional distribution of the White River Group across the Great Plains showing the location of other important study areas. P = the Pinnacles area of Badlands National Park; C = the Lance Creek, WY area; L = the Little Badlands near Dickinson, ND; R = the Red River Valley of Clark (1937, 1954); S = the Slim Buttes area near Reva, SD; T = the Toadstool Park area near Crawford, NE. See Fig. 6 for measured sections at each of these locations. Major faults in the Big Badlands area include the Sage Fault Zone (SFZ) and Pine Ridge/White Clay/Sandoz Fault Zone (PWSFZ).

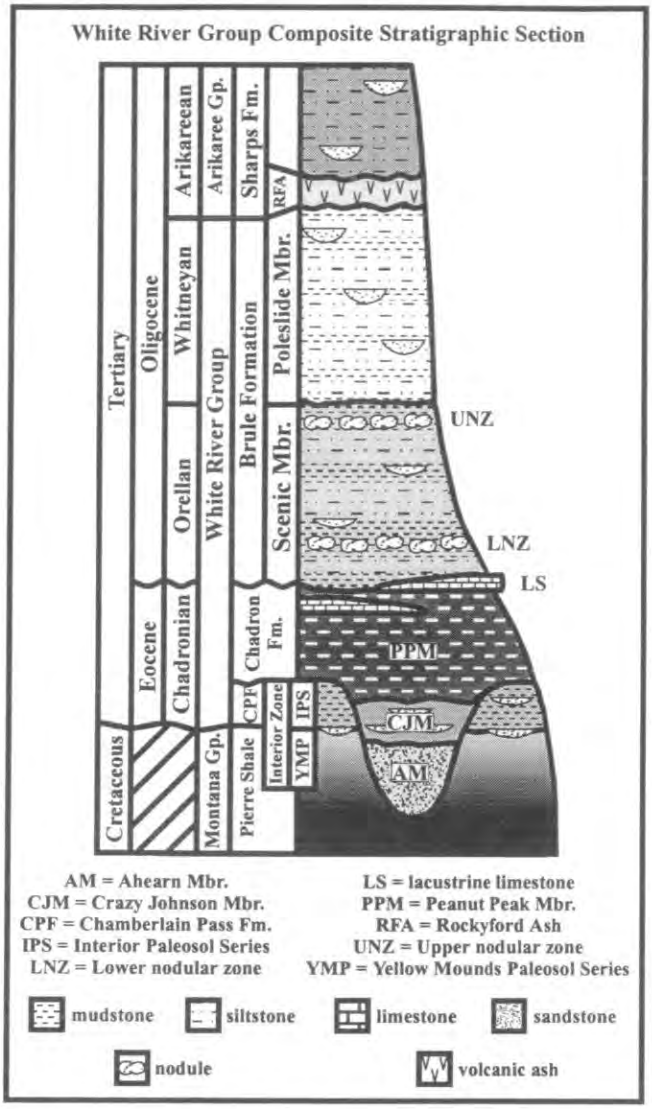


FIGURE 2 - Composite stratigraphic section of the White River Group in Badlands National Park, SD. This section incorporates recently published lithostratigraphic changes within the bottom part of the White River Group (Terry, in press; Terry and LaGarry, in press). This section is not to scale, but is instead drawn to show the paleogeomorphic and geologic relationships of various rock units. This composite section also incorporates data from Bump (1956), Retallack (1983), Martin (1987), Prothero and Swisher (1992), Evans and Terry (1994), Terry and Evans (1994), and Terry et al. (1995). Modified from Terry (1996).

The base of the White River Group is marked by the Chamberlain Pass Formation (Evans and Terry, 1994). The Chamberlain Pass Formation is composed of white channel sandstones that were assigned to the Slim Buttes Formation by Clark et al. (1967) (Fig. 3A), red overbank mudstones that were modified by pedogenesis into Retallack's (1983) Interior Paleosol Series (the upper of the two paleosols in the Interior Zone) (Fig. 3B), and greenish proximal overbank mudstones and siltstones that were modified into the Weta Paleosol Series of Terry and Evans (1994).

The Chadron Formation is composed of the Ahearn, Crazy Johnson, and Peanut Peak members (Fig. 2). According to Clark (1954) and Clark et al., (1967), the Ahearn Member consists of 0-24 m of red and green sandstones and claystones that fill the bottom of, and are confined to, a paleovalley (the "Red River Valley") that cut through the Chamberlain Pass Formation and Yellow Mounds Paleosol into unaltered Pierre Shale (Figs.3C, D, 4). The base of this unit is marked by a coarse gravel of quartz, quartzite, and granitic debris. The Crazy Johnson Member is a 12-15 m succession of greenish claystones and sandstones, also confined to the Red River Valley, that contain fossils of brontotheres, rhinoceroses, *Mesohippus*, and *Archaeotherium* (Figs. 3D, E, 4). The overlying Peanut Peak Member is 6-9 m of massive buff and green claystones that contain numerous discontinuous limestone lenses and occasional, sharply restricted greenish sandstone lenses (Fig. 3A-E). Clark (1937, 1954) recognized the upper member based on the decrease in the amount of sandstone and the disappearance of brontothere bones.

The Brule Formation is composed of the Scenic and Poleslide members (Bump, 1956). It is easily distinguished from the underlying Chadron Formation by a change from greenish-gray hummocky mudstones to brown and beige cliff forming mudstones, siltstones, and channel sandstones (Fig. 3F). The Scenic Member is dominated by siltstones and sheet sandstones, whereas the Poleslide Member is dominated by siltstones with occasional fluvial sandstones. Harksen and Macdonald (1969) placed the top of the Brule Formation at the contact with the overlying Rockyford Ash Member of the Sharps Formation (Arikaree Group) (Fig. 3G). Tedford et al. (1996) suggested a correlation of the Rockyford Ash to the Nonpareil ash zone in northwestern Nebraska, which is dated at approximately 30 Ma (Swisher and Prothero, 1990).

Paleosols of the White River Group indicate a trend toward increasingly arid climates during the Paleogene in the Big Badlands (Retallack, 1983). This climatic shift is indicated by a decrease in the size of root traces within paleosols that corresponds to a change from forested environments to open savannas. Paleosols at the base of the sequence resemble modern soils formed under humid, forested conditions (Retallack, 1983; Terry and Evans, 1994). Subsequent paleosols gradually change to types resembling those found in drier, grassland ecosystems (Retallack, 1983).

THE SOUTH UNIT AS AN IMPORTANT GEOLOGIC AREA

The rock strata, volcanic ashes, and fossil resources of the North and South units of Badlands National Park are diverse and unevenly distributed (Figs. 3B, C, 5). Strata in the South Unit are unique within Badlands National Park for the period of time they represent, their position within the geologic column, and also for the paleoclimatic, paleoenvironmental, and faunal data that they contain (Figs. 2, 3C, 4). The strata in the South Unit of Badlands National Park are used as standards of comparison for lithostratigraphy, biostratigraphy, and magnetostratigraphy across the northern Great Plains (Clark, 1937; Clark et al., 1967; Evans and Terry, 1994; Prothero, 1996; Tedford et al., 1996; Terry, 1998). Of the three members of the Chadron Formation exposed in the South Unit (Fig. 3C), only the Peanut Peak Member has regional extent (Terry, in press; Terry and LaGarry, in press) (Figs. 3B, 6). The Ahearn and Crazy Johnson Members are restricted to the Red River Valley (Clark et al., 1967) (Figs. 3C, 4). It is very likely that other late Eocene paleovalley systems with similar lithologies extend off the eastern flank of the Black Hills. Evanoff (1990) has documented numerous late Eocene paleovalley systems in central and eastern Wyoming that contain "White River" deposits and fossils, but the temporal and lithologic relationships to deposits in South Dakota are unknown.

SOUTH UNIT PROJECT BACKGROUND

Mapping was done on enlarged (400%) U.S.G.S. 7.5 minute topographic maps. The majority of secs. 33 and 34, T. 43 N., R. 45 W., parts of secs. 27, 28, 29, and 32, T. 43 .N, R. 45 W., and secs. 3 and 4, T. 42 N., R. 45 W. of the Heutmacher Table 7.5 minute quadrangle in the vicinity of Big Corral Draw were surveyed. Mapping began after reexamination of the type sections for the Ahearn, Crazy Johnson, and Peanut Peak Members of the Chadron Formation established by Clark (1937, 1954). I have revised Clark's (1937, 1954) members slightly, restricting the Ahearn Member to the basal channel sands and gravels (Fig. 3D), the Crazy Johnson Member to the interbedded channel sandstones and overbank mudstones overlying the Ahearn Member (Fig. 3E), and the Peanut Peak Member to the uppermost massive greenish-gray mudstones (Fig.

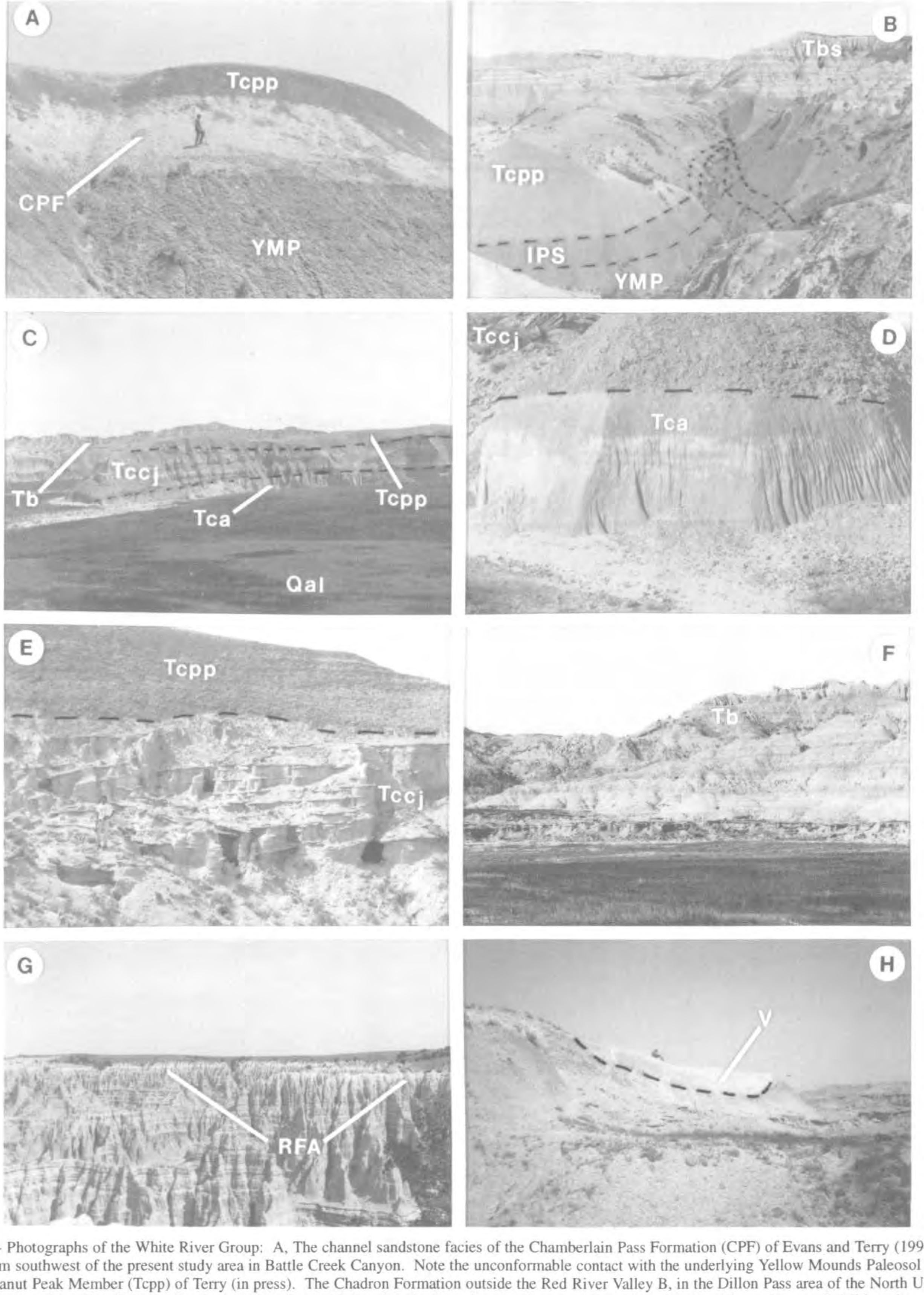


FIGURE 3 - Photographs of the White River Group: A, The channel sandstone facies of the Chamberlain Pass Formation (CPF) of Evans and Terry (1994) approximately 6.5 km southwest of the present study area in Battle Creek Canyon. Note the unconformable contact with the underlying Yellow Mounds Paleosol (YMP) and overlying Peanut Peak Member (Tcpp) of Terry (in press). The Chadron Formation outside the Red River Valley B, in the Dillon Pass area of the North Unit (see Fig. 5), and inside the paleovalley C, in the South Unit of Badlands National Park. Note that the three members of the Chadron Formation are divisible only within the Red River Valley. Tca, Tccj, and Tcpp = the Ahearn, Crazy Johnson, and Peanut Peak Members of the Chadron Formation, respectively. IPS = Interior Paleosol Series of Retallack (1983), Tb = undifferentiated Brule Formation, Tbs = the Scenic Member of the Brule Formation, and Qal = undifferentiated Quaternary deposits. D, The Ahearn and Crazy Johnson Members of the Chadron Formation within the Red River Valley of Clark (1937, 1954) in the Big Corral Draw area, South Unit, Badlands National Park. The hammer in the center is 40 cm long. E, Channels sandstones of the Crazy Johnson Member. The person is approximately 2 m tall. F, Photograph of the Brule Formation in the Cottonwood Pass area within the South Unit of Badlands National Park. G, Rockyford Ash Member (RFA) of the Sharps Formation at Sheep Mountain Table. H, Photograph of the volcanic ash layer (V) that mantles paleotopography within the Crazy Johnson Member. Note person for scale.

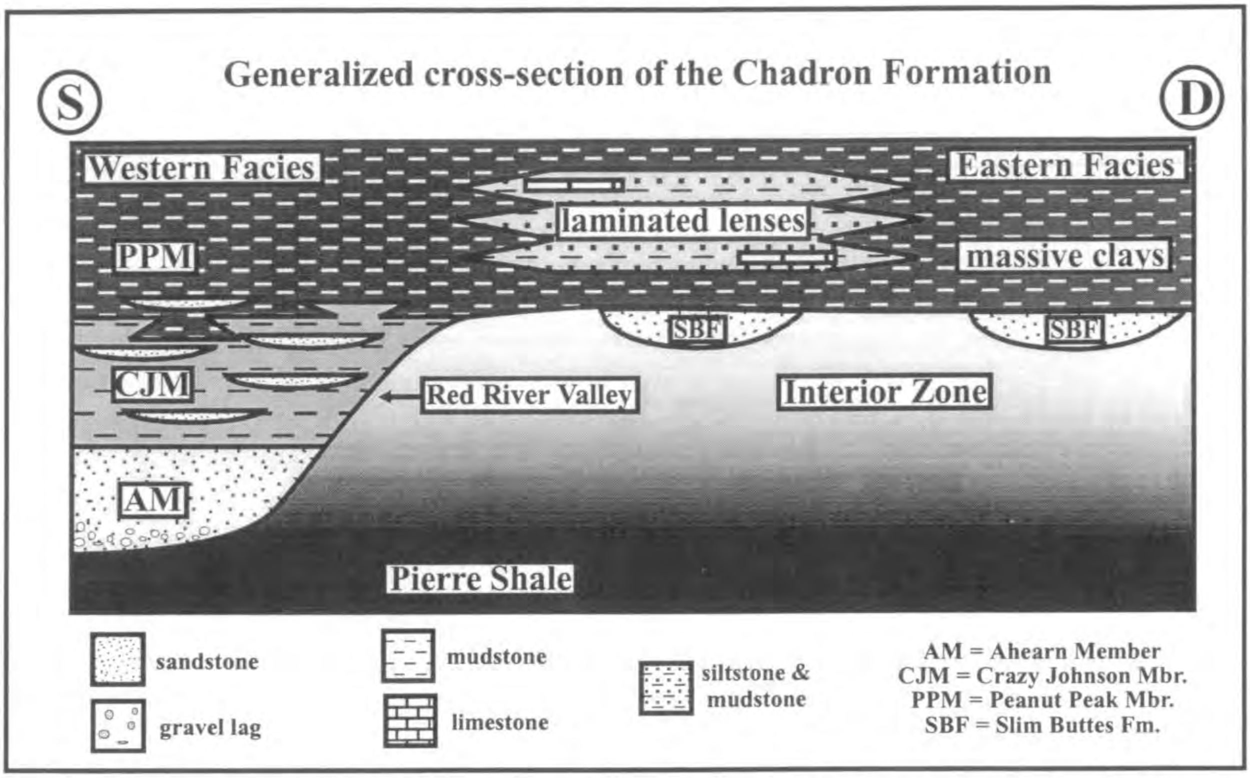


FIGURE 4 - Diagram showing the generalized paleogeomorphic and geographic distribution of the various members and facies of the Chadron Formation, using the terminology of Clark (1937, 1954), between points S and D (Fig. 5). The channel sandstones of the Slim Buttes Formation are now included in the Chamberlain Pass Formation of Evans and Terry (1994), and the Peanut Peak Member has been expanded to include the massive clays of the eastern facies Terry (in press).

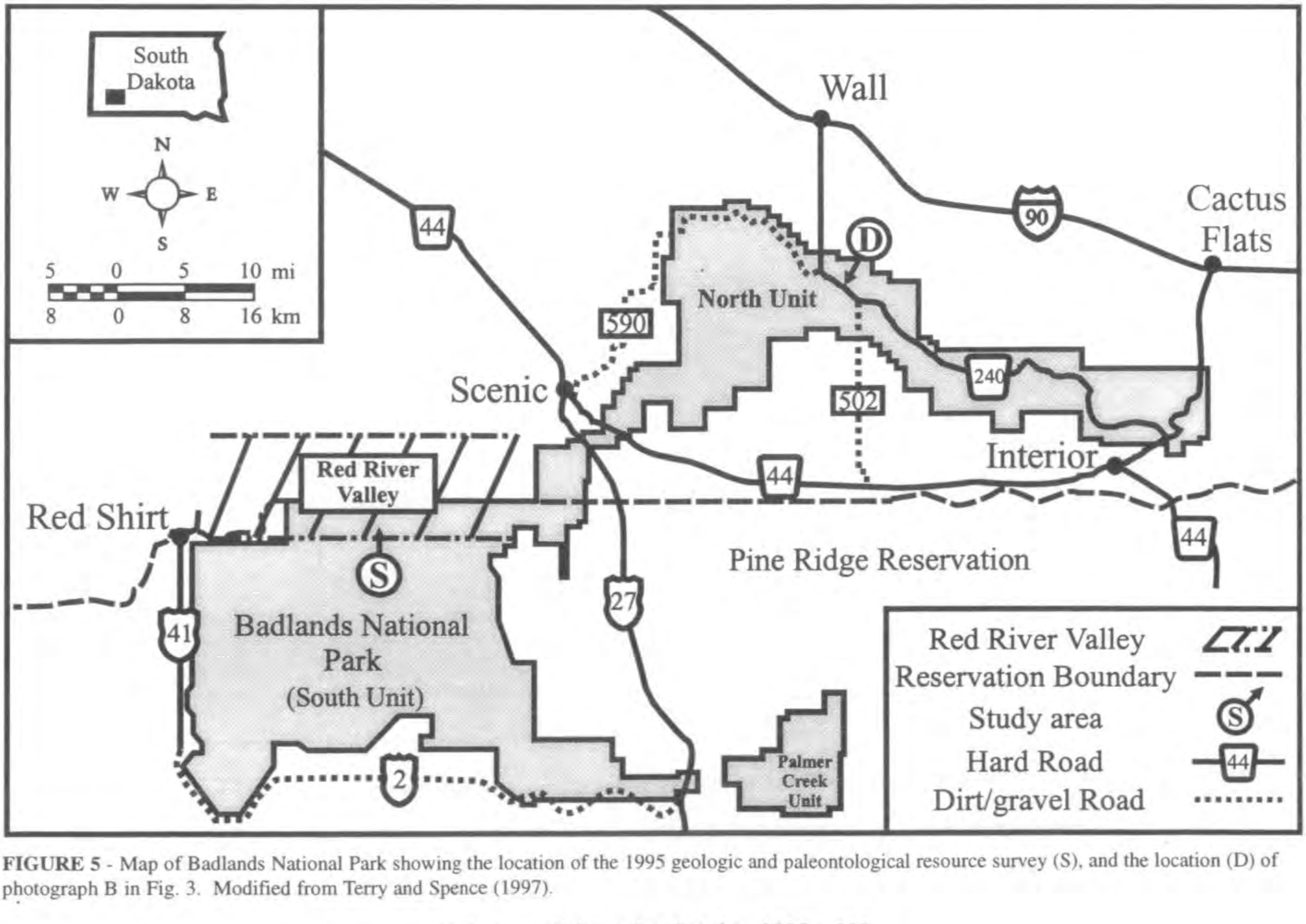


FIGURE 5 - Map of Badlands National Park showing the location of the 1995 geologic and paleontological resource survey (S), and the location (D) of photograph B in Fig. 3. Modified from Terry and Spence (1997).

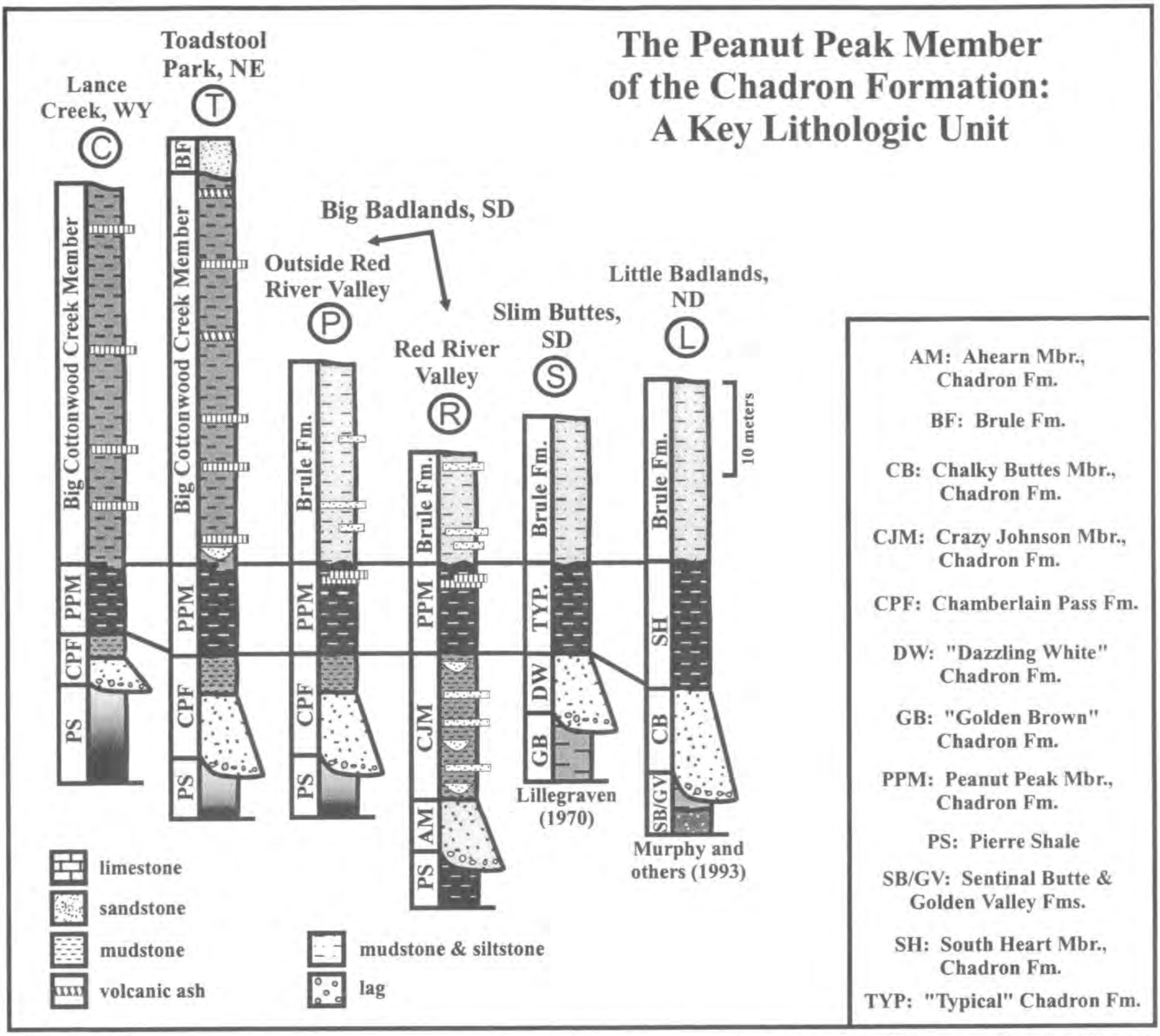


FIGURE 6 - Measured sections of the White River Group across the Great Plains showing the regional relationships of lithostratigraphic units with respect to the Peanut Peak Member of the Chadron Formation as defined by Terry (in press). The Big Cottonwood Creek Member of the Chadron Formation is a newly defined lithostratigraphic unit (Terry and LaGarry, in press). See Fig. 1 for the location of these sections. Modified from Terry and Spence (1997).

3E). While these revised units more closely follow the tenants set forth by the North American Commission on Stratigraphic Nomenclature (NACSN, 1983) for the establishment and mapping of lithostratigraphic units, the following descriptions *do not* constitute a formal revision of these strata.

MEASUREMENTS AND OBSERVATIONS

Raymond and King (1976) and King and Raymond (1971) produced geologic maps of Badlands National Park based on earlier mapping projects (see King and Raymond, 1971). King and Raymond's (1971) geologic maps of the South Unit were done on U.S.G.S. 7.5 minute quadrangles at the formation level, and then compiled into a larger 1:31,680 scale map. They recognized the Cretaceous Pierre Shale, the Interior Zone of the Pierre Shale, the Chadron and Brule formations of the White River Group, and the Sharps Formation of the Arikaree Group. Quaternary deposits were not mapped.

The Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation, as defined in this report, were mapped in the Big Corral Draw area within Clark's (1937, 1954) Red River Valley (Fig. 7). King and Raymond's (1971) geologic map of the South Unit shows the Red River Valley as a generally east to west trending feature defined by the disappearance of the Interior Zone of the Pierre Shale (Kpi) where the Red River Valley incised into unaltered Pierre Shale (Fig. 4). The exhumed paleotopography of the Red River Valley can be recognized in the field. The western end of the paleovalley grades up onto the flanks of the Black Hills and is filled with coarse clastics. The eastern extent of the paleovalley is unknown.

Chadron Formation

Ahearn Member (Tca)--The Ahearn Member is composed of 7 m of red, white, and pale green, coarse-grained, poorly cemented, and fossiliferous arkosic and subarkosic sandstones (Fig. 3D). The .9-1.2 m basal gravel lag that Clark et al. (1967) reported was not observed in the mapping area (Fig. 8). Fragmented fossils are common within the Ahearn Member. The unconformable lower contact with the Cretaceous Pierre Shale was not exposed. The contact with the overlying Crazy Johnson

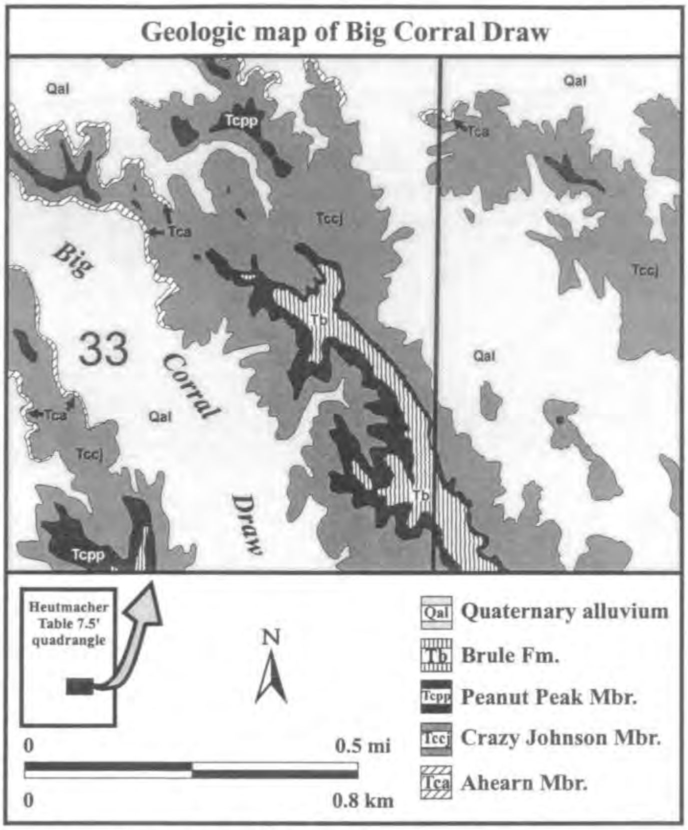


FIGURE 7 - Geologic map of a part of the study area in Big Corral Draw. This map shows a part of secs. 33 and 34, T. 43 N, R. 45 W. of the U.S.G.S. 7.5 minute Heutmacher Table quadrangle. Modified from Terry and Spence (1997).

Member is gradational into bluish-green and gray mudstones and greenish, ledge forming channel sandstones (Figs. 3D, E). This contact is usually covered by slope wash.

Crazy Johnson Member (Tccj)--The Crazy Johnson Member is composed of 19 m of bluish-green and gray, smectite-rich mudstone, numerous coarse, ledge forming channel sandstone bodies, and rare, thin lacustrine limestones (Figs. 3E, 8). The channel sandstones are fine to coarse-grained, angular to rounded, poorly sorted, calcite-cemented arkoses and subarkoses composed of granitic, metamorphic, and sedimentary rock fragments from the Black Hills and reworked overbank material. These sandstones show numerous sedimentary structures, including fining upwards sequences, rib and furrow structures, trough crossbedding, planar bedding, and lateral accretion surfaces. The Crazy Johnson Member is the most fossiliferous unit in the study area. Almost all brontothere bones in the study area were found either within or near channel sandstones. Bone fragments are common as clasts within the channel lags, and as smaller fragments throughout the channel bodies. Stromatolites and oncolites are also found in association with the sandstones. The overlying contact with the Peanut Peak Member is gradational and marked by the disappearance of coarse, ledge-forming channel sandstones (Fig. 3E).

Peanut Peak Member (Tcpp)--The Peanut Peak Member is composed of 9 m of bluish-green and gray, smectite-rich, mudstone that weathers into popcorn-textured haystack mounds and hills (Figs. 3A, B, C, E), and occasional thin lacustrine limestones (Fig. 8). The upper contact with the Brule Formation is recognized by a change in relief to steep brown, beige, and tan slopes and spires (Figs. 3B, F), and is occasionally marked by the top of lacustrine limestones of the Peanut Peak Member.

Brule Formation (Tb)

The Brule Formation consists of steeply spired brown and tan volcaniclastic mudstones and siltstones, and fluvial sandstones that were

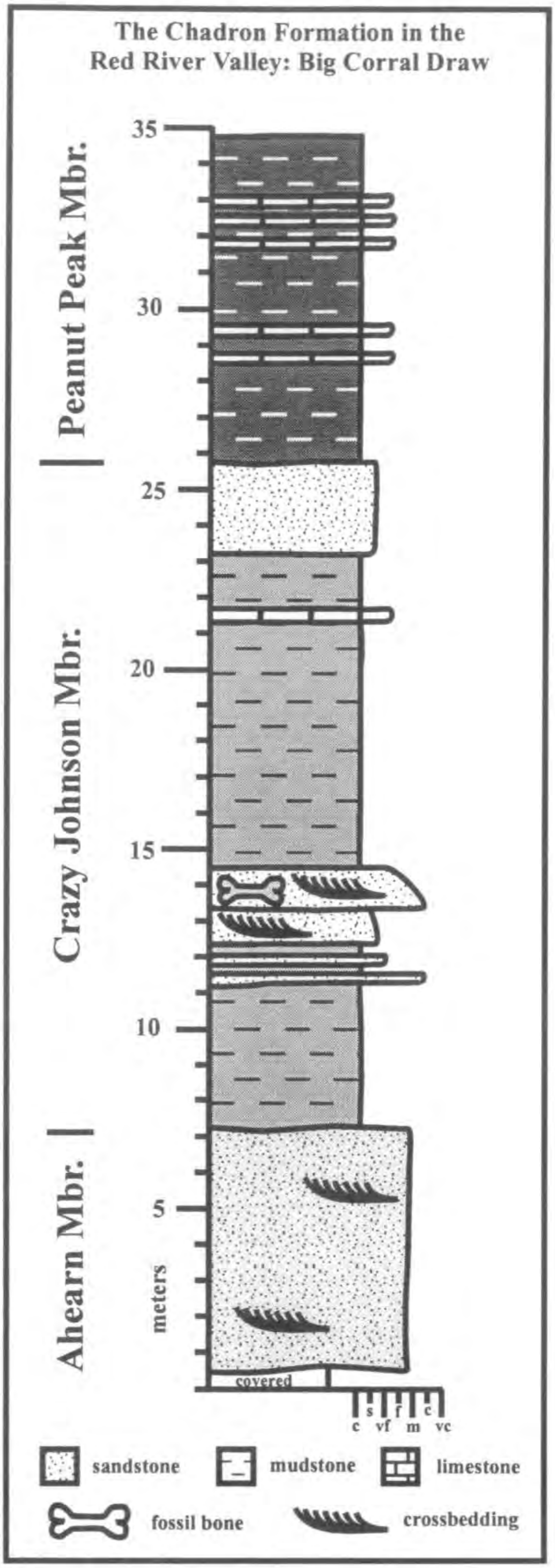


FIGURE 8 - Measured section of the Chadron Formation in Big Corral Draw. The section is located in the SW1/4, NW 1/4, sec. 33, T. 43 N, R. 45 W. of the U.S.G.S. 7.5 minute Heutmacher Table quadrangle. Modified from Terry and Spence (1997).

modified by ancient pedogenesis (Fig. 3F). Paleosol horizons appear as parallel reddish and greenish bands in outcrops. Clark et al. (1967) reported a thickness of 27-39 m for the Scenic Member and 82 m for the Poleslide Member. The Brule Formation was not divided into members during mapping.

Quaternary Alluvium (Qal)

Quaternary deposits are primarily alluvial deposits within modern drainages and sod tables remaining from the dissection of older landscapes (Fig. 3C). These deposits consist of light gray channel sands, gravels, and silts, and overbank silts and muds. Several episodes of cutting and filling are evident, but they were not differentiated during mapping.

FOSSIL RESOURCE INVENTORY

Fossils were located by pedestrian survey and plotted on the geologic maps as sensitive sites (SS) following the terminology of LaGarry and Hunt (1996). Only fossils deemed of commercial value or scientifically important were recorded and bone fragments were ignored. Twenty two sensitive sites were documented.

Fossil Distribution Patterns

The greatest abundance (77%) of fossils was documented within the Crazy Johnson Member (Fig. 9). Whether this is an actual trend or an artifact of the outcrops covered during the survey is unknown. The Crazy Johnson Member makes up a greater proportion of the outcrops in the study and is more accessible than the overlying Peanut Peak Member (Fig. 7). Clark (1937) also noted a greater abundance of fossils within the Crazy Johnson Member. The highest concentration of sensitive sites was 12 sites/square mile. Fossils occur as isolated elements within the channel sandstone facies, but also as extensive bone beds stretching for several hundred meters along outcrops. Fragmented cranial and postcranial brontothere bones comprise the vast majority of identifiable fossils (Fig. 10A), although fossilized wood and roots, algal stromatolites, and pelecypods were also observed. No evidence of fossil poaching was discovered in the study area. This may be the result of the inaccessibility to fossil outcrops or preferential exploitation of well-known fossil beds outside the study area.

Noteworthy Discoveries

Algal Stromatolites, Oncolites, and Pelecypods--Large algal stromatolites, oncolites, and pelecypods were discovered within mudstones and sandstones of the Crazy Johnson Member. Stromatolites occur as both spheroidal bodies and planar mats on both rocky substrates and large pelecypod valves (Figs. 10B, C). In cross section the stromatolites display laminar growth patterns with occasional sand and clay clasts incorporated into the algal structure (Figs. 10D-F). The surfaces of the planar mats are sharp and angular, sometimes with elongate furrows that may represent feeding/grazing traces of aquatic organisms. The bottom surfaces of the planar mats are smooth with a platy and cracked appearance (Fig. 10C). Microscopic analysis indicates that the majority of original structure of the stromatolites has been destroyed, likely due to replacement and recrystallization with calcite, although some traces of filamentous structures are present (Fig. 10E).

Oncolites occur as rounded algal masses that formed around rock fragments and are predominantly found in association with the finer grained channel sandstone facies of the Crazy Johnson Member (Fig. 10G). The paleoenvironment in which the stromatolites and oncolites formed is unknown, although they likely formed within an oxbow or small siliciclastic-dominated lake within the Crazy Johnson Member. Both stromatolites and oncolites were noted within the Chadron Formation of South Dakota by earlier workers, including Clark (1937), Gries and Bishop (1966), Clark et al. (1967), and Wanless (1923), who mentioned algal limestones and horizons of algal balls.

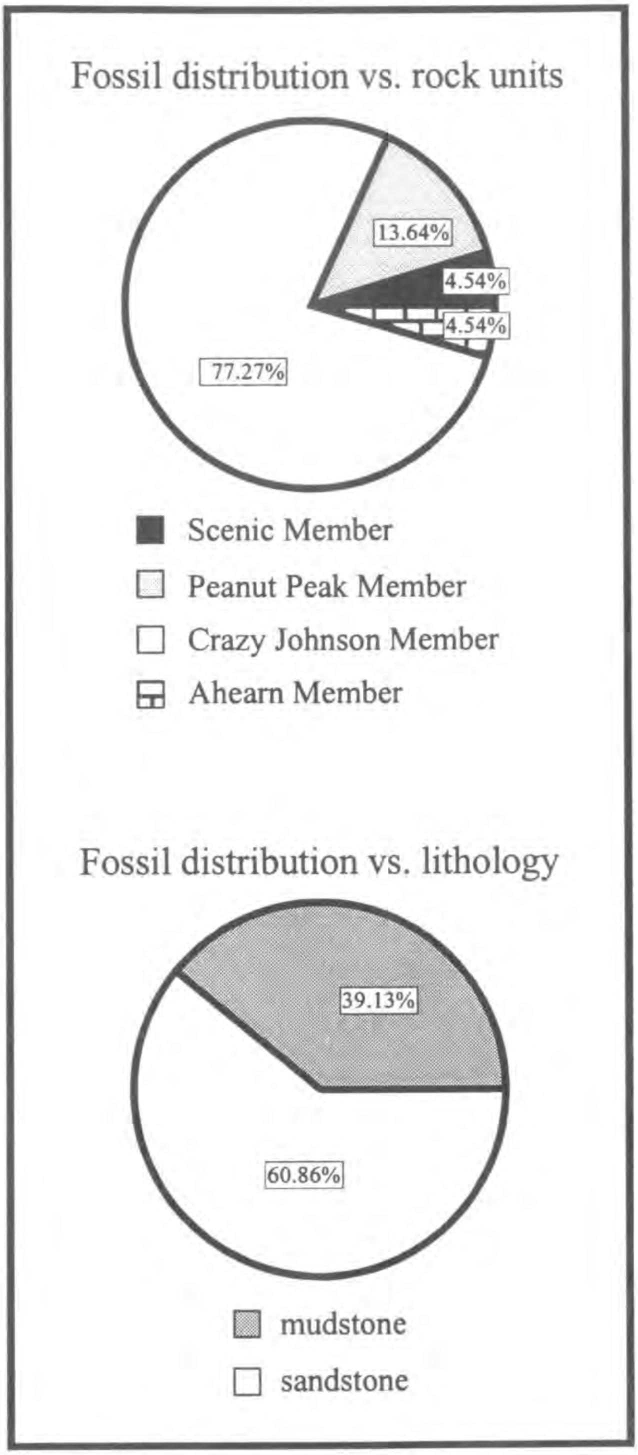


FIGURE 9 - Diagrams showing the distribution of fossil sites with respect to specific members of the Chadron Formation and host lithologies.

The pelecypods were found in direct association with the stromatolites and commonly formed a base for stromatolite growth (Fig. 10H). Most pelecypods occur as single valves, although one complete specimen was recovered. The shell has been destroyed, leaving an external mold created by stromatolitic overgrowths. Pelecypods have been noted within the Chadron Formation of South Dakota by earlier workers. Clark (1937) and Clark et al. (1967) classified them as *Unio* shells, but Gries and Bishop (1966) noted a similarity to *Lampsisus*. Gries and Bishop's specimens (1966) were preserved as internal molds. Cook and Mansfield

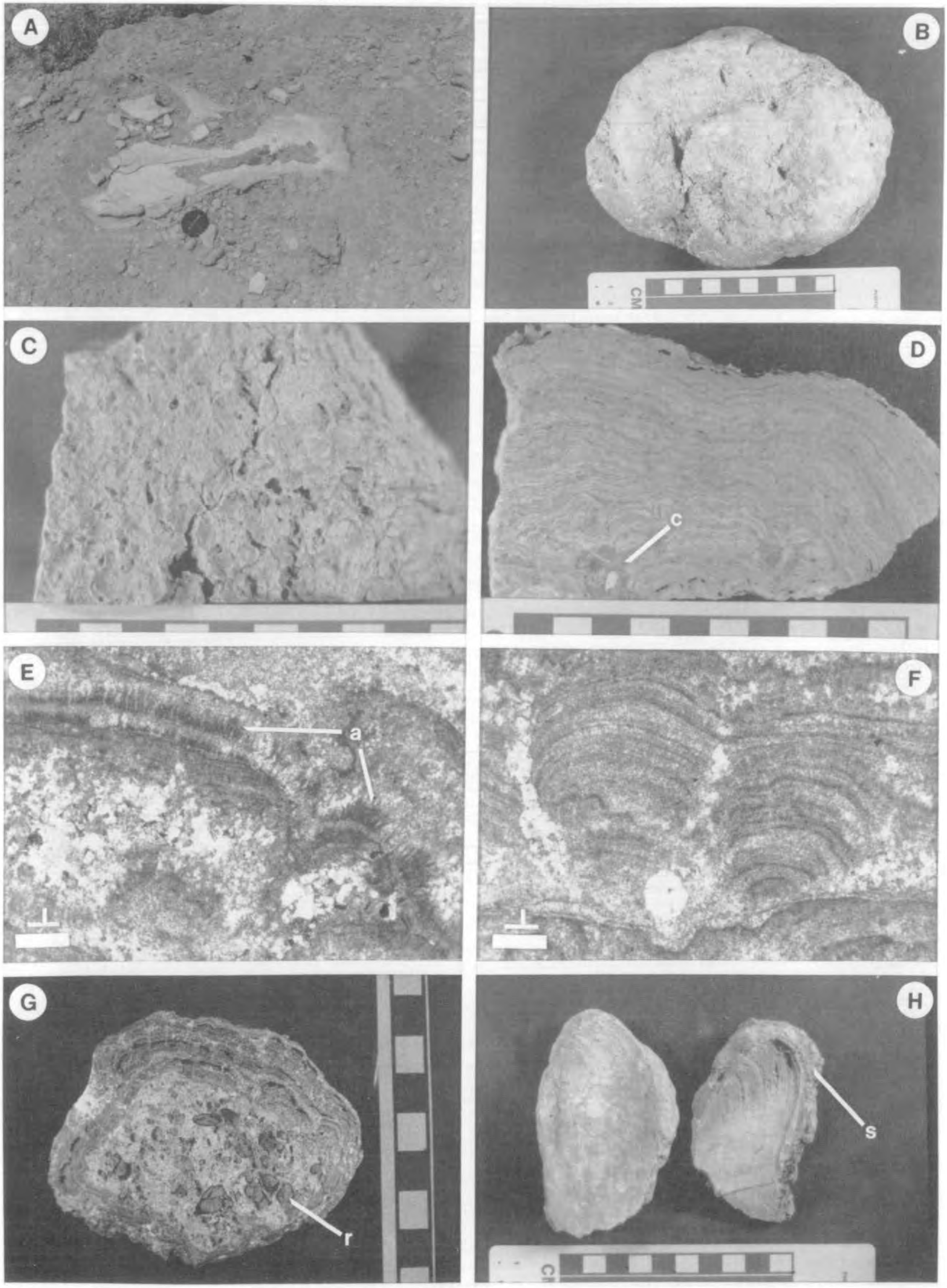


FIGURE 10 - Photographs of various paleontological resources from the Chadron Formation in the South Unit of Badlands National Park: A, Brontothere scapula from the channel sandstone facies of the Crazy Johnson Member. The lens cap is 5 cm wide. B, The top of a stromatolite mound. Scale is in centimeters. C, The bottom of a planar stromatolite body. Scale is in centimeters. D, Cross section of a stromatolite body showing clastic debris (c) trapped along the stromatolite surface during growth. Scale is in centimeters. E, F, Photomicrographs of stromatolites showing algal filaments (a) and laminations. The scale bar in both photographs is 0.3 mm long. The short arm of the inverted "T" points in the original up direction. G, The interior of an oncolite from the Crazy Johnson Member. Note the inclusion of rock fragments (r). Scale is in centimeters. H, Pelecypod specimens preserved as an external mold formed by stromatolitic overgrowth (s). Scale is in centimeters.

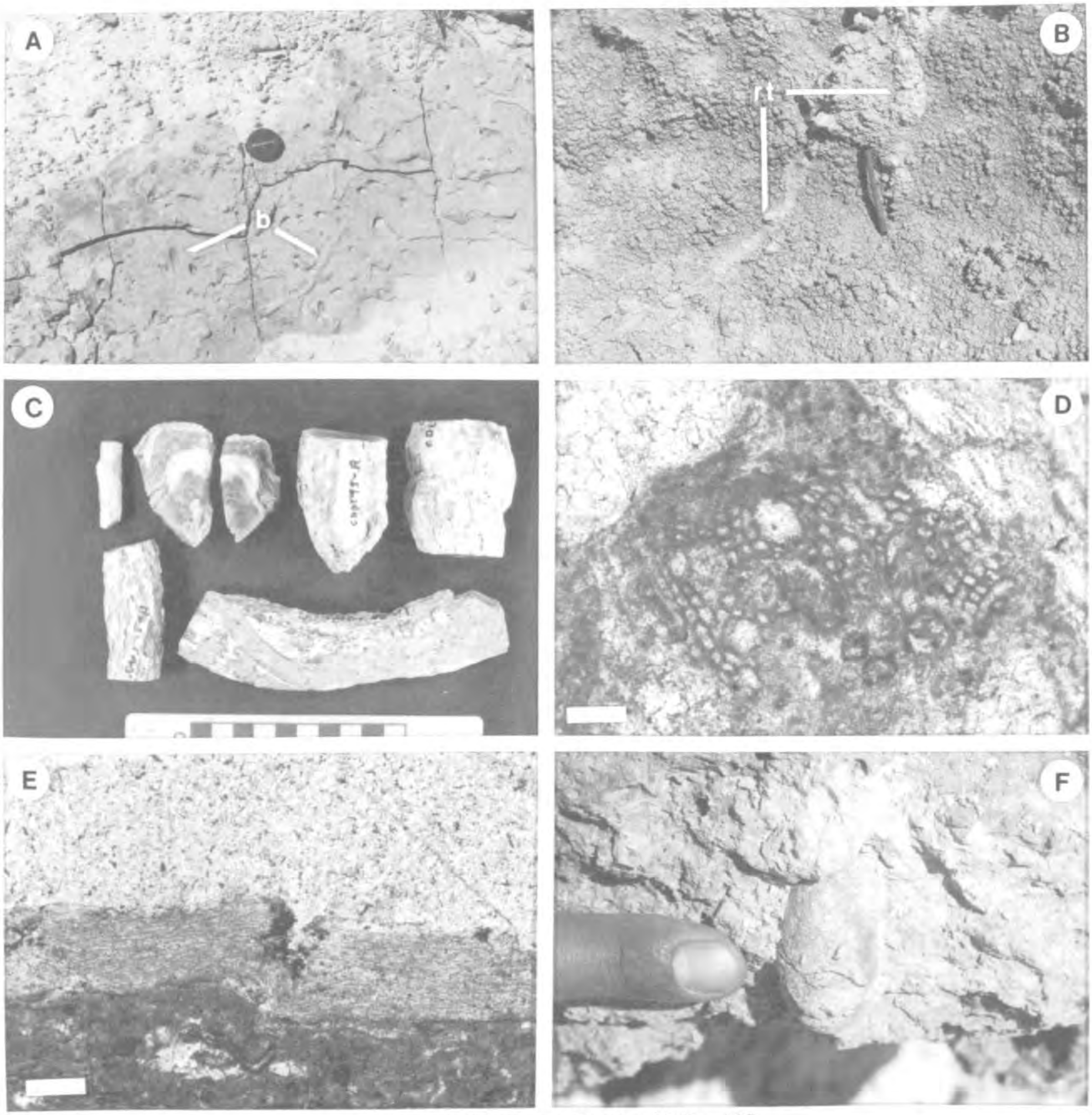
(1933) reported clams in the Chadron Formation of northwestern Nebraska and classified them as *Lampsilus (?) chadronensis* Mansfield.

Volcanic Ashes--One volcanic ash was found within the Crazy Johnson Member. The ash is a thick white bed that varies from 0.5 to 2.7 m and fills depressions on an ancient landscape (Fig. 3H). The ash has been partially altered to smectite, but still contains identifiable glass shards. No attempt has been made to mineralogically correlate this ash with those in the Douglas or Flagstaff Rim areas of Wyoming (e.g. Larson and Evanoff, in press) or to obtain radiometric dates. This ash may correlate to one reported by Terry (1998) at the base of the Crazy Johnson Member in the Indian Creek drainage, approximately 10 km northeast of the present study area, or possibly the one reported by Clark (1975) 4 km north of Red Shirt, South Dakota. The ash in Indian Creek was mineralogically correlated to the F ash at Flagstaff Rim, Wyoming area (E. Evanoff, written communication to D. Terry, 1994).

INTERPRETATIONS

The Chadron Formation is predominantly fluvial, with minor amounts of lacustrine sedimentation. Fluvial deposits are composed of channel and overbank facies that were modified by ancient pedogenesis. The channel facies displays two main morphologies depending on their stratigraphic position. Channel sandstones within the Ahearn Member are multi-storied bodies with fining upwards sequences and cross-bedding, including trough, tabular, and planar bedding (Fig, 3d). Channels of the Ahearn Member have a lower width to depth ratio than the overlying Crazy Johnson Member and resemble typical lenticular channel sand bodies. These sands filled the bottom of the Red River Valley as aggradation proceeded (Fig. 4).

FIGURE 11 - Photographs of various paleontological resources from the Chadron Formation in the South Unit of Badlands National Park: A, Burrows (b) within sandstone of the Crazy Johnson Member. The lens cap is 5 cm wide. B, Drab haloed root traces (rt) sensu Retallack (1983) within the Peanut Peak Member. The pen is 13.5 cm long. C, Silicified roots from the Peanut Peak Member. Scale is in centimeters. Preserved cellular structures within silicified roots D, and along the outer surface E, The scale bar is 0.3 mm long. Photomicrographs are perpendicular to the long axis of the roots. F, Subterranean insect pupa cell within a calcareous mudstone of the Crazy Johnson Member.



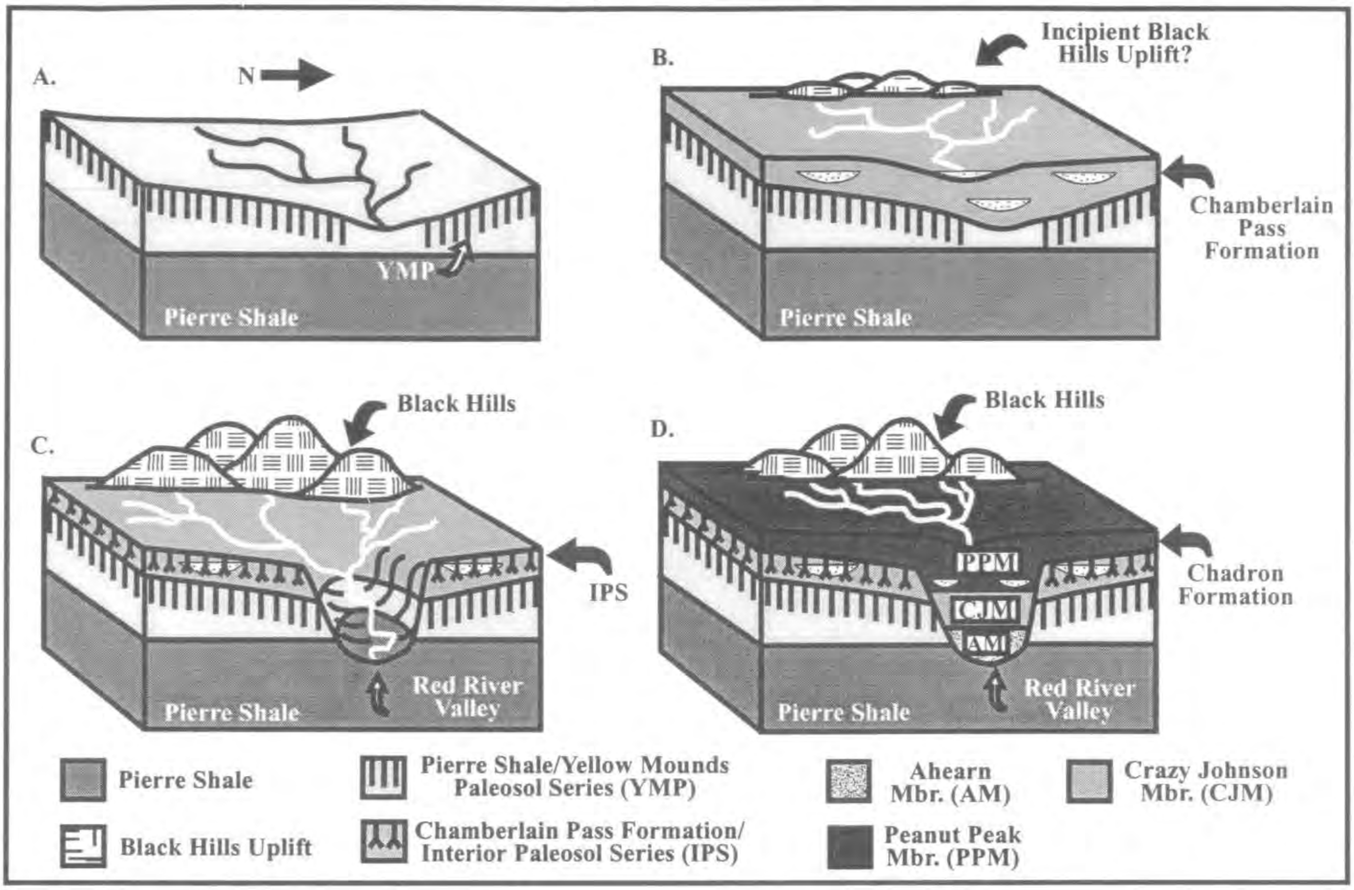


FIGURE 12 - Diagram showing episodes of base level changes east of the Black Hills during the Paleogene and the subsequent formation of A, the Yellow Mounds Paleosol Series (YMP) of Retallack (1983), B, deposition of the Chamberlain Pass Formation of Evans and Terry (1994), C, cutting of the Red River Valley of Clark (1937, 1954) and continued pedogenic modification of the Chamberlain Pass Formation to form the Interior Paleosol Series (IPS) of Retallack (1983), and D, backfilling of the ancient Red River Valley to form the three members of the Chadron Formation. Modified from Evans and Terry (1994).

Channel morphologies within the Crazy Johnson Member are broader and thinner compared to those in the Ahearn Member (Fig. 3E). Channels of the Crazy Johnson Member are also multistoried and contain a variety of sedimentary structures, including fining upwards sequences, trough crossbedding with rib and furrow structures on upper bedding surfaces, planar bedding, lateral accretion surfaces, and current lineations. Channel sandstones within the Crazy Johnson Member are commonly bioturbated (Fig. 11A).

The overbank mudstone facies is restricted to the Crazy Johnson and Peanut Peak members (Fig. 8). This facies is represented by smectite-rich, bluish-green and gray claystones and mudstones that weather into popcorn-textured surfaces. The channel sandstones within the Crazy Johnson Member shield the overbank facies from erosion. The Peanut Peak Member lacks sandstones, which allows the overbank facies to erode into hummocky, haystack-like hills and slopes (Figs. 3A-E). Although no paleosol profiles were measured during this project, paleosol are indicated by abundant root traces (Fig. 11B), silicified wood (Figs. 11C-E), micromorphological pedogenic features, and structures interpreted as subterranean insect pupae cells (Fig. 11F). Lacustrine deposits comprise a small percentage of the Chadron Formation, and are readily identifiable as thin limestone units within the Crazy Johnson and Peanut Peak members (Fig. 8).

In general, the depositional environment of the Chadron Formation can be characterized as an aggrading fluvial system that formed in response to local changes in base level (Fig. 12). Channel morphologies changed from confined, lenticular deposits in the floor of the paleovalley to broad, thin deposits of shallow river systems with increasingly wider floodplains as the paleovalley filled. As aggradation proceeded, the sediment accommodation space (the Red River Valley) was eventually filled (Fig. 4). Evans and Terry (1994) presented a model of deposition for the Chamberlain Pass and Chadron Formations as it related to several episodes of relative base level change east of the Black Hills during the Eocene (Fig. 12). This is summarized as follows.

The retreat of the Cretaceous Interior Seaway, the subsequent subaerial exposure of the Pierre Shale, and the formation of the Yellow Mounds Paleosol Series was the result of a change in base level across the northern Great Plains. The basal strata of the White River Group also record significant changes in base level east of the Black Hills during the Paleogene, including: 1) base level rise and deposition of the Chamberlain Pass Formation, 2) base level fall and subsequent cutting of the Red River Valley, 3) increased pedogenic modification of the Chamberlain Pass Formation to form the Interior Paleosol Series, and pedogenic destruction of sedimentary structures and primary mineralogy within the channel sandstone facies, and 4) base level rise and subsequent backfilling, and eventual overtopping, of the Red River Valley to form the Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation. The change in base level during the retreat of the Cretaceous Interior Seaway was eustatic, whereas subsequent changes were likely influenced by local subsidence in a fault-bounded basin (Fig. 1), a response to tectonic uplift of the Black Hills and response to eustacy along with increased input of volcanic ash and/or paleoclimatic change.

RESEARCH WITHIN THE SOUTH UNIT

Research within the South Unit of Badlands National Park is ongoing. New fossil discoveries and geologic interpretations are continuously forcing a reevaluation of our understanding of these important deposits (Terry et al., in press). Therefore, it is critical that the fossil and geologic resources of the South Unit be carefully managed. This preliminary survey forms the groundwork for developing a detailed program to inventory and monitor fossil resources. With the addition of global positioning satellite technology (GPS) and geographic information systems (GIS) to fossil resource studies, the exact locations and spatial relationships of fossil occurrences can be documented and interpreted with respect to individual rock units and ancient depositional environments (e.g. Mead, 1995; Terry, 1996; Kruse, 1997). The implementation of a detailed annual fossil resource inventories using GPS and GIS will have a profound effect on methods of resource management and paleontological studies. Detailed data bases will allow resource management specialists to help protect fossil resources and to predict areas that potentially might yield large fossil concentrations. Scientists interested in studying fossil distributions can add to the database by reporting new fossil finds, and also by using the data base in their research. The implementation of GPS and GIS will also provide a means to document the theft of vertebrate fossils, thus allowing resource management specialists to target sensitive areas for increased protection.

SUMMARY

The Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation were mapped throughout the Big Corral Draw area in the South Unit of Badlands National Park. The Peanut Peak Member has regional extent, but the Ahearn and Crazy Johnson members are confined to the Red River Valley. The Crazy Johnson member is the most fossiliferous, containing 77% of all sensitive sites. Sensitive sites range from isolated bones to extensive bone beds and "graveyards" of brontothere remains. Other sensitive sites contain stromatolites and oncolites, pelecypods, silicified wood, and insect pupae traces. The largest concentration of fossil sites was 12 sites/square mile. No evidence of fossil theft was found within the study area.

Exposures in the Big Badlands, particularly the South Unit area, are considered standards for classifying strata of the White River Group across the northern Great Plains. In addition, it is also a historically important area that represents the development of the science of vertebrate paleontology in North America. Vertebrate fossils from the Big Badlands region were some of the first to be discovered and described during initial scientific explorations of the western United States. Because of its scientific importance, the South Unit of Badlands National Park is deserving of increased protection and resource management. This preliminary survey forms a framework for development of a GPS/GIS program to inventory and monitor fossil resources, locate areas of illegal fossil collection, and to gather geologic and paleontological data that will be of great use to later researchers. Annual inventories may eventually determine the relationship of rock units and ancient depositional environments to fossil distributions, and also provide a powerful tool for predicting fossil-rich areas. This will allow resource specialists to better manage the geologic and paleontological resources of Badlands National Park.

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CONSERVATION

Understanding Cyanoacrylate Adhesives and Consolidants and Their Use in Vertebrate Paleontology

Ann S. Elder, Cathy Wenz, and Scott K. Madsen

UNDERSTANDING CYANOACRYLATE ADHESIVES AND CONSOLIDANTS AND THEIR USE IN VERTEBRATE PALEONTOLOGY

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ABSTRACT--Under ideal conditions, vertebrate fossils should be conserved without applying chemicals to the specimens. If this is not possible, as is often the case, and scientific information will be lost without the use of chemicals, then educated decisions must be made. Familiarity with the uses and properties of a wide variety of adhesives and consolidants will improve the decision making process.

Cyanoacrylates (known generically as superglues) are water-thin, organic liquids. Developed for other industries, they were first used to conserve vertebrate fossils in the 1980s. Interest in these easy-to-use, quick-to-cure adhesives has increased. Today they are routinely referenced in fossil preparation literature.

The chemistry and properties of various viscosities of cyanoacrylates are discussed, as well as effective usage. Both pure ethyl cyanoacrylate and ethyl cyanoacrylate with poly (methyl methacrylate) harden by means of anionic polymerization that is initiated by the presence of a weak base. Long chain-like molecules form until all of the material is hardened or an acid terminates the process. Adhesive bonds of cyanoacrylate can be broken (reversed) with overnight exposure to one of four solvents. In general, thin, pure ethyl cyanoacrylates are best used as consolidants. Pure ethyl cyanoacrylates penetrate deeply into porous bone and have high tensile strength. Though brittleness increases with time (suggesting poor aging properties), use as a consolidant minimizes these drawbacks. Thicker ethyl cyanoacrylates containing poly (methyl methacrylates) are best used as adhesives because of their strength, improved aging properties, and ability to more evenly coat bond lines.

HISTORY

As with many compounds used in the conservation of vertebrate fossils, cyanoacrylates were developed for use in other industries. The earliest patents on cyanoacrylates were issued in 1949 to Alan Ardis and assigned to the B.F. Goodrich Company. His patents refer to the use of cyanoacrylates for the production of "hard, clear, glass-like resins," which were obtained by heating the compound (Wells, 1981). Throughout the 1950s, 1960s and 1970s, a number of other patents were issued to the Research Laboratories of Eastman Kodak, and later to Johnson and Johnson and Japanese entrepreneurs as the adhesive qualities of cyanoacrylates were refined to produce a general-purpose glue. Popular for its short cure time, it was most often used for bonding small parts that were hard to clamp. Other uses were found in the medical field with much research being conducted on the repair of soft tissues using cyanoacrylates (Wells, 1981). It was not until the 1980s that references could be found relating to the use of cyanoacrylates in fossil conservation (Howie, 1984; Horie, 1987). These early accounts record a growing interest in cyanoacrylates for fossil preparation because of their ease of use and quick cure time. The disadvantages of these products were also recognized early on with concern expressed regarding the difficulty of removing the hardened compound and uncertain aging characteristics.

By the 1990s, the mention of cyanoacrylates began appearing regularly in publications dealing with fossil preparation (Amaral, 1994; Shelton and Chaney, 1994; Howie, 1995; Lindsay, 1995; Shelton and Johnson, 1995; Madsen, 1996; Elder et al., 1997). Today, cyanoacrylates are generally recognized as strong, easy to use, fast curing adhesives with questionable reversibility and uncertain aging characteristics. Lack of impartial physical testing by conservation agencies such as the Canadian Conservation Institute and the Getty Conservation Institute makes it difficult to describe cyanoacrylates in more definitive terms. This lack of impartial data is widely recognized and has split the paleontological community into those who believe that they should not be used until testing is done, and those who believe that the benefits of their use outweigh the unknowns.

CHEMISTRY

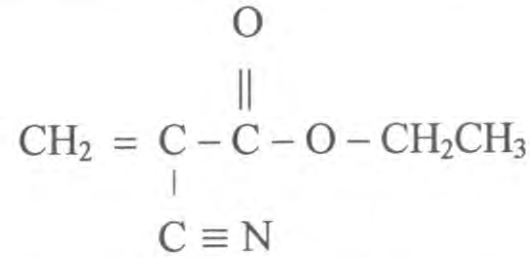
Though few of us have an in-depth understanding of chemistry, a rudimentary understanding is necessary to make informed decisions about the numerous preservatives available today. Therefore, a brief digression into organic chemistry is appropriate.

Cyanoacrylates are water-thin, organic liquids. Those available on the market today are usually ethyl cyanoacrylates. Their chemical structure can be seen in Fig 1. Ethyl cyanoacrylates are highly reactive and harden (polymerize) quickly by means of anionic polymerization at room temperature in the presence of a weak base (Coover et al., 1990). Even the base found in moisture (hydroxyl group) is sufficient to initiate the reaction. The entire polymerization reaction proceeds in three steps forming a long, chain-like molecule. Polymerization continues until the reaction is terminated by an acid (Coover et al., 1990) (Fig 2). Stronger bases, as found in prepared activators or accelerators, will make the reaction proceed even more quickly. Because polymerization begins at the point where the liquid contacts a weak base and proceeds back towards the center of the adhesive layer, hardening is not dependent on evaporation as with solvent based adhesives (such as Butvar B-76). Therefore, cyanoacrylates will harden completely even if the glue on the surface of a treated bone polymerizes before the glue deep within the substrate.

The presence of acids on the substrate will inhibit or retard the polymerization process and therefore may require the use of an accelerator. Likewise, acids are used to keep cyanoacrylate liquids from hardening during storage. The type and amount of acid will affect the shelf life (increase it), but at the same time will retard the cure rate when the product is used. The amount of acid has no effect on the resulting strength of the polymer.

Cyanoacrylates come in a variety of viscosities. They are made thicker by dissolving an additional polymer in the liquid ethyl cyanoacrylate. In most cases the polymer is poly (methyl methacrylate). Cyanoacrylates that have the viscosity of petroleum jelly usually contain hydrophobic silicas as well as poly (methyl methacrylates).

To make educated decisions concerning when and where to use cyanoacrylates in fossil conservation, one must know the chemical composition of the specific brand of adhesive at hand. Manufacturers of



$$\mathrm{CH_2 = \underset{\displaystyle C \equiv N}{\underset{|}{C}} - \overset{\displaystyle O}{\overset{\|}{C}} - O - CH_2CH_3}$$

FIGURE 1 - Chemical structure of ethyl cyanoacrylate. C (carbon), H (hydrogen), O (oxygen), N (nitrogen), - (single bond), = (double bond), ≡ (triple bond), 2 (two atoms), 3 (three atoms).

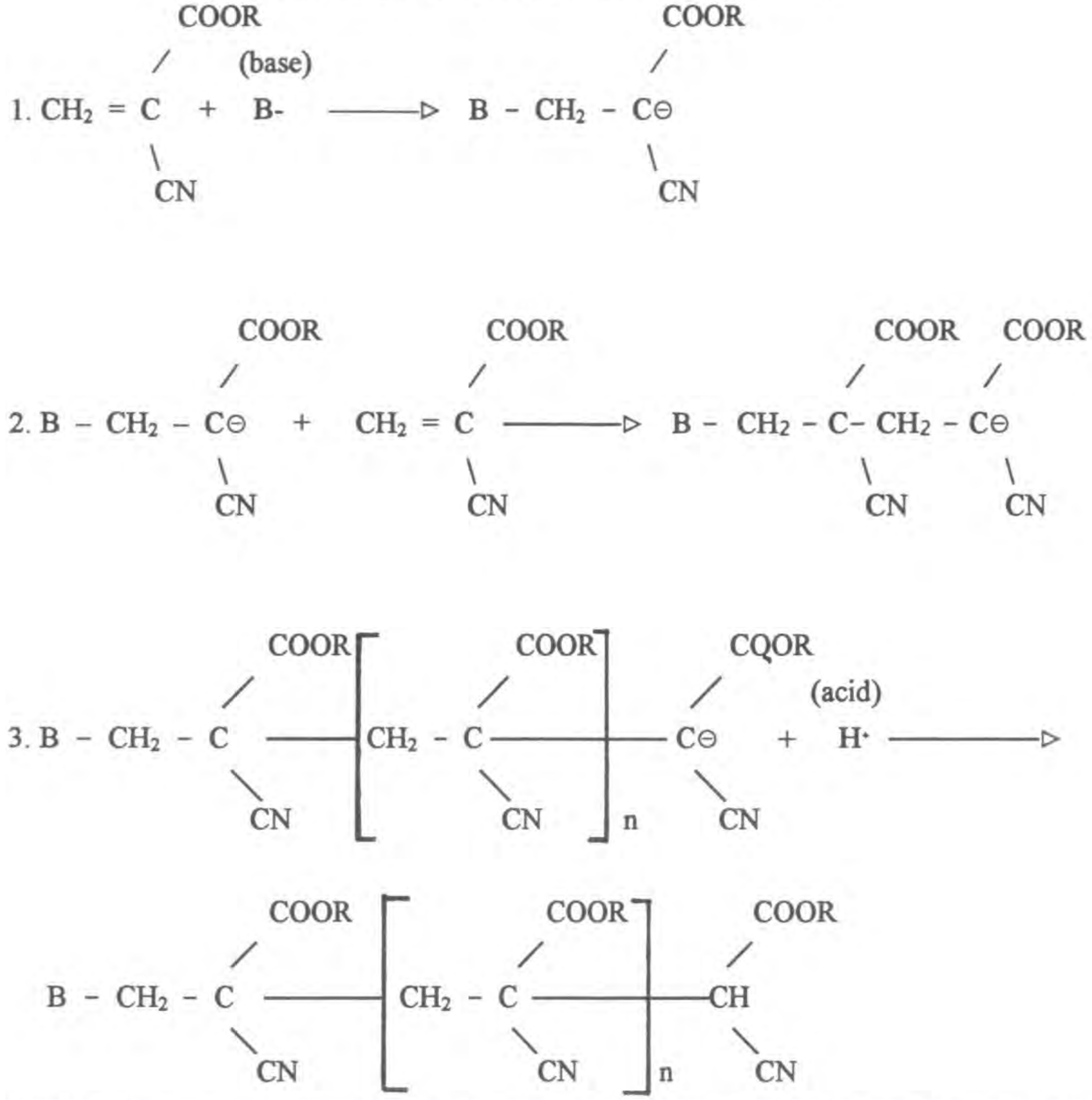


FIGURE 2 - Three step curing mechanism (anionic polymerization) for cyanoacrylates. A weak base initiates polymerization (step 1). Polymerization proceeds as in step 2 until a long, chain-like molecule, called a polymer, is formed. The reaction proceeds until all liquid has hardened, or until an acid (step 3) terminates it. C (carbon), H (hydrogen), O (oxygen), N (nitrogen), B (base), R (variable group), n (large number of repeating units).

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cyanoacrylates (and other adhesives) are required to provide Material Safety Data Sheets (MSDS) upon request. Though these sheets will not describe special proprietary formulas, they will state the percentage of basic ingredients such as ethyl cyanoacrylate and poly (methyl methacrylate). These sheets also provide a variety of health and safety information and are essential for any lab.

PROPERTIES

The properties of thin, ethyl cyanoacrylates are much different from those of ethyl cyanoacrylates thickened with some percentage of poly (methyl methacrylate). Therefore, the two groups will be discussed separately.

Pure ethyl cyanoacrylate penetrates deeply into porous substrates. It does not deeply penetrate non-porous substrates. When used to glue two, non-porous pieces together, the bond has very high tensile strength (reaching full strength after 8-24 hours) but is brittle and has low impact and peel strength (Coover et al., 1990). In other words, the strength of the bond varies drastically depending on the direction in which stress is applied. The brittleness continues to increase with time, suggesting that long-term durability is not good. Heat increases the brittleness. Temperature and humidity cycling resistance is poor as well (Coover et al., 1990).

Thicker cyanoacrylates, which are a mixture of ethyl cyanoacrylate and poly (methyl methacrylate), have additional useful properties. Cyanoacrylates composed of as little as 5-10% poly (methyl methacrylate) are reported to have twice the impact strength of thin, pure ethyl cyanoacrylates, as well as increased peel strength (Coover et al., 1990). This decrease in brittleness suggests that the thicker cyanoacrylates will not degrade with time as readily as thin, pure ethyl cyanoacrylates, though analytical testing has not been done on either group of compounds to quantify aging properties.

Bonds of both the thin and thick cyanoacrylates can be weakened or dissolved slowly with various solvents. The adhesive bonds will be destroyed overnight by immersion in either dimethylformamide, nitromethane, dimethyl sulfoxide, or aceto-nitrile (Pollar, 1981). Off-the-shelf cyanoacrylate solvents generally contain one of these solvents. Adhesive bonds will also be destroyed with extended immersion in methanol, acetone, or aqueous acids or alkalis (Pollar, 1981).

EFFECTIVE USAGE

No discussion on the usage of a specific adhesive or consolidant in fossil conservation is appropriate without first addressing their general use. In striving for the ideal situation, it is best to conserve vertebrate fossils without applying any chemicals. This "dry preparation" decreases the possibility that future data will not be able to be extracted from a particular specimen because of chemical contamination. Though some would argue that many solvent based adhesives and consolidants are reversible, it is the assertion of the authors that applying any chemical affects the fossil on a molecular level. Adhesive bonds can be broken, but no compound is completely reversible on the molecular level. As one colleague so aptly put it, reversing a glue applied to a bone is like trying to remove water from a soggy sponge without being able to squeeze it.

If the ideal situation cannot be obtained and scientific information will be lost without the use of chemicals, then, well-informed decisions must be made. Every conservation situation is unique. Sweeping generalizations (common in fossil preparation), such as "no glue should be used which is stronger than the specimen" or "all glues should be reversible" must be abandoned in favor of closely evaluating each individual situation with an open mind. If an adhesive is called for, those who know how to use the greatest variety of adhesives have the most options and will therefore make better decisions.

Pure ethyl cyanoacrylates work best as consolidants. They penetrate well into porous substrates, cure completely even if the surface cures first, and are very strong. Deepest penetration occurs when the cyanoacrylate is left to cure as slowly as possible, without the aid of an accelerator. When used as a consolidant rather than as an adhesive, brittleness and resistance to mechanical force may become a relatively unimportant consideration. If the fossil surface is not porous, thin cyanoacrylates form a sheet over the specimen that can usually be pealed off after hardening. This type of usage has field applications, though again, every situation is unique. As with any chemical, one should test it on an insignificant fossil fragment to be sure that the desired results are achieved.

Thicker cyanoacrylates work best as adhesives because they are less brittle, have better long-term aging characteristics, and more evenly coat bond lines than do thin, pure ethyl cyanoacrylates. Cyanoacrylates in general form stronger bonds when bonding non-porous surfaces. Because bone surfaces are usually porous, to achieve a strong bond, porous surfaces need to be changed to non-porous ones. This can be accomplished by first using a thin cyanoacrylate as a consolidant on the two broken surfaces, letting the surfaces dry, and then using a thicker cyanoacrylate to glue the two surfaces. Choosing the correct thickness of cyanoacrylate is very important and is dependent on the size of the pieces being glued and how tightly the two surfaces fit together. Because as little as 5-10% poly (methyl methacrylate) increases aging properties and decreases brittleness, it is not always necessary to use the thickest possible adhesive. Consult the MSDS for specific percentages.

Accelerators or activators should be used sparingly. They should be used to initiate the hardening process for a specific purpose (to stop penetration at a particular point for instance), not as a replacement for patience. Accelerators can cause staining when they come in contact with certain iron-rich minerals and are highly reactive when exposed to wide temperature fluctuations as can occur in fieldwork.

Cyanoacrylate bonds can be reversed (broken) with prolonged exposure to dimethylformamide, nitro-methane, dimethyl sulfoxide, and aceto-nitrile (Pollar, 1981). These compounds are marketed as cyanoacrylate solvents under a variety of names, depending on the company. As is the case with solvent-based glues, successfully reversing a bond is heavily dependent on being able to get the solvent to the adhesive. All too frequently in fossil conservation solvents can only be applied to the surface of the adhesive. It then becomes a slow (and often repetitive) process of allowing the solvent to turn the surface adhesive gummy, removing the gummy adhesive mechanically, and then applying more solvent. Preliminary tests comparing cyanoacrylates to solvent-based Butvar B-76 suggests that both are equally "reversible" under these conditions.

Because cyanoacrylates begin to harden in the presence of a weak base, such as is found in moisture, they can not be used effectively in damp areas. Likewise, once a bottle of liquid cyanoacrylate is open, it should not be exposed to wide temperature fluctuations, which can cause condensation to collect in the container. Unopened cyanoacrylate should be stored at freezing temperatures to prolong shelf life, though liquid cyanoacrylate should be allowed to warm to room temperature before using.

CONCLUSIONS

Vertebrate fossils are best conserved without the application of chemicals. If this is not possible and an adhesive or consolidant is necessary, then educated, well-informed decisions must be made. Gone are the days when decisions could be based exclusively on what had been used before. Today, a basic understanding of the chemistry and properties of adhesives is required to make good decisions.

Cyanoacrylates are one of many adhesives available to the conservation community. Like all glues, cyanoacrylates have their advantages and disadvantages. Only by understanding their chemistry and properties can they be properly used.

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