Sedimentology and taphonomy of a dinosaur bonebed from the Upper Cretaceous (Campanian) Judith River Formation of north central Montana

by Jeffrey William LaRock

A thesis submitted in partial fulfillment Of the requirements for the degree of Master of Science In Earth Sciences
Montana State University

Abstract:

Excavations of the JDM Quarry north of Malta, Montana, have revealed a multi-individual pauspecific dinosaur bonebed. Over 1300 specimens have been removed from the quarry with over 90% of the material assignable to the Hadrosaur genus Brachylophosaurus. At least five individuals are present from two different age classes (adult and sub-adult). In addition to the vertebrate remains there is abundant plant material including a tree trunk which trends east-west. The bonebed lies within a sandstone body approximately 1.8 meters thick. The tan to brown sandstone is a friable, fine grained, quartz rich sandstone bounded above and below by gray mudstone. The sandstone body is dominated by trough cross-bedded sandstone in the lower 1.5 meter and ripple cross-lamination in the upper 0.3 meters suggesting lower flow regime conditions. The stratigraphic position of the bonebed suggests a nearshore depositional environment.

The bones are distributed within the lower 1.4 meters of the sandstone. Some long bones show an average northwest-southeast trend generally paralleling the tree. The highest concentrations of bones are found directly in contact or in close proximity to large wood fragments. Articulation/association of the brachylophsaur material is generally high and none of Voorhies Groups (1969) are under or over represented. Most of the bones experienced little to no weathering (stage 0-1, Behrensmeyer, 1978). Compaction and breakage varies throughout the quarry but is more pronounced on the north side of the tree where the density of bones is at its peak. Five specimens show evidence of predator or scavenger activity (bite marks).

Taphonomic and sedimentological investigation suggests the brachylophosaurs were transported in a shallow (< 1.8m deep), low-gradient, distributary fluvial channel. The close association of the bones with the plant material and their near parallel alignment suggests the fallen tree played a role in the accumulation of the brachylophosaur material. The minimal winnowing, uniform weathering, lack of abrasion and high degree of articulation/association suggests the brachylophosaurs arrived at the site as bloated carcasses. Subsequent to the carcasses interment they were scavenged, disarticulated and subaerialy exposed.

SEDIMENTOLOGY AND TAPHONOMY OF A DINOSAUR BONEBED FROM THE UPPER CRETACEOUS (CAMPANIAN) JUDITH RIVER FORMATION OF NORTH CENTRAL MONTANA

by

Jeffrey William LaRock

A thesis submitted in partial fulfillment
Of the requirements for the degree

of

Master of Science

In

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

December 2000

APPROVAL

of a thesis submitted by

Jeffrey William LaRock

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

James G. Schmitt James Schmitt 11-30-00
(Signature) Date

Approved for the Department of Earth Sciences

James G. Schmitt James Schmitt 11-30-00
(Signature) Date

Approved for the College of Graduate Studies

Bruce McLeod Bruce L. McLeod 12-1-00
(Signature) Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature ______________________

Date 11-30-2000

Acknowledgements

I would like to thank Jim Schmitt for being a great advisor, friend, teacher, sports enthusiast, and bowler. I have learned more in the time I have spent as his student then at any other point in my education. I would like to thank Jack Horner for providing me with the opportunity to work on a great project and providing intellectual and financial support over the last three years. I would also like to thank Dave (Potato) Varricchio for showing me around collections and giving me a feel for taphonomy as well as the great conversations. This research may never have gotten off the ground without the financial assistance from the Department of Earth Sciences, Museum of the Rockies, Jurassic Fund and Dianamation International. I couldn't have gotten this far without the crew from Malta. I would like to especially thank Chris for teaching me the ins and outs of caps, Tobin for his fear of breaking bones, Joe Cooley for his joy in breaking bones, and Nels for being Nels. Numerous graduate students have offered advise, sympathy and beer along the way including Stewy "I'm sorry" Dixon, Mike " Do you wanna Bond" O'Connell, Garret "bacon man" Slaugenhop, Ben " Lets Kill 'em" Shoup, Chuck "stink bomb" Lindsay, Al, "camera man" Prieto-Marchez, Kerri Fleming, Jim Rassmussen, Cal Ruleman, Adam Morrill, Dave Spector, and Jamie Clark. The rest of the paleo crew also deserves a shout out including Bob Harman, Carrie, Ellen, Joe B., Cynthia, and all those who prepared bones from Malta. Special thanks also to Frankie Jackson and Rebbeca Hanna for sharing there knowledge of dinosaurs and taphonomy. Thanks to Jen for helping me through all of this and sticking through it with me. Most importantly I would like to thank my Mom and Dad and my Pop and Gram for all the support they have given me over the years. Without them I never would have made it this far.

TABLE OF CONTENTS

TABLE OF CONTENETS- CONTINUED

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES- CONTINUED

Figure Page

LIST OF PLATES

ABSTRACT

Excavations of the JDM Quarry north of Malta, Montana, have revealed a multi-individual pauspecific dinosaur bonebed. Over 1300 specimens have been removed from the quarry with over 90% of the material assignable to the Hadrosaur genus *Brachylophosaurus*. At least five individuals are present from two different age classes (adult and sub-adult). In addition to the vertebrate remains there is abundant plant material including a tree trunk which trends east-west. The bonebed lies within a sandstone body approximately 1.8 meters thick. The tan to brown sandstone is a friable, fine grained, quartz rich sandstone bounded above and below by gray mudstone. The sandstone body is dominated by trough cross-bedded sandstone in the lower 1.5 meter and ripple cross-lamination in the upper 0.3 meters suggesting lower flow regime conditions. The stratigraphic position of the bonebed suggests a nearshore depositional environment.

The bones are distributed within the lower 1.4 meters of the sandstone. Some long bones show an average northwest-southeast trend generally paralleling the tree. The highest concentrations of bones are found directly in contact or in close proximity to large wood fragments. Articulation/association of the brachylophsaur material is generally high and none of Voorhies Groups (1969) are under or over represented. Most of the bones experienced little to no weathering (stage 0-1, Behrensmeyer, 1978). Compaction and breakage varies throughout the quarry but is more pronounced on the north side of the tree where the density of bones is at its peak. Five specimens show evidence of predator or scavenger activity (bite marks).

Taphonomic and sedimentological investigation suggests the brachylophosaurs were transported in a shallow (< 1.8m deep), low-gradient, distributary fluvial channel. The close association of the bones with the plant material and their near parallel alignment suggests the fallen tree played a role in the accumulation of the brachylophosaur material. The minimal winnowing, uniform weathering, lack of abrasion and high degree of articulation/association suggests the brachylophosaurs arrived at the site as bloated carcasses. Subsequent to the carcasses interment they were scavenged, disarticulated and subaerialy exposed.

CHAPTER 1

INTRODUCTION

Vertebrate bones can accumulate by several mechanisms including floods (Wood et al., 1988), drought (Rogers, 1990; Schwartz, 1994; Fiorillo et al., 2000), debris flows (Schmitt et al., 1998), reworking of floodplain deposits (Behrensmeyer, 1982), and predator accumulations (Brain, 1981; Haynes, 1988). Dinosaur bonebeds have often been used to infer such group behavior as herding (Horner, 1982; 1984b; 2000; Rogers, 1990; Fiorillo, 1991b; Varricchio and Horner, 1993; Varricchio, 1995) and pack hunting (Ostrom, 1969; Maxwell and Ostrom, 1995). However, understanding how a bone accumulation is formed is essential before making paleoecological or paleo-behavioral interpretations of extinct organisms(Behrensmeyer and Kidwell, 1985). The taphonomic context of the bonebed assemblages is crucial for determining whether the remains accumulated over days, centuries or longer.

The taphonomy of a bonebed is determined by interpreting the bone features and characterization of the depositional environment. The depositional environment that a bonebed accumulates in can only be determined by detailed lithofacies analysis of the bone-bearing unit and surrounding strata. Characterizing the depositional setting of a bonebed can determine what processes led to the genesis of the assemblage and approximate the time it took to accumulate. Only by careful investigation of the assemblage while still *in situ* can the processes of deposition and implications for our understanding of paleo-ecosystems be fully determined.

Collection of geologic information in many taphonomic studies is often limited to the description and interpretation of only the fossil-bearing unit. While lithofacies analysis has been widely practiced by sedimentologists for over twenty years, site specific taphonomic studies rarely include lithofacies data. Deciphering of the bonebed depositional environment can only be made after investigation of the fossiliferous interval and the related lateral and vertical strata.

A recently discovered bonebed in the Upper Cretaceous (Campanian) Judith River Formation of north central Montana has yielded over 1,300 bones. The Malta bonebed represents one of the most prolific deposits of dinosaur bones in the Judith River Formation south of the Canadian Border. This paucispecific bonebed is dominated by the hadrosaur genus *Brachylophosaurus sp.* and the bones are exquisitely preserved.

In addition to the vertebrate remains, abundant plant material including a large conifer trunk with branches is also present. Bones are in direct contact with and within close proximity to the tree. The bones and plant fossils are entombed in a medium grained, well sorted, friable sandstone.

The presence of abundant plant and animal material preserved together leads to an interesting series of questions concerning the influences of woody debris on the genesis of the assemblage including: How much influence did the woody debris have on the accumulation of the bones? How long could the woody debris have acted as an accumulation mechanism for vertebrate remains? How important a role has woody debris played in the accumulation of vertebrate bonebeds in the geologic past?

The bonebed lies in close stratigraphic proximity to the underlying marine Claggett Shale suggesting that these dinosaurs might have lived near the Western Interior Seaway. Most of the dinosaur faunas from Montana are found in strata deposited farther inland. Because this portion of the Judith River Formation has not been extensively studied, it can provide us with new information concerning the Late Cretaceous ecosystems and depositional systems of the distal alluvial plain.

While the Judith River Formation has long been renowned for its dinosaur fossils it is only in the last three decades that taphonomic studies of these deposits have been conducted (Dodson, 1971; Beland and Russell, 1978; Beland and Russell, 1979; Currie and Dodson, 1984; Wood et al., 1988; Brinkman, 1990; Eberth, 1990; Fiorillo, 1991b; Blob and Fiorillo, 1996; Brinkman et al., 1998;). Dodson (1971) conducted an exhaustive formational taphonomic study of the Judith River Formation within Dinosaur Provincial Park (Canada). Similarly Beland and Russell (1978,1979), Wood et al. (1988), and Brinkman et al. (1998) conducted large scale studies within Dinosaur Provincial Park looking at formational trends in taphonomy. Brinkman (1990), Eberth (1990) and Blob and Fiorillo (1996) focused on microvertebrate sites and the taphonomic factors involved in their genesis. Only Currie and Dodson (1984) and Fiorillo (1991b) focused on site-specific studies. Both of these studies have a paucity of geologic data.

The purpose of this study is to characterize the taphonomy and determine the depositional environment of the Malta bonebed to better understand its genesis. Specific goals of this research include determining: (1) the depositional environment of the bonebed itself and the associated strata lateral to and vertically above and below the bonebed using detailed lithofacies analysis, (2) stratigraphic relationship of the bonebed to the underlying coastal and marine formations, (3) degree of bone modification, (4) the means by which the bones accumulated, (5) time-averaging represented within the assemblage.

Location and Geologic Setting

The Malta bonebed is located in Phillips County, approximately 17 miles north of Malta, Montana and 54 miles south of the Canadian Border (Figure 1). The Judith River Formation there is exposed in badlands-like outcrops atop Fanny Hill between the Cottonwood and Little Cottonwood Creek drainages (Figure 2). The quarry is located on Bureau of Land Management land.

The bonebed is located stratigraphically in the lower portion of the Upper Cretaceous (Campanian) Judith River Formation (Figure 3). The Judith River Formation represents the distal portion of an eastward thinning clastic wedge deposited between the rising Cordilleran orogen to the west and Cretaceous Western Interior Seaway to the east (Rogers, 1995). Sediments deposited as the Judith River Formation were derived from erosion of the Cordilleran fold and thrust belt and Elkhorn Mountain Volcanic center to the west. The Judith River Formation is significant paleontologically for having been the location of the first formally described dinosaur material in North America (Leidy, 1856).

The Judith River Formation is a time-transgressive unit and correlative to the Two Medicine Formation in western Montana. It is bounded unconformably below by the marine Claggett Shale and above by the marine Bearpaw Shale in eastern and central

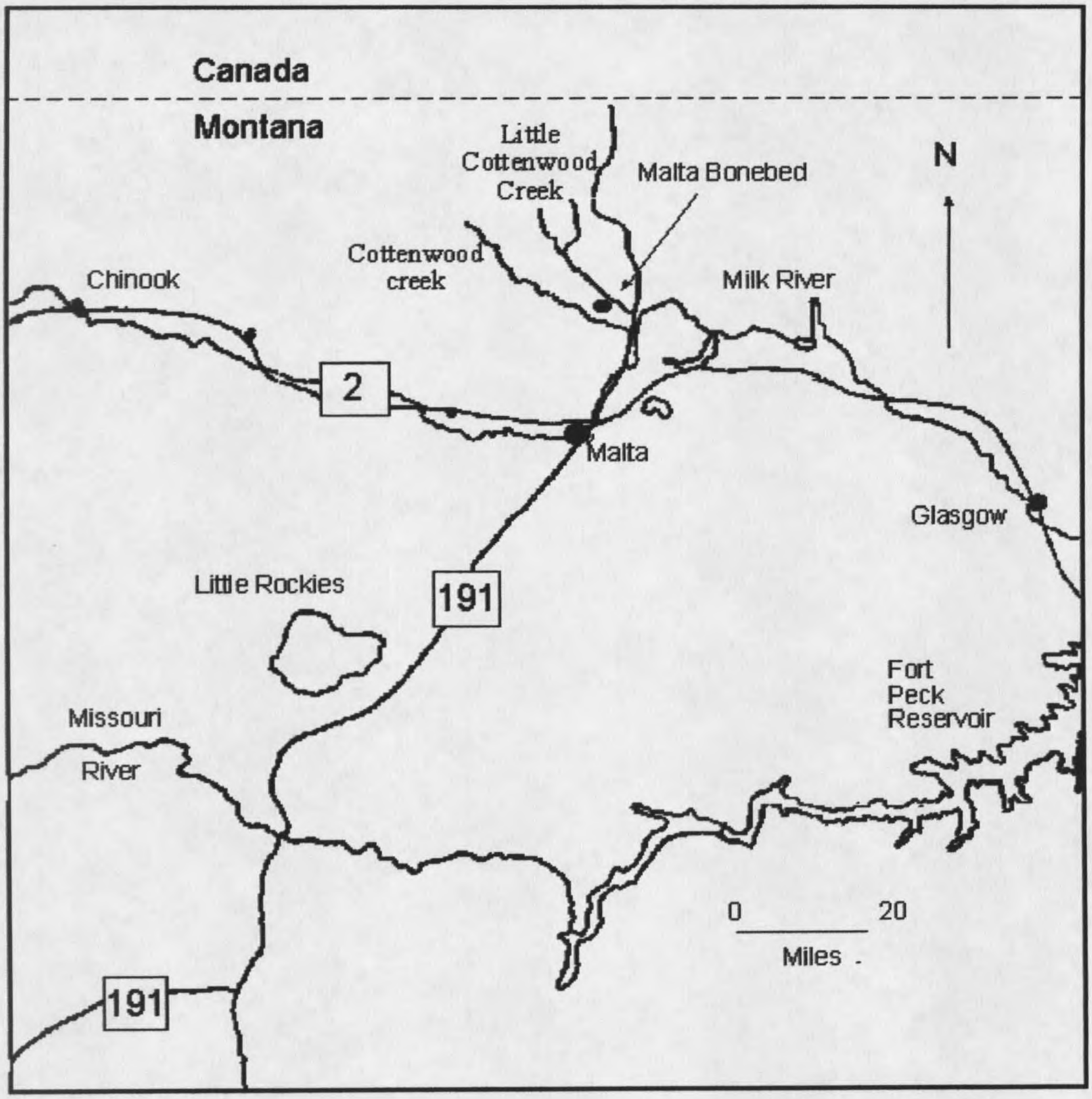


Figure 1. Location of the Malta bonebed in north central Montana.

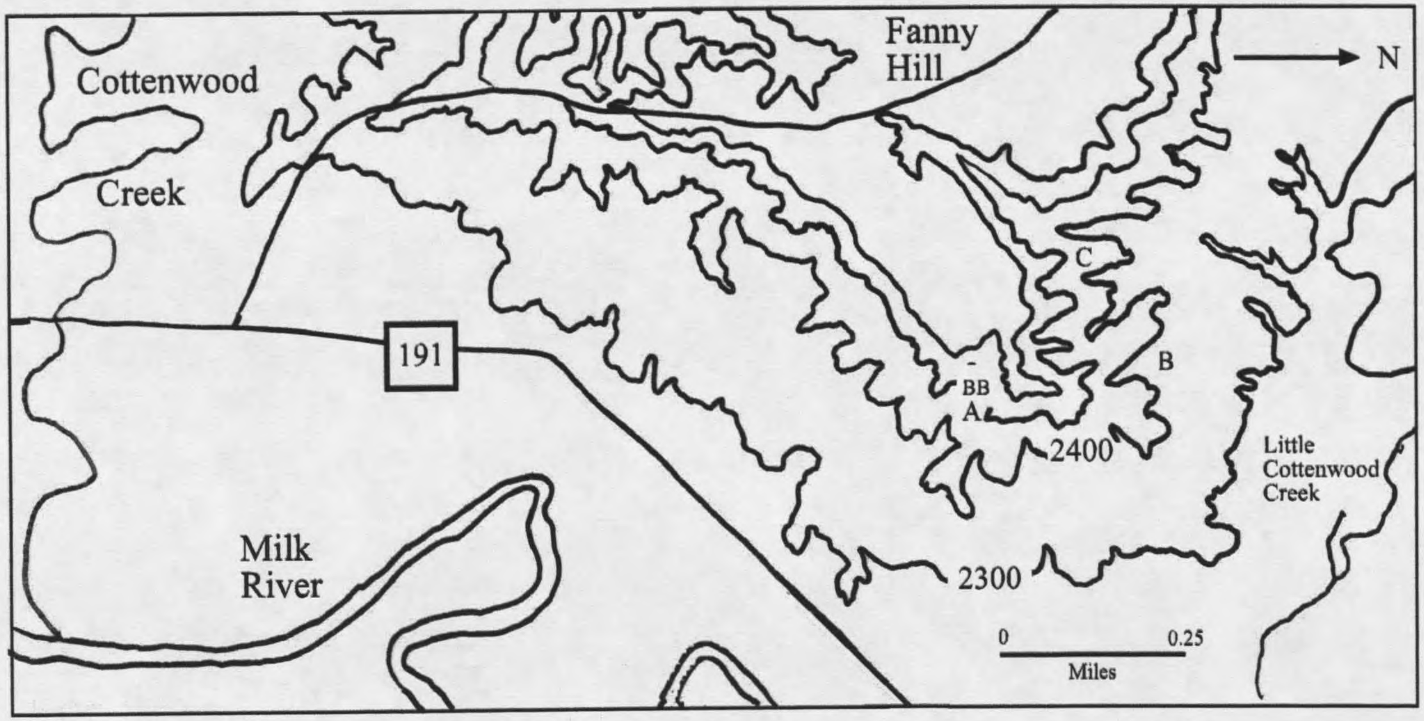


Figure 2. Detailed location map of the Malta bonebed (BB) and the locations of the meaured sections (A,B,C). Contour interval =100ft.

Montana (Fig. 3). The Judith River Formation of north central Montana is correlative to the Judith River Group comprising the Foremost, Oldman, Dinosaur Park Formations as well as the Belly River Group and the marine Pakowski Formation in Canada (Eberth, 1997).

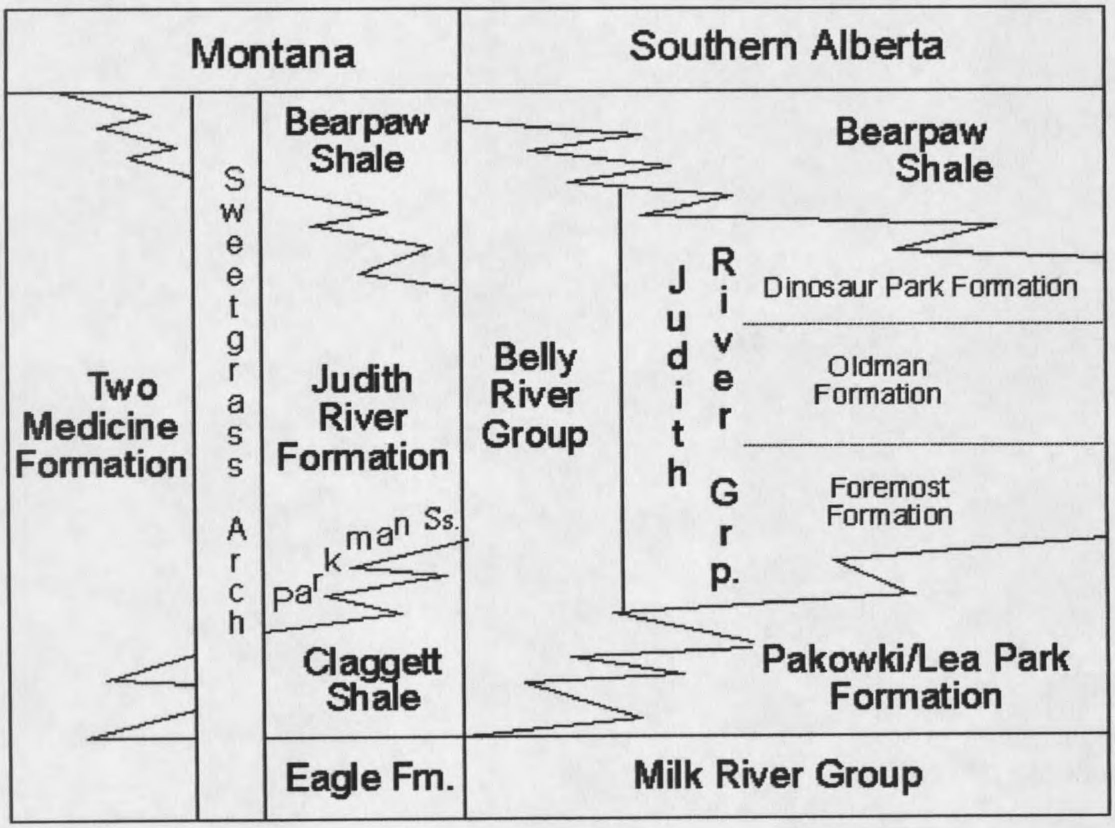


Figure 3. Stratigraphic correlation chart for the Judith River Formation and equivalent Age rocks from Montana and southern Alberta (modified from Eberth, 1997).

The Two Medicine and Judith River Formations were deposited during Campanian time during a major regressive-transgressive cycle of the Cretaceous Western Interior Seaway (Kauffman, 1977; Kauffman and Caldwell, 1993; Rogers, 1998). Erosion of the deposits of the middle part of the clastic wedge occurred due to the post-Cretaceous uplift of the Sweetgrass arch.

The Campanian coastal plain was characterized by fluvial, lacustrine, and deltaic deposition and subtropical to temperate climates (Horner, 1989). The rivers of the Judith River formation were generally deeper and wider than those of the Two Medicine Formation. Swamps and ponds were more abundant, perhaps because of the proximity to the seaway (Rogers, 1993).

Approximately 30m of the Judith River Formation are exposed in the vicinity of the Malta bonebed. It conformably overlies the Claggett Shale and is unconformably overlain by Pleistocene glacial till. In the field area the Judith River Formation consists of interbedded fine to medium grain sandstone and mudstone. Plant material is common throughout the Judith River Formation and consists of isolated wood fragments and interbedded sand and plant material layers. Vertebrate material is also common within the Judith River Formation and rare in the Claggett Shale. Museum of the Rockies (MOR) field work has uncovered an articulated adult *Brachylophosaurus* (Ancell et al., 1998) as well as the articulated hind quarters of a sub-adult *Brachylophosaurus*, and several isolated bones and smaller bone accumulations within both the Judith River Formation and Claggett Shale in the vicinity of the Malta bonebed.

Methods

Crews from MOR excavated the Malta bonebed in the summers of 1998 and 1999. During the summer of 1999 detailed taphonomic and sedimentologic studies were undertaken to accurately characterize the deposit. Bones where extracted from the sandstone matrix using ice picks and brushes and encased in plaster jackets to insure their safety. The sandstone matrix was screen washed only on the west side of the quarry only after small bones had been previously found there. After several meters where sifted through and no additional material was found sifting of the matrix was abandoned.

All bones where mapped in place to determine their spatial relationship to one another. Bones were mapped using a meter grid system that was further subdivided into ten centimeter intervals using a movable grid. Depth of each bone was measured from the top of the bonebed-bearing unit using a level and stadia rod. The orientation (trend and plunge) of long bones was measured in the field using a Brunton compass. Bone surfaces were inspected both in the field and laboratory after preparation for evidence of weathering, abrasion, crushing, and tooth marks as well as any other distinguishing marks. Weathering was assessed using Behrensmeyer's weathering stages (Behrensmeyer, 1978). The degree of winnowing within the assemblage was determined using Voorhies Groups (Voorhies, 1969). The minimum number of individuals was estimated using the MNI index (Badgley, 1986). Specimens are curated at the Museum of the Rockies under specimen number 1071, locality JR-224.

Initial excavation of the Malta bonebed in the summer of 1998 did not involve taphonomic data collection. Bones from the initial summer were not mapped on a meter grid system. A quarry map was made for the bones that were excavated but the error is expected to be higher for this data than for the data collected in 1999. Given this possible data bias the 1998 and 1999 spatial data were not combined onto one map. Orientation and depth of the elements were also not collected during the 1998 field season. Therefore sections referring to these data are exclusive to 1999. No separation of data was made for calculation of bone modification since this is not affected by the lack of field data. Articulation of some elements from the 1998 field season could be assessed by photographs taken during excavation and by mapping of the elements.

Stratigraphic sections were described in order to determine the spatial relation of the bonebed to the underlying Claggett Shale. Lithofacies analysis was used to determine the depositional environments of the bone bed and surrounding strata. Lithofacies present in the study area were defined on the basis of grain size, texture and types of sedimentary structures. Lithofacies terminology used was based on the work of Miall (1977) and modified slightly for the study area. Architectural element analysis was not possible due to the lack of exposure within the field area.

CHAPTER 2

LITHOFACIES

Within the study area the Judith River Formation is composed of two dominant lithologies: sandstone and mudstone. The most abundant lithofacies include massive sandstone (Sm), trough cross-bedded sandstone (St), ripple cross-laminated sandstone (Sr), and massive mudstone (Fm). Also present but rare are low angle trough cross-bedded sandstone (Sl), trough cross-bedded sandstone with organic laminae (Sto), horizontally bedded sandstone (Sh) hummocky cross-stratified sandstone (Shes), and mudstone with root traces (Fr). Detailed descriptions of these lithofacies are given in Table 1.

Sandstone Lithofacies

Trough Cross-Stratified Sandstone (Facies St)

Description. Trough cross-stratified sandstone(Figure 4a) is typically fine to medium grained and moderately to well sorted. Pebble sized intraformational rip-up clasts can occur near the base of sets. This facies occurs as both single sets (0.1-0.25m) and cosets (0.5-2.4m). Underlying contacts are typically abrupt. Overlying contacts can be abrupt or gradational. Trough cross-stratified sandstone (St) is typically overlain by ripple cross-laminated sandstone (Sr). It is also interbedded with massive sandstone (Sm), trough

Lithofacies		Description
St	Trough cross-stratified sandstone	Occurs as both sets (0.1-0.25m) and cosets (0.5-2.4m) contacts with both over and underlying beds are abrupt. Trough cross-bedded sets are interstratified with massive sandstone (Sm), low angle trough cross-bedded sandstone (Sl), trough cross-bedded sandstone with organic laminae (Sto), ripple cross-laminated sandstone (Sr), hummocky cross-stratified sandstone (shes) and massive mudstone (Fm).
Sto	Trough cross-bedded sandstone with organic Laminae	Occurs as sets between 0.2-0.5m thick. Contacts are gradational. This facies is interstratified with trough cross-stratified sandstone (St) and ripple cross-laminated sandstone (Sr).
Sr	Ripple cross-laminated sandstone	Occurs rarely as individual sets (0.03-0.15m) and more commonly as cosets (0.4-1.5m). Contacts with over and underlying sets can be gradational or abrupt. Ripple cross-laminated sandstone is interstratified with trough cross-bedded sandstone (St), massive sandstone (Sm), or massive mudstone (Fm).
Sm	Massively bedded sandstone	Massive ungraded beds of sandstone occur as beds between 1.0-1.7m thick. Contacts with over and under lying beds are abrupt. Massive sandstone can be interstratified with trough cross-bedded sandstone (St), ripple cross-laminated sandstone (Sr), hummocky cross-stratification (Shes) and massive mudstone (Fm).
Sl	Low-angle trough cross-bedded sandstone	Occurs mostly as solitary sets between 0.15 and 0.25m in thickness. Contacts with over and underlying beds are abrupt. Low-angle trough cross-bedded sandstone is interstratified with trough cross-bedded sandstone (St).
Sh	Horizontally bedded sandstone	Occurs as thin beds (0.1-0.5m) within the upper 2-4m of the Clagget Shale. Interstratified with massive mudstone (Fm) hummocky cross-stratified (Shes) and ripple cross-laminated sandstone (Sr).
Shes	Hummocky cross-stratified sandstone	Occurs interstratified with trough cross-bedded (St), horizontally stratified (Sh), and massive sandstone (Sm) and massive mudstone (Fm). Contacts are gradational. Sets are generally small (6-20cm) and occur only within the upper Clagget and lower Parkman.
Fm	Massive mudstone	Massive mudstone occur as beds 0.6-8m in thickness. Interstratified with ripple cross-laminated mudstone (Fr), mudstone with root traces (Fr), massive sandstone (Sm), ripple cross-laminated (Sr), trough cross-bedded (St) and hummocky cross-stratificatied sandstone (Shes).
Fr	Mudstone with root traces	Massive mudstone with abundant root traces. Interstratified within beds of massive mudstone (Fm), and ripple cross-laminated (Sr), and trough cross-bedded sandstone (St).

Table 1. Detailed description of lithofacies in the Clagget Shale, Parkman Sandstone and Judith River Formation in the study area of the Malta bonebed.

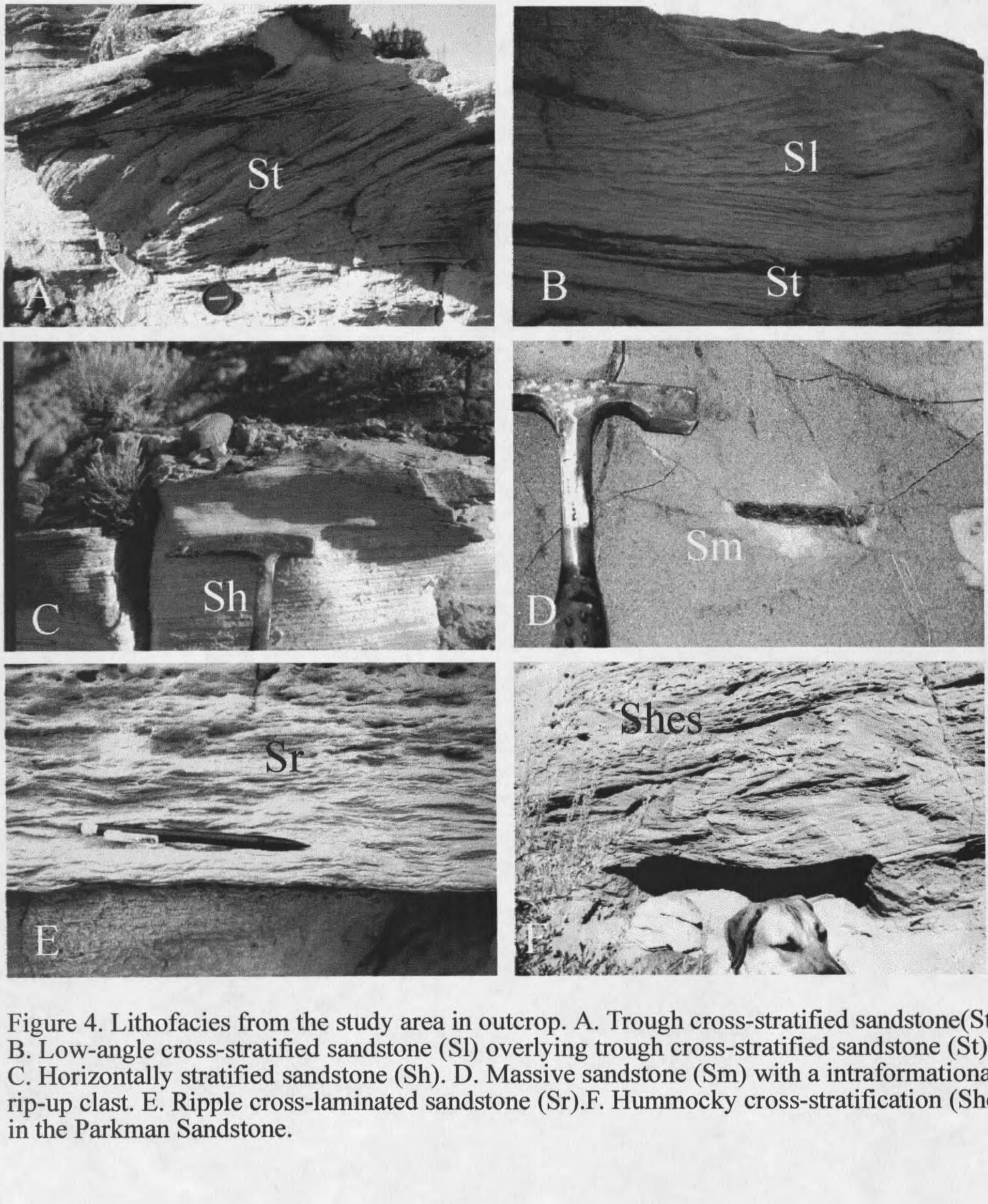


Figure 4. Lithofacies from the study area in outcrop. A. Trough cross-stratified sandstone(St). B. Low-angle cross-stratified sandstone (Sl) overlying trough cross-stratified sandstone (St). C. Horizontally stratified sandstone (Sh). D. Massive sandstone (Sm) with a intraformational rip-up clast. E. Ripple cross-laminated sandstone (Sr).F. Hummocky cross-stratification (Shes) in the Parkman Sandstone.

cross-stratified sandstone with organic laminae (Sto), massive mudstone (Fm) and rarely with hummocky cross-stratification (Shes) and Low-angle cross-stratification (Sl). A variation of this facies can include abundant interbedded plant debris (Sto). Trough cross-stratified sandstone with organic laminae (Sto) is exclusively interbedded with trough cross-stratified sandstone (St). Sets are 0.2-0.5m in thickness and contacts with other trough cross-stratified sandstone (St) are gradational.

Interpretation. Trough cross-stratified sandstone is interpreted to have formed by migration of subaqueous dunes, under lower flow regime conditions (Miall, 1977). The vertical transition from trough cross-stratified sandstone to ripple cross-stratified sandstone is interpreted to be the result of deposition through shallowing water and decelerating flow velocity. The organic laminae of facies Sto represent abundant plant material that collected on the dune face and was subsequently buried.

Low Angle Cross Stratified Sandstone (Facies Sl)

Description. Low-angle cross-stratified sandstone (Figure 4b) is medium grained and well sorted. It occur as solitary sets (0.15-0.25 m) interstratified with trough cross-bedded sandstone (St). Both the lower and upper contacts are gradational.

Interpretation. This facies is interpreted to have formed by shallow high velocity flow in low relief scours (Rust, 1978). It is also interpreted to form by unidirectional flow under upper flow regime conditions (Cotter and Graham, 1991). This facies can also be the result of bi-directional flow deposition by tidal or longshore currents (Slm of George, 1994). The interbedding of underlying trough cross-stratified sandstone (St) and overlying low-angle cross-stratified sandstone (Sl) indicates a transition from lower to upper flow regime conditions.

Horizontally Stratified Sandstone (Facies Sh)

Description. Horizontal stratification (Figure 4c) is found in very fine grained to medium grained well sorted sandstone. Beds are between 0.1 and 0.5m thick. Lower contacts are generally abrupt. Upper contacts can be gradational with ripple cross-lamination (Sr) or abrupt. This facies is interstratified with massive mudstone (Fm), hummocky cross-stratified (Shes), ripple cross-laminated (Sr), and trough cross-stratified sandstone (St).

Interpretation. This facies is interpreted to have formed under upper flow regime conditions generated by tidal currents or shoaling waves (Shm of George, 1994). The tidal influence is also supported by the presence of this facies in association with hummocky cross-stratified sandstone (Shes).

Massive Sandstone (Facies Sm)

Description. Massive sandstone (Sm) (Figure 4d) is typically ungraded, fine to medium grained, and well sorted. Beds are between 1.0-2.0m thick. Rounded pebble-sized intraformational mud rip ups are common. Contacts can be abrupt or gradational. Massive sandstone is interbedded with trough cross-stratified (St), ripple cross-laminated (Sr), and hummocky cross-stratified sandstone (Shes), and massive mudstone (Fm).

Interpretation. Massive sandstones are interpreted to have formed from channel bank collapse, liquefaction of sandy bars and bioturbation of sandstone bodies. Any and all of these could have resulted in the massive sandstones observed. Weathering and poor exposures of this facies could also result in this structure within the sand body.

Ripple Cross-Laminated Sandstone (Facies Sr)

Description. Ripple cross-laminated sandstone (Figure 4e) is typically medium grained but may also be very fine to fine-grained and is typically well sorted. Ripple cross-laminated sandstone occurs as both sets (0.03-0.15m) and cosets (0.4-1.5m). Contacts can be both abrupt and gradational. Ripple cross-laminated sandstone typically overlies trough cross-stratified sandstone (St) and can also be interbedded with horizontally stratified sandstone (Sh), massive sandstone (Sm) and massive mudstone (Fm). Ripple form sets include both asymmetrical and symmetrical types. Asymmetrical ripple forms have wavelengths between 3-5cm and amplitudes 0.5cm. Symmetrical ripple forms have wavelengths between 7-11cm and amplitudes between 0.7-0.9 cm.

Interpretation. Ripple cross-laminated sandstone facies is interpreted as having formed by subaqueous ripple migration under lower flow regime conditions in shallow water (Miall, 1977). Asymmetrical ripple forms are indicative of unidirectional flow conditions. Symmetrical ripple forms are attributed to bi-directional currents.

Hummocky Cross-Stratified Sandstone (Facies Shcs)

Description. This facies is characterized by medium to very fine-grained, well-sorted, sandstone (figure 4f). Hummocky cross-stratified sandstone occurs as sets between 0.05 and 0.5 m thick. These sets are interstratified with trough crossbedded sandstone (St), massive sandstone (Sm), horizontally stratified sandstone (Sh) and massive mudstone (Fm). Contacts are gradational with other sandstone facies and abrupt with massive mudstone (Fm). No bioturbation is observed within these beds.

Interpretation. Hummocky cross-stratification is interpreted to have formed under the oscillatory currents of waves or in combined flows of unidirectional and oscillatory currents (Cheel and Leckie, 1993). This is often produced by storms in shoreface and offshore environments (Bourgeois and Leithold, 1983; Cheel and Leckie, 1993; Walker and Bergman, 1993). The hummocky cross-stratified sandstone sits abruptly on marine shales is also indicative of nearshore depositional environments (Walker and Bergman, 1993). Lack of bioturbation is interpreted to be the result of rapid deposition (Martel and Gibling, 1991).

Mudstone Lithofacies

Massive Mudstone (Facies Fm)

Description. This facies is composed of massive unlaminated mudstone. Beds are between 0.6-15m in thickness. Massive mudstone (Fm) intervals have abrupt to gradational bases and sometimes exhibit erosional upper contacts. These occur interstratified with mudstone with root traces (Fr), massive sandstone (Sm), ripple cross-laminated mudstone, trough cross-bedded sandstone, hummocky cross-stratified sandstone (Shes) and horizontally laminated sandstone (Sh).

Interpretation This facies is interpreted to be offshore marine deposits in cases were it contains marine gastropods, bivalves and ammonites. Marine mudstones are laterally continuous throughout the study area. They tend to be thick (10-30 m) and interbedded with hummocky cross-stratified (Shes), ripple cross-laminated (Sr), and horizontally laminated (Sh) sandstones. When interbedded with trough cross-stratified sandstone (St) and mudstone with root traces (Fr) it is interpreted as overbank fines from the settling of fines from suspension (Miall, 1977).

Massive Mudstone with Root Traces (Facies Fr)

Description. This massive ungraded mudstone is differentiated from massive mudstones (Fm) by the presence of root traces. These can be interstratified with massive mudstone (Fm) and with ripple cross-laminated sandstone (Sr). They are commonly 1-4cm in length and less than a cm in width. They are commonly coated with calcite. They are rare in the field area.

Interpretation. This facies is interpreted to be the result of settling out of overbank fines. The root traces are interpreted as evidence that the floodplains were vegetated.

CHAPTER 3

DEPOSITIONAL ENVIRONMENTS

Facies Associations of the Claggett Shale

Only the uppermost 15-30 m of the Claggett Shale is exposed locally in the study area (Figure 5). This marine unit consists mostly of massive mudstones (Fm). In the upper portion of this formation there are thin (0.2-1m) very fine grained, very well sorted sandstone units interstratified within the mudstone (Fm) which exhibit trough cross-stratification (St), low angle trough cross-stratification (Sl), ripple cross-lamination (Sr) and hummocky cross-stratification (Shcs) (Fig 5b). Symmetrical ripple forms are present on some sandstone bedding surfaces. Locally there are also thin (8-20cm) horizontally bedded sandstone units (Sh). Cone-in-cone structure is also present within massive mudstones (Fm) indicating post depositional dewatering of clays. Marine fossils, including unidentified gastropods, bivalves, ammonites, and shark teeth are abundant locally. Occasional hadrosaur bones are present within the unit. Most of these bones are poorly preserved and infilled with gypsum.

Interpretation

The thick (10-25 m) sequences of massive mudstone (Fm) are interpreted to be the deposits of offshore marine deposition on the innner shelf. The associated marine fossils support this interpretation. Thin sandstone beds in the upper 10m of the Claggett Shale are interpreted to have formed within lower shoreface environments. Horizontally stratified

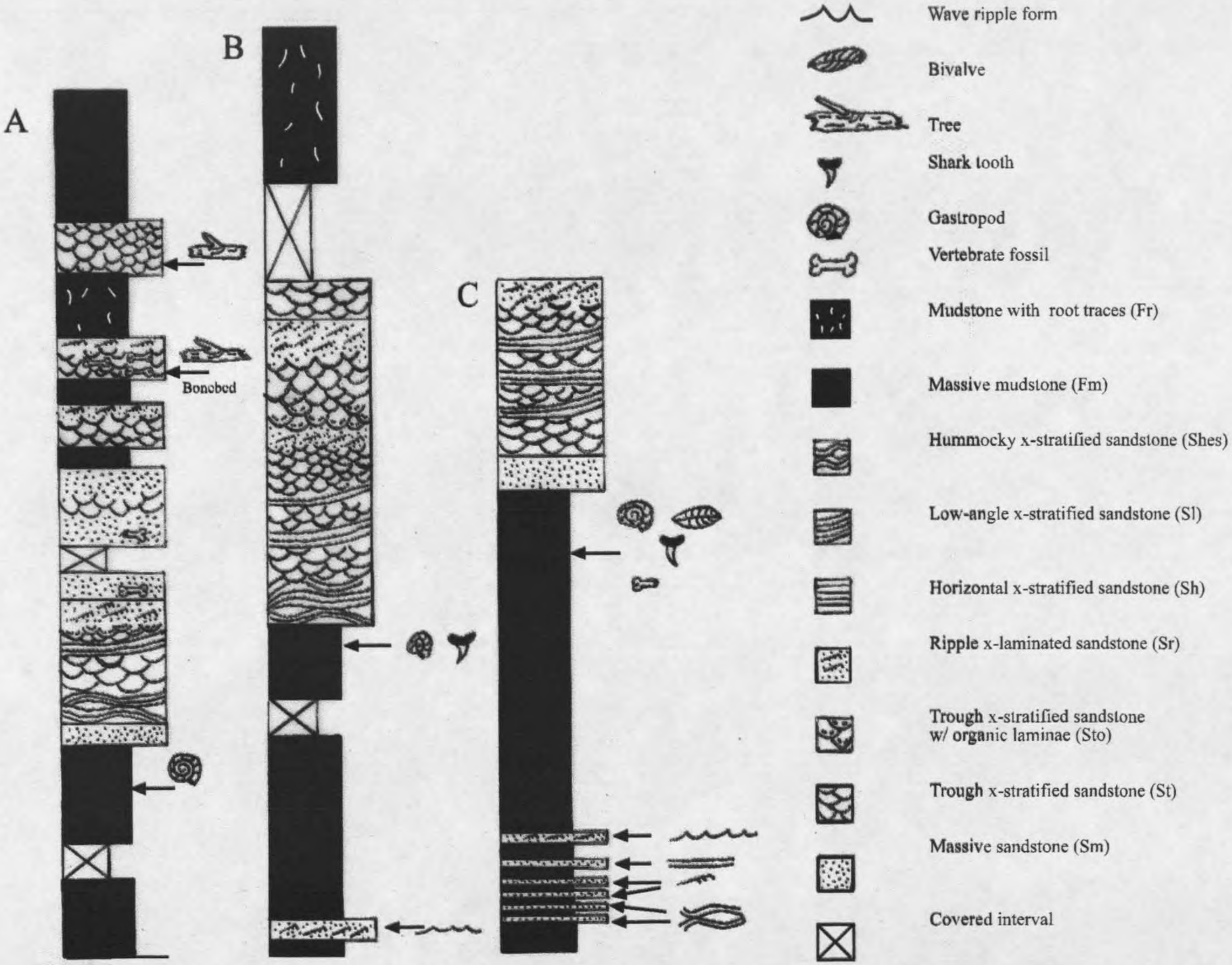


Figure 5. Measured sections from the vicinity of the Malta bonebed. Section A was measured through the strata containing the bonebed.

sandstone (Sh) indicates deposition by tidal or shoaling waves. The hummocky cross-stratified sandstone interstratified with massive mudstone is interpreted to be the result of storm deposition within the lower shoreface environment (Cheel and Leckie, 1993). Symmetrical ripple forms are interpreted to be the result of moderate to high energy waves in the lower shoreface (Martel and Gibling, 1991). The vertical succession of massive mudstone overlain by interbedded thin sand bodies and mudstone indicates a shoaling upward change in environments. This is indicative of a prograding shoreline. The presence of hadrosaur bones within the Claggett Shale indicates those individual bones and perhaps bloated carcasses were transported into the Cretaceous Seaway. This suggests that the fluvial systems of the Judith River Formation had outlets to the seaway.

Facies Associations of the Parkman Sandstone

The Parkman Sandstone is the basal shoreface member of the Judith River Formation as defined by Knechtel and Patterson(1956) in Wyoming. Gill and Cobban (1973) correlated the Parkman to outcrops in Montana. Within the study area the Parkman Sandstone forms a resistant bench. Beds are laterally continuous for tens of meters. Thickness varies from 5-8m locally (Fig. 5). The unit coarsens upward slightly. The Parkman is composed entirely of sandstone. The sandstone is generally well sorted and medium grained regardless of the sedimentary structure. The basal (0.5-1) Parkman is sometime massive (Sm) and in other places exhibits hummocky cross-stratification (Shcs) (Fig. 4). Above the lowermost meter, the Parkman Sandstone comprises 2-4 m of medium scale trough cross-stratified sets (St) interbedded with thin sets (0.15-0.25m) of low-angle cross-stratified sandstone. Sets of trough cross-bedded sandstone with organic laminae (Sto) are interbedded within the trough cross-bedded sandstone (St) sets. The upper portion (1-2 m) of the Parkman is dominated by small scale ripple cross-laminated sandstone (Sr). No vertebrate fossils have been recovered from the Parkman Sandstone within the study area.

Interpretation

The Parkman Sandstone is interpreted to be the deposits of the upper shoreface and foreshore environments. Stratigraphically, the Parkman Sandstone sits conformably on the marine Claggett Shale suggesting shoreface deposition. Additionally, the vertical facies sequence and coarsening upwards nature of the unit agree with this interpretation. Massive sandstones at the base of the Parkman Sandstone are interpreted to be the result of bioturbation. The presence of hummocky cross-stratified sandstone (Shes) is interpreted to be the result of storm deposition on the uppermost lower shoreface (Olsen et al., 1999). The paucity of bioturbation within this facies is suggested to indicate rapid deposition. Trough cross-stratified (St) and low-angle trough cross-stratified (Sl) sandstone is indicative of upper shoreface environments (George, 1994; Olsen et al., 1999). The trough cross-stratified sandstones are interpreted to be the result of migration of three-dimensional dunes by oscillatory currents (Olsen et al., 1999). Low-angle cross-stratified sandstone (Sl), ripple cross-laminated sandstone (Sr) and trough cross-stratified sandstone in the upper two meters are indicative of foreshore deposits (Reineck and Singh, 1973). Lack of bioturbation and sedimentary structures in the upper Parkman Sandstone indicates shallow water deposition in the uppermost shoreface. The coarsening upwards and vertical change in sedimentary structures (Shes-St-Sl-St-Sr) is interpreted to be the result of a shoaling upwards sequence in a regressive shoreface deposit (Leckie and Walker, 1982; Olsen et al., 1999).

Facies Associations of the Judith River Formation

The Judith River Formation is approximately 170m thick at the type section in the Missouri Breaks of central Montana (Sahni, 1972). Rogers (1995) proposed three new reference sections for the Judith River Formation near the type area with an approximate thickness of 180m. Only the lowermost 20-30m of the Judith River Formation (excluding Parkman Member) is exposed in the study area (Fig. 5). Judith River Formation outcrops in this area consist of interbedded sandstone and mudstone.

Sandstones of the Judith River Formation are generally medium grained, well sorted and vary from 1-4m in thickness. Sandstone unit geometry could not be determined due to the lack of continuous lateral exposure; however, some sandstones could be traced laterally for distances of up to 20m. Sandstones are typically tan to buff, medium grained, and quartz rich. Beds are weakly cemented and friable with calcite and clay mineral cements.

The most common facies in the Judith River sandstone bodies are trough cross-bedded (St) and ripple cross-laminated sandstone (Sr). Massive sandstone (Sm) is also common. Locally, trough cross-bedded sets with organic laminae (Sto) can be abundant.

Within the Judith River sandstone bodies, trough cross-stratified sandstone (St) often grades vertically into ripple cross-laminated sandstone (Sr). In addition, isolated trough cross-stratified sandstone (St) is also present. Isolated ripple cross-laminated sandstone (Sr) is present but rare. Massive sandstone can occur in vertical sequences with both ripple cross-laminated (Sr), trough cross-stratified (St) sandstone, or as isolated beds. Trough cross-stratified sandstone with organic laminae (Sto) is present interbedded with sets of trough cross-stratified sandstone (St) exclusively.

Sandstones usually have an erosive base with some exhibiting convolute bedding at the base. Convolute bedding usually consists of folded and interbedded mudstone and sandstone. Pebble sized intraformational rip-up clasts are found commonly in trough cross-stratified (St) and massive sandstone (Sm). Rip-up clasts commonly form lags at the base of sandstone bodies.

Large woody debris (20-60cm in diameter) is common in trough cross-stratified (St) and massive sandstone (Sm) facies. Pieces of woody debris exceeding a half meter in length were found in three sand bodies within the study area. Plant material is also found in trough cross-stratified sandstone (St) commonly as organic laminae (Sto). Fossil vertebrates are also common including disarticulated bones, articulated skeletons and microsites. Most vertebrate material is found in trough cross-stratified (St) or massive sandstone (Sm). Microsites have been found at the base of trough cross-stratified sandstone (St) with the bones at the base of a scour. All articulated skeletons (Ancell et al., 1998) excavated within the study area have been found in trough cross-bedded sandstone (St) which grades upward into ripple cross-laminated sandstone (Sr).

Mudstone intervals can vary from 2-8 m in thickness. They are generally light to dark gray, dominantly massive (Fm) with occasional root traces (Fr) and laterally continuous in outcrop where exposure is good. Fossil plant and vertebrate remains are exceedingly rare within the mudstone. No vertebrate material was recovered from mudstone units within the field area. Crushed gastropods and bivalves as well as plant material can be concentrated within mudstones.

Interpretation

Sandstone units of the Judith River Formation are interpreted to be the deposits of fluvial channels. Trough cross-stratified and ripple-cross laminated sandstone is interpreted to have formed by the migration dunes and ripples respectively within the channels. Massive sandstones are interpreted to have formed by bank collapse or bedform liquefaction. The bankfull depth of the channels within the Judith River Formation is estimated to be between 1.5-4 m based on the thickness of the sandstone bodies throughout the study area (Leeder, 1973; Ethridge, 1978; Miall, 1996). Leeder (1973) demonstrated that the bankfull width of a channel is related to the bankfull depth in high sinuosity streams. Based on the thickness of sand bodies in the study area, the fluvial channels had bankfull widths between 15-60m. The grain size, sedimentary structures, and channel dimensions suggests that the channels were shallow, sandy meandering channels. The lack of caliche development and mudcracks within the deposits of the Judith River Formation suggest the streams were perennial. The presence of intraformational clasts is interpreted to be the result of reworking of the channel banks and incision into underlying mudstone.

Massive mudstone intervals within the Judith River Formation are interpreted to record overbank deposition of the settling out of fines. Abundant woody debris within trough cross-stratified (St) and massive sandstone (Sm) indicates that the interfluve areas were vegetated.

Given the stratigraphic proximity of the fluvial deposits to the underlying marine (Claggett Shale) and shoreface deposits (Parkman Sandstone) it is possible that the channels were close to the paleoshoreline (Fig 6). Presence of hadrosaur bone in the underlying Claggett Shale indicates the fluvial systems of the Judith River Formation drained into the seaway, sometimes carrying vertebrate carcasses and bones. The small scale of the channels could indicate the channels were distributary in nature, although perhaps not directly tidally influenced. The presence of ray teeth within the channels of the Judith River Formation suggests the channels were connected to the Cretaceous Seaway (Wood et al., 1988).

Stratigraphic Position of Malta Bonebed

Figure 5a shows the stratigraphic relationship of the bonebed to the underlying marine and shoreface units. The bone-bearing sandstone is located approximately 16m above the underlying marine Claggett Shale and 9m above the shoreface Parkman Sandstone. Separating the bonebed sandstone from the Parkman Sandstone are approximately 9m of fluvial sandstone and mudstone. The stratigraphic position of the

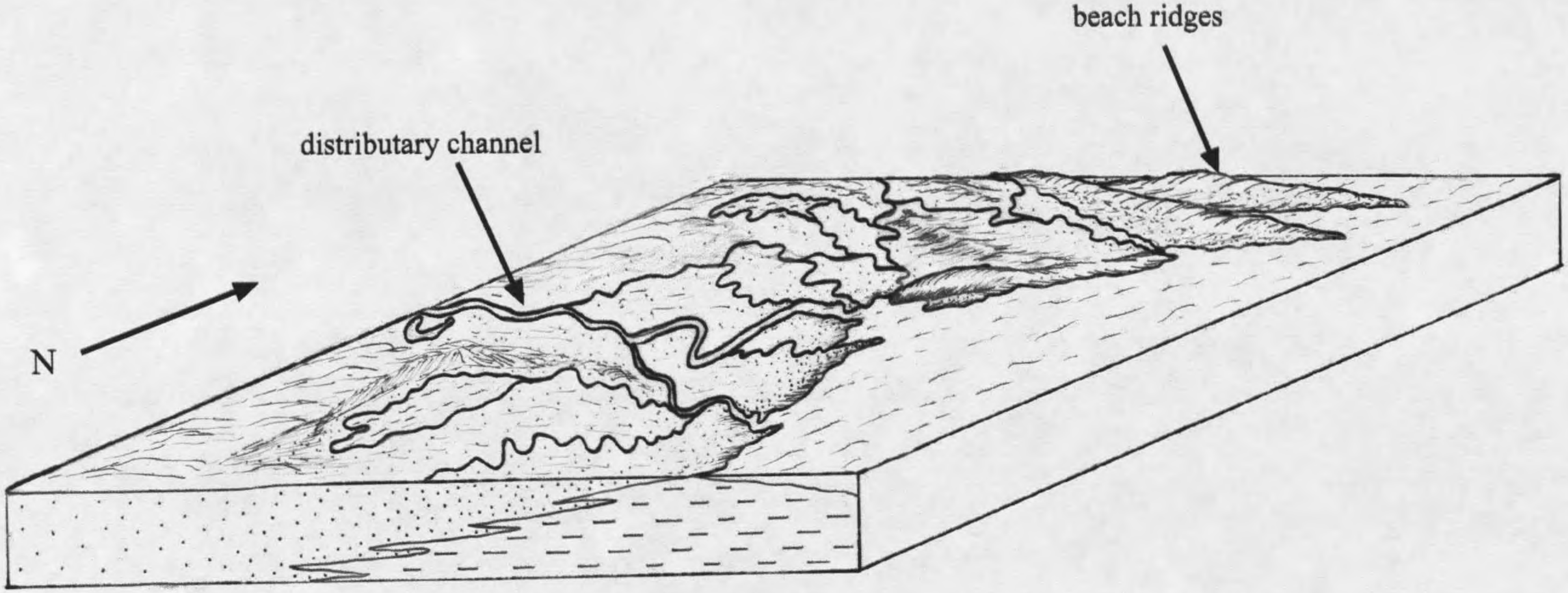


Figure 6. Paleogeographic reconstruction of the distal coastal plain of Montana during Late Cretaceous (Campanian) time. The distal coastal plain would have been characterized by distributary channels and estuaries. Shoreface deposits such as the Parkman Sandstone represent the progradation of the paleoshoreline during the regression Cretaceous Western Interior Seaway.

bonebed infers fluvial sandstones were deposited in close proximity to the Cretaceous Interior Seaway. The lack of heterolithic cross-stratification, normally found in estuaries could rule out a tidal influence for the channel (Koster and Currie, 1987; Eberth, 1996; Eberth and Brinkman, 1997), although the size of the channels might preclude this from forming.

Bonebed Geology

The Malta bonebed sandstone is a fine-grained, well sorted, tan to brown, friable sublitharenite. The sandstone body is approximately 1.8 m thick although this can vary between 4-10 cm laterally. The bonebed sandstone has an erosive contact with an underlying mudstone (Fm) unit and gradually fines upward into the overlying mudstone (Fm). Immediate lateral relationships to the bonebed sandstone could not be determined due to vegetative cover. Bones are concentrated within the lower meter of the sandstone, though they do occur higher in the sandstone body. Plant fossils are especially abundant and include small conifer cones, branches, and a discontinuous tree trunk that is oriented approximately east-west. Most pieces of the tree range from 16-40cm in diameter and between 3-5m in length. Large tree fragments were excavated along the same trend for a distance of approximately 13m.

Mudstone rip-up clasts are common throughout the entire sand body. The lower 0.2-0.4m of the sandstone exhibits convolute mud and sand folding and interbeds. The sandstone body is trough cross-bedded (St) through the middle meter and ripple cross-laminated (Sr) in its upper 40 cm.

Interpretation

The sandstone is interpreted to be the deposits of a fluvial channel. Bankfull channel depth is estimated to be 1.8 m based on the thickness of the sandstone (Leeder, 1973; Ethridge and Schumm, 1978). Bankfull channel width is estimated to be approximately 17m based on the thickness of the bonebed sandstone (Leeder, 1973; Ethridge and Schumm, 1978). The presence of rip-up clasts within the sandstone and the erosive base of the sandstone are interpreted to be the result of channel incision into the underlying mudstone. Trough cross-stratified (St) and ripple cross-laminated (Sr) sandstone are interpreted to be formed by migrating dunes and ripples, respectively, within the channel. The presence of sandstone with trough cross-stratification (St) and ripple cross-lamination (Sr) interstratified with mudstones is indicative of a channel deposit. The erosive base, vertical sequence of facies (Fm-St-Sr-Fm), medium grain size, and the presence of rip-up clasts indicate that the channel was a sandy meandering channel.

CHAPTER 4

TAPHONOMIC DATA

Taxonomic data

Over 1,300 bones have been recovered from the Malta bonebed. Most of this material is defined as hadrosaurid. All of the cranial material from the Malta bonebed is assignable to the hadrosaur genus *Brachylophosaurus sp.* Given that this portion of the Judith River Formation has yielded no other Hadrosaur genus (Horner, pers. com), it is likely that all of the material is from brachylophosaurs. Of the 837 prepared and identifiable bones from the Malta bonebed, 97% (n=813) are considered to be hadrosaurid and thus *Brachylophosaurus,* classifying this a paucispecific bonebed. In addition to the brachylophosaur bones, several other dinosaurian remains have been found including hind limb elements of an unidentified hypsilophodontid, a juvenile ceratopsian humerus, several theropod teeth and pterodactyl limb elements. Non-dinosaurian remains include gar scales, ray teeth, turtle carapace, crocodilian teeth, and a small mammal jaw. Plant remains consist of a trunk and branches from an unidentified conifer.

The Minimum Number of Individuals (MNI) index (Badgley, 1986) was used to calculate the number of individuals when it was determined that the material was associated. The Number of Identifiable Specimens (NISP) index was used to calculate the number of individuals for vertebrate material that was fragmentary and not associated. At least six brachylophosaurs are present in the assemblage based on six left dentaries using the MNI index. Two age classes are represented in the quarry, four sub-adults and two adults based on morphologic and morphometric differences including fusion of the braincase in two specimens (Prieto-Marquez, pers. com.).

Taxa	MNI	NISP
Hadrosaurid Brachylophosaur sp.*	6	813
Hypsilophodontid	1	9
Ceratopsian	1	1
Pterosaur	3	3
Unkown Theropod	1	1
Unkown Dinosaur	18	18
Champsosaurus	2	2
Crocodile	2	2
Ray	3	3
Gar	1	1

Table 2. Minimum number of individuals for each taxa found within the Malta bonebed. MNI index was used to calculate the number of individuals for articulated and associated material. The NISP index was used to determine the number of individuals for unassociated material. Numbers are based on prepared material. (* based on left dentaries)

Table 2 shows a complete list of the individuals found within the bone bed. The MNI index was used to calculate the number of individuals for the hypsilophodont since the material was associated. Numbers of individuals for the other vertebrate material were calculated using the NISP index since the material showed no signs of association or articulation (Badgely, 1986).

Spatial Distribution

Brachylophosaur bones within the sandstone are concentrated towards the larger tree fragments as seen in figure 7 and Plate 1. In the $8m^2$ which the tree trunk is present there are at least 20 bones per square meter. Highest brachylophosaur bone density exceeds 45 elements per m^2 within this portion of the bonebed. The meter grids in the immediate vicinity to those containing the tree also show significantly higher bone densities. In some places bones were stacked five high (Figure 8). Bones within a meter of the tree trunk possess more bone to bone contacts than those further away. Bones were less common away from the tree and when found they are often more dispersed. In general robust bones are more prevalent on the north side of the tree as are articulated and possible associated bones. Brachylophosaur material was found stacked against and lying on top of the tree. The presence of bones in these positions suggests the tree was present within the channel prior to the arrival of the brachylophosaurs. On the south side of the tree trunk vertebrae, ribs and podials are common. Limb and cranial elements are not as abundant. Bones on the south side of the tree are stratigraphically higher in the sandstone

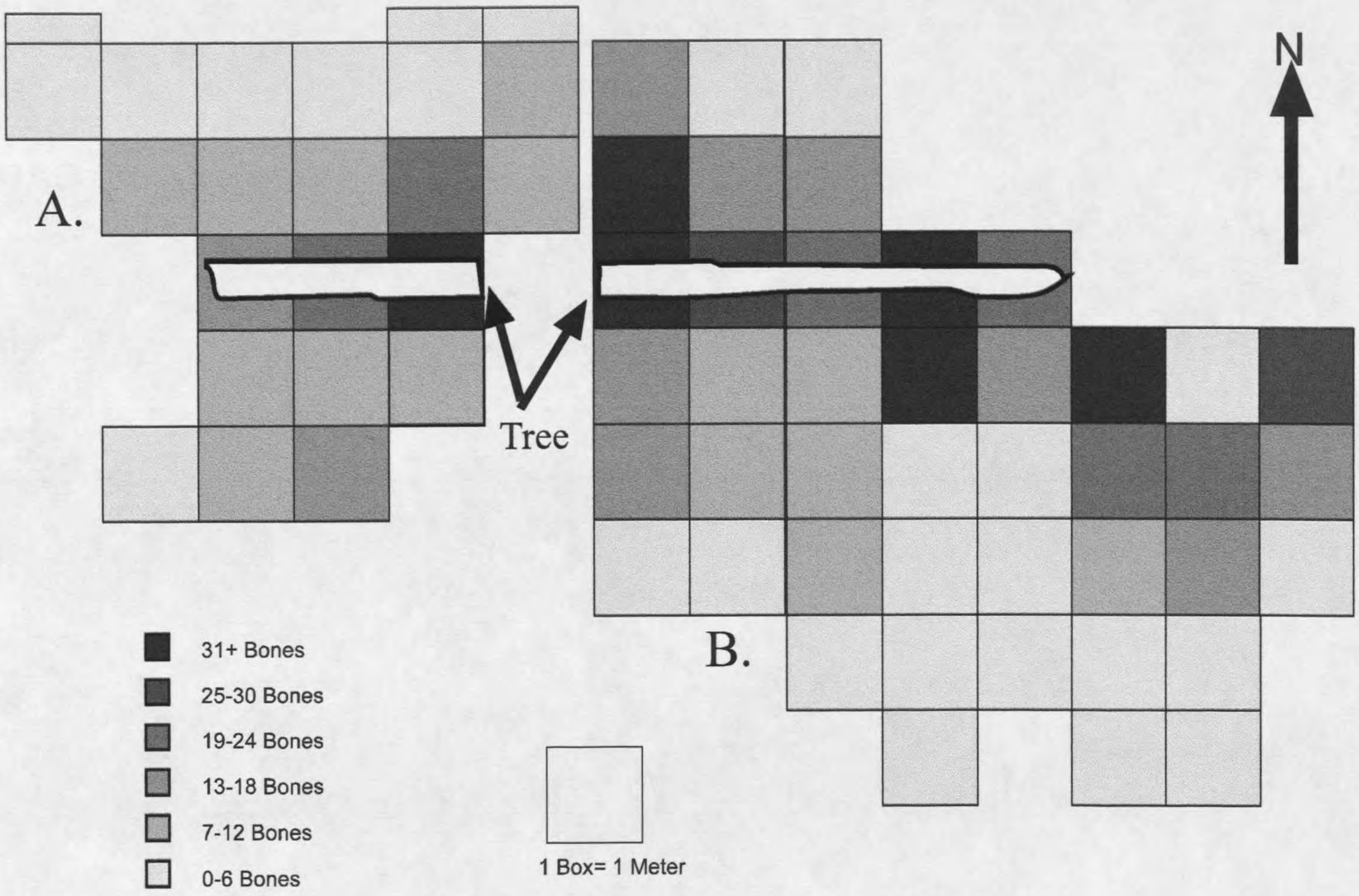


Figure 7. Spacial distirbution and density of bones within the Malta Bonebed. Bone density is highest within 1-1.5m of the tree. Data from 1998 was not mapped on a meter grid mapping system, but was subsequently subdivided into a grid. The 1999 data were mapped in situ on a grid system.

and are often more dispersed. Small branches are still present but decrease away from the tree to the south.

Figure 8. Example of high bone density in the Malta bonebed within a meter of the tree. At least five elements are stacked (1-5) on top of one another.

Articulation/Association

Bones within the quarry show some articulation and a degree of association. Several brachylophosaur specimens were found articulated including three sets of vertebrae, two braincases, a tibia and fibula, and a hind leg (femur-phalanx). All examples of articulation were found on the west side of the quarry and north side of the tree. It has previously been reported that in mammals, vertebrae and limbs are the last parts to become disarticulated during transport (Toots, 1965). While it is unclear if this same pattern occurs in dinosaurs those are the elements most commonly found articulated with the Malta bonebed. In addition, a hadrosaur skin impression was found within the bonebed. The presence of this feature along with several sets of articulated elements suggest the brachylophosaurs were articulated when they arrived at the site.

Several sets of caudal vertebrae were considered to be associated based on their close proximity, similar size and similar orientation of the neural spines. Podial elements were also considered associated based on the non-repetition of elements and their position with respect to one another. It is possible that some of the apparent associations are the result of mixing of elements from the six brachylophosaurs.

The hypsilophodontid material was also loosely associated. This was based on the non-repetition of elements, close spatial distribution of the bones, and fact that all the elements are from the hind limb. The remaining dinosaurian and non-dinosaurian material was neither articulated nor associated. Most consisted of isolated elements, fragments or teeth.

Skeletal Representation

The bones of these Brachylophosaurs are well represented throughout the bonebed. The bones generally occur in proportions expected from six complete individuals. It is likely that some of the elements that are missing remain in the unexcavated portion of the bonebed. Others might have been weathered out before excavation began. Dodson (1973) demonstrated that smaller bones are most easily transported and removed under fluvial conditions. Voorhies (1969) demonstrated that lighter elements such as ribs and vertebrae are the first to be removed from an assemblage.

The presence of very small bones (distal phalanges and distal caudal vertebrae) and abundance of both ribs and vertebrae suggests very little winnowing occurred within the assemblage. Even though the skeletons are disarticulated, most of their constituent bones are present.

The only other taxon represented by significant remains is the hypsilophodontid. The other dinosaurian and non-dinosaurian vertebrates are represented by teeth and small fragmentary remains. None of the non-brachylophosaur bones exceed 20cm in length suggesting they could be more easily transported.

Orientation

Trend and plunge were measured for all long bone specimens while excavation was underway during the 1999 field season. Long bones were separated into two populations based on their position relative to the tree and plotted on stereonets as prescribed by Fiorillo (1988). The separation of the long bones into two populations was based on the authors observation of two distinct groups of orientations on the quarry map (Plate 1). The orientations were then plotted as two separate groups to determine if indeed two populations existed within the data set. The lowest contour level has a value of E. Each subsequent contour line has a value of 2σ. Values of $E+4\sigma$ are considered significant to the 95% confidence level (Jowett and Robin, 1988).

Population A was defined as all the bones found distances greater than 1.5m from the tree. A northwest-southeast (azimuth=155-335) peak orientation is shown in figure 9a. Population B was comprises all the long bones within 1.5m of the tree. These bones

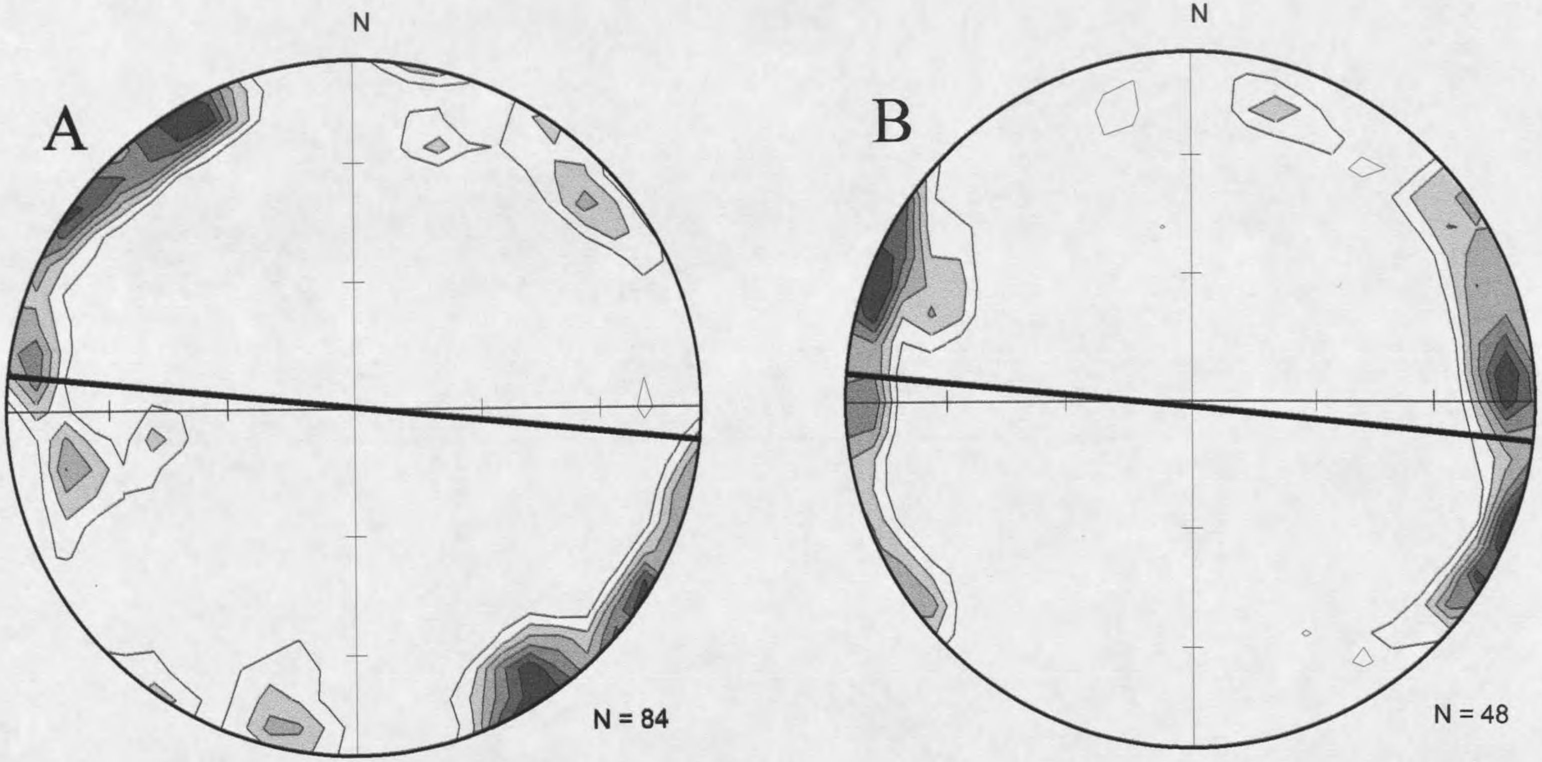


Figure 9. Lower hemisphere stereoegraphic projections for the two bone populations represented within the bonebed. Dark line trending 275-95 in both diagrams represnts the orinetation of the tree. The tree is horizontal within the sandstone. A. Stereographic projection of the trend and plung of long bones which are further than 1.5m from the tree. There is a prefered northwest southeast orientation. B. Stereographic projection of the trend and plunge of long bones which are within 1.5m of the tree. In this case long bones are oriented more closely to east-west and parallel to the tree.

are oriented closer to east-west with significant peaks at 85° and 120-300° as seen in figure 9b. This is similar to the tree's orientation (azimuth= 275-95°). There is some overlap within the two populations but the significant peaks (>3 contours) do not overlap suggesting that these are indeed two populations of bones.

Population A is made up mostly of ribs, a Voorhies Group I (1969) element. These more easily transported bones could have been mobilized after disarticulation and transported to the downstream side of the tree. Once away from the tree their orientation could be dictated by the direction of flow within channel rather than the tree. A great majority of the other bones within this portion of the bonebed are Group I elements, suggesting the direction of transport was indeed to the southeast.

Population B is made up of more robust bones including limb and pelvic elements. The orientation of this population indicates the tree was the primary influence on their orientation. Woody debris in channels influences the direction and velocity of flow (Bragg et al., 2000). These processes might have led to the orientation seen in population B. Long bones from both populations were mostly horizontal or slightly inclined from horizontal. Only three specimens had plunges greater than 15°. The tree was only slight off of horizontal (plunge=2°).

Bone Modification

The bones from the JDM quarry are typically tan to light brown in color. Most specimens are complete, including two articulated braincases and dentaries with intact tooth batteries. The bones themselves have undergone minimal permineralization or infilling.

Weathering of the Brachylophosaur bones is minimal throughout the bonebed with 99.9% falling within Stages 0-1 of Behrensmeyer's Weathering Stages (1978) (Table3).

Element	Weathering Stage	0	1	2	3	4	5
Vertebrae		129	39	-	1	-	-
Cranial *		57	1	-	-	-	-
Podials		116	13	-	-	-	-
Long bones+		105	-	-	-	-	-
Total number of specimens		407	53	-	1	-	-
Percent of sample		88%	11.5%	-	0.0%	-	-

Table 3. Summary of weathering data from the Brachylophosaur bones of the Malta bonebed. Only bones that were more than 50% complete were considered. Bones that were extensively crushed or damaged during excavation were not counted. All prepared elements that met the above criteria were considered. Weathering stage was assessed using Behrensmeyer's Weathering Stages (1978). * Two complete braincases are Stage 0. + Includes limb, pelvic, and rib bones.

Stage 1 weathering is typically seen as mosaic-cracking patterns on the articular surface of some vertebrae and distal limb elements (phalanges, ungals, etc.)(Figure 10). Seventy-three percent of the bones with Stage 1 weathering are vertebrae, the majority of which (n=34) are caudal vertebrae. The significance of Stage 1 weathering on smaller and distal elements is unclear. This could be related to the size of the element or the likelihood of

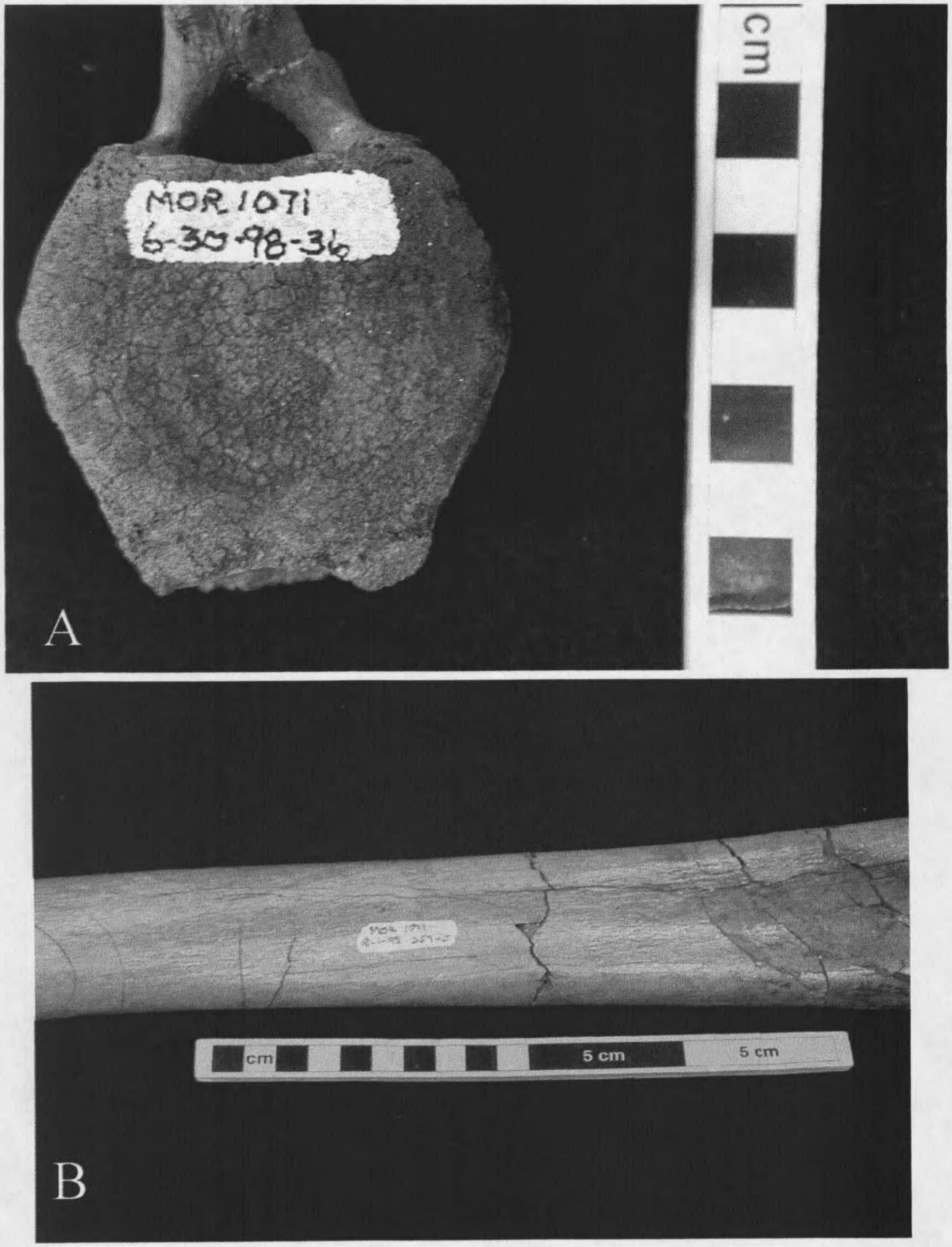


Figure 10. A. Mosiac weathering pattern typical of Stage 1 weathering. This feature is most commonly found on caudal vertebrae and distal phalanges. It is only present on the articular surfaces. B. Brachylophosaur Ulna showing the Stage 0 weathering which is normally observed on long bones within the Malta bonebed. Perpendicular fractures seen here are indicative of post-fossilization breaks.

distal elements to disarticulate first. One hundred percent of the long bones surveyed exhibit Stage 0 weathering and show no signs of subaerial desiccation (Figure 10). Only one element exhibits higher than Stage 1 weathering suggesting it is possibly not related to the other Brachylophosaur elements. Weathering stage does not appear to vary by taxa within the quarry as all other dinosaurian remains fall within Stages 0-1. Bones that have been exposed since fossilization (i.e. surface collections) typically show higher stages of weathering and have a bleached appearance. These were not considered when the analysis of the bone weathering took place.

Five bones did not fit a clear weathering stage. These problematic bones include four brachylophosaur bones (fibula-tibia, two ulnas) and a juvenile ceratopsian humerus. The shafts of the two brachylophosaur ulnas (MOR 1071-99-4, 99-77) appear unweathered yet the ends of the bones have been removed. The juvenile ceratopsian humerus also has what appear to be deeply weathered ends of the bone. This bone exhibits some degree of compaction. It is unclear from the elements whether the ends were broken and then weathered or simply weathered alone.

The brachylophosaur tibia and fibula (MOR 1071-98-516, 516A) are even more confounding. They were found articulated and have evidence of prefossilization breakage (spiral fracture). One end of each of the bones has been removed and the other ends show no evidence of weathering. The ends that are missing show evidence of compaction, but it can not be determined if fracturing and breakage of bone led to weathering or if the weathering weakened the bone to the point of fracture. Nevertheless the presence of strikingly different patterns of weathering and breakage on different ends of the same bones suggests that perhaps the more heavily modified ends of the fibula and tibia were exposed while the other ends of the bone were buried.

Bone breakage varies within the quarry in relation to distance from the tree. Bone concentration increases towards the tree, as does degree of breakage and compaction. Where compaction is high, bones exhibit abundant longitudinal and perpendicular fractures. Bones stacked on top of one another often have fractures that displace the bone in the sandstone.

Spiral fracture patterns are common and inferred to be the result of prefossilization breakage. Some bones without any visible contact with other bones are also sheared. Abrasion or rounding of the bones is absent in specimens from the Malta bonebed.

At least five bones from the assemblage exhibit deep grooves that are interpreted as tooth marks. One occurs on a dentary as a pair of parallel grooves (Figure 11). The other four are single grooves, two on vertebrae and two on cranial fragments. Two other bones have deep puncture marks. These could also be tooth marks or possibly borings. A minimum of eight bones within the bonebed have pathologies although it is yet unclear as to what significance these have (Hanna et al., 1999).

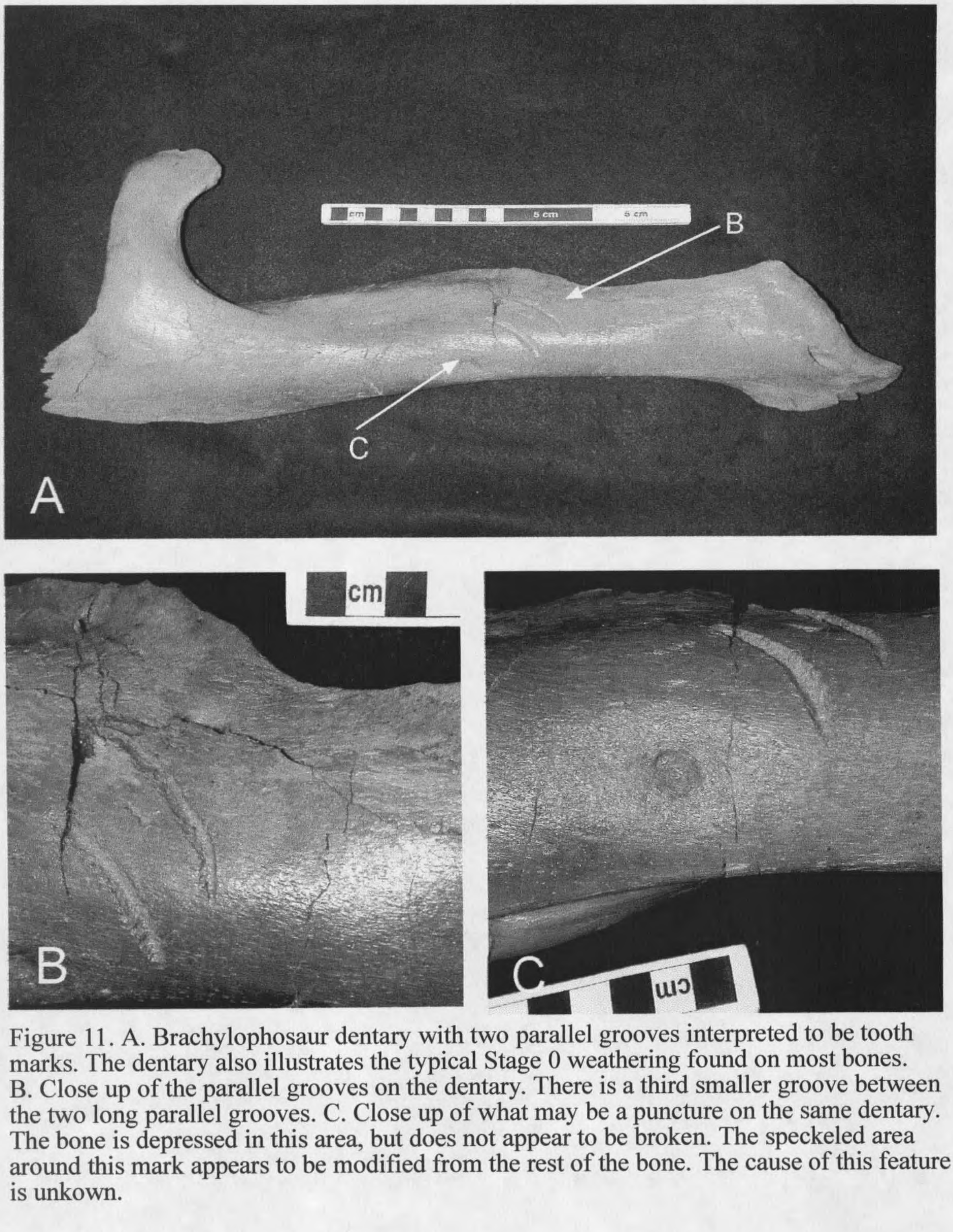


Figure 11. A. Brachylophosaur dentary with two parallel grooves interpreted to be tooth marks. The dentary also illustrates the typical Stage 0 weathering found on most bones. B. Close up of the parallel grooves on the dentary. There is a third smaller groove between the two long parallel grooves. C. Close up of what may be a puncture on the same dentary. The bone is depressed in this area, but does not appear to be broken. The speckeled area around this mark appears to be modified from the rest of the bone. The cause of this feature is unkown.

CHAPTER 5

DISCUSSION

Interpretation

The presence of bones stacked against and on top of the tree and the parallel alignment of some long bones with the tree suggests that it played a role in the accumulation of the brachylophosaurs. Fiorillo (1991b) described a similar occurrence of vertebrate material and woody debris for the Careless Creek Quarry located in the Judith River Formation of central Montana.

Fiorillo (1991b) interpreted the accumulation of the associated large vertebrate remains of the Careless Creek Quarry to be the result of carcass accumulation in a logjam. Evidence from the assemblage to support this conclusion included presence of several pieces of large woody debris, a bone density of 5 per m^2 in the area surrounding the large woody debris, some association of skeletal material, low weathering attributes and a lack of winnowing. The woody debris was interpreted to predate the vertebrate remains in the assemblage based on the parallel alignment of some of the long bones with the woody debris. While Firoillo (1991b) demonstrates association of woody debris and vertebrate remains his argument for a logjam falls short of convincing.

The Malta bonebed provides another locality in which to test the paleo-logjam model. The presence of a large tree trunk, approximately 13m long and 20-45cm in diameter, oriented east west within the bonebed provides a sufficient capture point for vertebrate material. The tree does not appear to be transported. Trunk pieces are distributed in the quarry along a nearly linear trend with one another. The tree would be considered large woody debris based on its diameter (> 20cm) and length (13m) (Bragg et al., 2000). Smaller branches of the tree and even cones were found in the bonebed suggesting that little, if any transport of plant material took place. Baillie et al. (1999) observed in modern stream of comparable size that woody debris had lost 51% of its dry weight after four years within a channel including the loss of bark. The presence of bark on the tree suggest that the trunk was exposed within the channel for a period of less than 5 years (Baillie et al., 1999; Bilby, 2000).

Lithofacies analysis of the bone bearing sandstone indicates that the wood and bones were collected in a shallow (< 1.8m) fluvial channel. The presence of trough cross-stratified (St) and ripple cross-laminated sandstone (Sr) within the sand body indicates that lower flow regime conditions were active in the channel during accumulation of the vertebrate and plant fossils.

Brachylophosaur bone density is significantly higher within 1.5 m of the tree than elsewhere in the bonebed. In this area bones can be piled five high and bone density can exceed 45 bones m^2. Bones are accumulated against and on top of the upstream portion of the tree. Together this indicates that the tree played a significant role in the accumulation of the brachylophosaurs. The presence of bones on top of and against the upstream side of the tree suggests the tree was present within the channel before the arrival of the brachylophosaurs.

Brachylophosaur bones are articulated in several places including three sets of vertebrae, three hind limbs, and a foot. This suggests that the brachylophosaurs were intact carcasses when they arrived at the site. Furthermore, the presence of a hadrosaur skin impression within the bonebed adds credence to the suggestion that the brachylophosaurs were indeed articulated at the moment of their entanglement.

A survey of the skeletal elements recovered indicates that none of Voorhies Groups (1969) are either over or under represented suggesting minimal winnowing of the assemblage. A high variation in the size of the elements preserved and the apparent lack of size sorting (Plate 1) within the bonebed suggests that fluvial transport of individual elements did not play a large role in the accumulation.

The lower flow regime condition, the lack of hydraulic equivalence (Behrensmeyer, 1975) of the bones with the sediment, and lack of bone abrasion suggest the idea that the brachylophosaur bones were not transported as isolated elements. This evidence along with the high degree of articulation/association within the quarry suggests that the brachylophosaurs arrived at the site as floating, bloated carcasses and accumulated along the upstream side of the fallen tree.

Dodson (1971) previously suggested carcass floatation as an important means of accumulation for dinosaurs in the Judith River Formation. The recognition of articulated skeletons of dinosaurs in the channel sandstones of the Judith River Formation of Dinosaur Provincial Park, Alberta, Canada, led Dodson (1971) to suggest that some of these animals had died in or around the channels and could be transported as bloated carcasses prior to burial. As previously mentioned, Fiorillo (1991b) suggested bloated hadrosaur and ceratopsian carcasses being caught in a paleo-logjam for the Careless Creek Quarry within the Judith River Formation.

The exact mechanism by which the carcasses came to rest at the site can not be determined. The abundance of long bones and articulated material on the upstream side of the tree suggests that the carcasses entered the channel from somewhere upstream and floated within the channel until they became entangled with the fallen tree. It is not possible to determine the degree to which the brachylophosaurs were autochthonous or allochthonous. They could have come from mere meters upstream or much farther.

Sometime after the brachylophosaurs were entangled with the tree they began to disarticulate. These processes would occur during decay of the carcasses and could be aided by the scavenging of the carcasses. Fish have been observed tearing at carcasses in channels (Weigelt, 1989) and gar fish specifically have been suggested as scavengers of a *Brachylophosaurus* carcass within the Judith River Formation (Ancell et al., 1998).

Weathering of some bones (n=53, Stage 1) indicates that at least some of the material was subaerialy exposed and desiccated. These bones could represent background hadrosaur material not related to the other material. Conversely some of the disarticulated bones could have been deposited on a bar in the channel or along the channel banks. The weathering is minimal (Stage 0-1) suggesting the bones where exposed for a period of 0-1 years (Behrensmeyer, 1978).

The bones also show evidence of scavenging as seen by the tooth marks on some specimens. These events most likely occurred after the brachylophosaurs were entangled with the tree suggesting that scavenging occurred within or very near the channel.

Crocodiles have been observed tearing at bloated carcasses in fluvial channels and have been observed dragging carcasses into channels (Weigelt, 1989). This type of scavenging could have played a role in the disarticulation of the carcasses. Tooth marks on several bones and scattered theropod and crocodilian teeth within the bonebed could possibly be related to this activity. It is also possible that the teeth were transported as bed load within the channel. The paucity of tooth marks (1%) on bones indicates the scavenging may not have been a significant part of the taphonomic history of the assemblage. Fiorillo, (1991a) suggested that theropods did not gnaw bones in the same manner as modern mammal predators and scavengers do. This too could explain the lack of tooth marks on the sample. It is possible some of the weathering of the bones occurred after scavenging took place.

The orientation of the bones suggests that while the assemblage was not extensively winnowed, some bones had begun to be transported and were aligned in the direction of the current. Despite the transport of some elements to the downstream side of the tree the deposit was not heavily winnowed based on the abundance of ribs and vertebrae both Group 1 elements of Voorhies Groups (1969). Transport probably occurred after scavenging and some disarticulation had begun. The lighter elements such as ribs, vertebrae and podials are the elements most commonly found on the south side of the tree. After disarticulation had begun some of these bones could have been transported to the downstream side of the tree by fluvial transport. It is also possible that scavenging of the carcasses led to the transport of some bones to the south side of the tree.

Many bones from the quarry have fractures and signs of compaction. There are few surfical scratches and no deeply plunging bones used as evidence for trampling as described by Fiorillo, (1989). The fractures are both longitudinal and perpendicular to the axis of the bone. Bones with the most fractures are those which had the greatest amount of bone to bone contacts. Spiral fracture patterns on several bones indicate the bones were fractured and crushed prior to fossilization. It seems likely that these fractures and signs of crushing were caused by lithostatic loading after deposition of the bonebed. Other bones have been sheared and distorted, also likely due to lithostatic load.

Cause of Death

From the evidence available it is impossible to determine the causal mechanism of death for the brachylophosaurs. Nonetheless, several mechanisms that have been previously suggested for vertebrate bonebeds can be ruled out. The presence of lower flow regime conditions within the bonebed as well as elsewhere in the field area rules out a flood as the cause. Volcanic eruptions have been previously cited for the cause of vertebrate bonebeds (Hooker, 1987; Voorhies, 1985). There is however, no evidence of volcanic activity anywhere in the field area and the known volcanic fields were all several hundred miles to the west at this time. Debris flows have also been documented as a cause of vertebrate accumulations (Schmitt et al., 1998) but they can also be ruled out due to presence of the facies (St, Sr) that were interpreted to be the result of migrating subaqueous dunes and ripples under lower flow regime conditions. Drought alongside waterholes has been suggested for dinosaur bonebeds within the Upper Cretaceous Two

Medicine Formation of Montana (Carpenter, 1987; Rogers, 1990; Varricchio, 1995), but there is no evidence of mudcracks, associated caliche horizons, vertical bones, or high weathering stages, all attributes of waterhole assemblages.

For the Careless Creek bonebed in the Judith River Formation of southcentral Montana which contains both logs and vertebrate remains, Fiorillo (1991b) suggested that the hadrosaurs where drowned in the channel in a weakened state based on a comparison to modern herding animals such as wildebeests. There is no other evidence to support this possible mechanism for the Careless Creek Quarry and it is doubtful that such evidence could be found. Furthermore this mechanism is dependent on hadrosaurs behaving in a similar manner to mammals, which can not be easily demonstrated. There is also no evidence to support this mode of death from the Malta bonebed. The brachylophosaur skeletal elements within the bonebed share similar weathering, abrasion, and disarticulation attributes, suggesting a similar taphonomic history for all, but is unclear how this related to their demise.

Time-Averaging and Paleoecology

It has been suggested by several authors that hadrosaurs were gregarious (Horner, 1982; 1984a; 2000;Rogers, 1990;Fiorillo, 1991b). Most of the evidence for this assertion is based on the occurrence of monospecific and paucispecific bonebeds dominated by hadrosaurs. While the dominance of one species within an assemblage is significant, the taphonomic context of the assemblage must be considered before this can be concluded.

Given the limitations of the geologic and taphonomic evidence it is impossible to directly determine how long it took for the brachylophosaur bones to accumulate. It is possible that the brachylophosaurs died at the same time or accumulated over a week, a month, a season or longer. Weigelt (1989) noted in coastal and fluvial settings of Texas that carcasses could accumulate over time to form a non-synchronous assemblage.

The presence of bones stacked near and on top of the large woody debris suggests that the tree was present within the channel prior to the arrival of the brachylophosaurs. Evidence from modern woody debris suggests a tree could remain within an active channel for a maximum of five years and still possess bark (Baillie et al., 1999; Bilby 2000). In a humid environment bark would be removed much more quickly (>2 years). The presence of bark on the tree trunk within the quarry limits the amount of time the tree could have been exposed (unburied) within the channel and affecting the accumulation of bones to less than five years.

The uniformity of weathering, lack of abrasion and other similar taphonomic features of the brachylophosaurs are consistent with the animals being together in some form of aggregation when they died; however, these observations likewise do not prove this assertion either. The low degree of weathering (Stage 0-1), the lack of winnowing, lack of abrasion and the degree of articulation/association suggest that the brachylophosaurs where exposed within the channel for only a brief period of time, probably less than a year.

Since the depositional environment of the bonebed is a fluvial channel it is likely that the brachylophosaurs took some time, however short or long it may have been, to accumulate. Given the evidence for bark on modern woody debris it is suggested that the six brachylophosaurs accumulated over a period of no more than five years.

The other vertebrate material in the quarry shows little to no association and often consists of individual elements. Many of these bones would fall into Voorhies Group I of easily transported material based on their size. These elements probably represent concentrated material spanning a much longer period of time, perhaps thousands of years, although it may have accumulated within the channel over a much shorter period of time and from a variety of source areas. This material could have been transported as bed load in the channel before and/or after the brachylophosaurs arrived. It could also have been transported over the floodplain or brought by a scavenger/predator to the site. Another possible scenario is that these elements were reworked from the channel banks, like the mud rip-up clasts found within the sandstone. Any one of these or all three could have taken place.

The dominance of the brachylophosaurs and minimal amount of other vertebrate bones limits what can be said about the overall flora and fauna. Since the non-brachylophosaur material is fragmentary and probably represents a much longer time frame (10^1-10^5 years) we can not assume that the brachylophosaurs lived at the same time as the associated fauna.

CHAPTER 6

CONCLUSIONS

A recently discovered bonebed in the Upper Cretaceous Judith River Formation of north central Montana has yielded a paucispecific assemblage of dinosaurian vertebrates. Sedimentologic evidence suggests that the deposit accumulated in a shallow (< 1.8m) sandy meandering channel under lower flow regime conditions. Given the relatively small scale of the channel and proximity (< 9m) of the deposit to the underlying shoreface Parkman Sandstone the channel may have been distributary in nature and close to the paleoshoreline.

At least six brachylophosaur individuals have been recovered from the bonebed representing at least two age classes (adult and sub-adult). The bones themselves show minimal weathering, no abrasion, some fractures and crushing and a few tooth marks. There are a few instances of articulation and a large degree of association among the brachylophosaurs. The bones are in stacked on top of, against and in the vicinity of a tree trunk and oriented generally parallel to the tree trunk suggesting that the tree influenced the accumulation of the bones. The high degree of association and lack of hydraulic equivalence (Behrensmeyer, 1975) between the sediment grain size and bones suggest the brachylophosaurs arrived in the quarry as bloated carcasses and accumulated on the upstream portion of a fallen tree.

Subsequent to their entanglement the carcasses were scavenged, disarticulated and weathered. Accumulation of the brachylophosaurs probably represents a short period (<5 years) based on the presence of bark on the tree. The other vertebrate material likely represents a much longer period of time and may have accumulated from a number of different processes.

As Fiorillo (1991b) has previously suggested, logjams have most likely acted as collection points for other fossil material to accumulate. The following criteria are suggested as the means to which identify such logjams in the fossil record; 1) presence of substantial large woody debris, defined here as wood fragments greater than a meter in length and twenty centimeters in diameter, 2) presence of the woody debris in a channel or similar environment were organic material could actively be accumulated, 3) demonstration that the woody debris was present before the accumulation of fossil vertebrates, 4) a high density of vertebrate bones within direct contact or the immediate vicinity of the woody debris compared to the area that lacks woody debris, 5) some degree of articulation demonstrating that complete carcasses accumulated within the deposit, and 6) possible orientation of long bones similar to the orientation of the tree.

The cause of death for the brachylophosaurs is unclear. Monospecific and pausispecific hadrosaur bonebeds have been previously used as evidence for herding. In this case there is no direct evidence that the brachylophosaurs were together when they died. It is suggested that the presence of mono- and pausispecific assemblages alone should not be used as evidence for gregarious behavior in extinct taxa.

REFRENCES CITED

Ancell, C. A., Harmon, R., and Horner, J. R., 1998, Gar in a duck-bill: preservation of a scavenger and its prey: Journal of Vertebrate Paleontology, v. 18 sup. no. 3, p. 24.

Badgley, C., 1986, Counting individuals in mammalian fossil assemblages from fluvial environments: Palaios, v. 1, p. 328-338.

Baillie, B. R., Cummins, T. L., and Kimberley, M. O., 1999, Measuring woody debris in the small streams of New Zealand's pine plantations: New Zealand Journal of Marine and Freshwater Research, v. 33, p. 87-97.

Behrensmeyer, A. K., 1978, Taphonomic and ecological information from bone weathering.: Paleobiology, v. 4, p. 150-162.

Behrensmeyer, A. K., 1982, Time resolution in fluvial vertebrate assemblages: Paleobiology, v. 8, p. 211-227.

Behrensmeyer, A. K., and Kidwell, S. M., 1985, Taphonomy's contributions to paleobiology: Paleobiology, v. 11, p. 105-119.

Beland, P., and Russel, D. A., 1979, Ectothermy in dinosaurs: Paleoecological evidence from Dinosaur Provincail Park, Alberta.: Canadian Journal of Earth Science, v. 16, p. 250-255.

Beland, P., and Russell, D. A., 1978, Paleoecology of Dinosaur Provincial Park (Cretaceous), Alberta, interpreted from the distribution of articulated vertebrate remains: Canadian Journal of Earth Sciences, v. 15, p. 1012-1024.

Bilby R. E., 2000, Decomposition and nutrient dynamics of wood in rivers: International Conference on Wood in World Rivers, Abstracts, p. 11.

Bourgeois, J., and Leithold, E. L., 1983, Wave-worked conglomerates-Depositional processes and criteria for recognition, *in* Koster, E. H. a. S., R. J., ed., Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists Memoir, p. 331-343.

Bragg, D. C., Kershner, J. L., and Roberts, D. W., 2000, Modeling large woody debris recruitment for small streams of the Central Rocky Mountains: USDA Forest Service Rocky Mountain Research Station General Technical Report, v. RMRS-GTR-55, p. 1-24.

Service Rocky Mountain Research Station General Technical Report, v. RMRS-GTR-55, p. 1-24.

Brain, C. K., 1981, The Hunters or the Hunted? An Introduction to African Cave Taphonomy: Chicago, University of Chicago Press, 365 p.

Brinkman, D. B., 1990, Paleoecology of the Judith River Formation (Campanian) of Dinosaur Provincial Park, Alberta, Canada: evidence from vertebrate microfossil localities: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 37-54.

Brinkman, D. B., Ryan, M. J., and Eberth, D. A., 1998, The paleogeographic and stratigraphic distribution of Ceratopsids (Ornithischia) in the Upper Judith River Group of Westen Canada.: Palaios, v. 13, p. 160-169.

Carpenter, K., 1987, Paleoecological significance of droughts during the Late Cretaceous of the western interior, Fourth Symposium on Mesozoic terrestrial Ecosystems: Occasional Papers of the Tyrell Museum of Palaeontology, no. 3, 42-47 p.

Cheel, R. J., and Leckie, D. A., 1993, Hummocky cross-stratification: Sedimentology Review, v. 1, p. 103-122.

Cotter, E., and Graham, J. R., 1991, Coastal plain sedimentation in the Late Devonian of southern Ireland: hummocky cross-stratification in fluvial deposits: Sedimentary Geology, v. 72, p. 210-224.

Currie, P. J., and Dodson, P., 1984, Mass death of a herd of ceratopsian dinosaurs, *in* Reif, W. E., and Westphal, F., eds.,, ed., Third Symposium of Mesozoic Terrestrial Ecosystems, Short Papers, p. 61-66.

Dodson, P., 1971, Sedimentology and taphonomy of the Oldman Formation (Campanian), Dinosaur Provincial Park, Alberta (Canada): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 10, p. 21-74.

Dodson, P., 1973, The significance of small bones in paleoecological interpretation: Contributions to Geology, University of Wyoming, v. 12, p. 15-19.

Eberth, D. A., 1990, Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 1-36.

Eberth, D. A., 1996, Origin and significance of mud-filled incised valleys (Upper Cretaceous) in southern Alberta, Canada: Sedimentology, v. 43, p. 459-477.

Eberth, D. A., and Brinkman, D. B., 1997, Paleoecology of an estuarine, incised-valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada: Palaios, v. 12, p. 43-58.

Ethridge, F. G., and Schumm, S. A., 1978, Reconstructing paleo-channel morphologic and flow charateristics: methodology, limitations and assessment, *in* Miall, A. D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir, p. 703-721.

Fiorillo, A. R., 1988, A proposal for graphical presentation of orientation data from fossils: Contributions to Geology, University of Wyoming, v. 26, p. 1-4.

Fiorillo, A. R., 1989, An experimental study of trampling implications for the fossil record, *in* Bonnichsen, R., and Sorg, M. H., eds., Bone Modification: Center for the Study of the First Americans: Orono, University of Maine, p. 61-72.

Fiorillo, A. R., 1991a, Prey bone utilization by predatory dinosaurs: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 88, p. 157-166.

Fiorillo, A. R., 1991b, Taphonomy and depositional setting of Careless Creek Quarry (Judith River Formation), Wheatland County, Montana, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 81, p. 281-311.

Fiorillo, A. R., Padian, K., and Musikasinthorn, C., 2000, Taphonomy and depositional setting of the *Placerias* quarry (Chinle Formation: Late Triassic, Arizona): Palaios, v. 15, p. 373-386.

George, 1994, Tidal sedimentation in part of the Late Silurian Grampians Basin, southeastern Australia: Journal of Sedimentary Research, v. 64, p. 311-325.

Gill, J. R., and A., C. W., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U. S. Geological Survey, Professional Paper 776, p. 37p.

Hanna, R. R., LaRock, J. W., and Horner, J. R., 1999, Pathological Brachylophosaur bones from the Upper Cretaceous Judith River Formation, northeastern Montana: Journal of Vertebrate Paleotology, v. 19, sup. no. 3, p. 49.

Haynes, G., 1988, Mass deaths and serial predation: Comparative taphonomic studies of modern large mammal death sites: Journal of Archeological Science, v. 15, p. 219-235.

Hooker, J. S., 1987, Late Cretaceous ashfall and the demise of a hadrosaurian "herd": Geological Society of America, Rocky Mountain Section, Abstracts with Programs, v. 19, p. 284.

Horner, J. R., 1982, Evidence of colonial nesting and site fidelity among ornithischian dinosaurs: Nature, v. 297, p. 675-676.

Horner, J. R., 1984a, The nesting behavior of dinosaurs: Scientific American, v. 250, p. 130-137.

Horner, J. R., 1984b, Three ecologically distinct vertebrate faunal communities from the Late Cretaceous Two Medicine Formation of Montana, with discussion of evolutionary pressures induced by interior seaway fluctuations, *in* Montana Geological Society Field Conference, Northwest Montana, Billings, p. 299-303.

Horner, J. R., 1989, The Mesozoic terrestrial ecosystems of Montana, *in* Montana Geological Society Field Conference Guidebook, p. 296-298.

Horner, J. R., 2000, Dinosaur reproduction and parenting: Annual Reviews of Earth and Planetary Science, v. 28, p. 19-45.

Jowett, E. C., and Robin, P.-Y. F., 1988, Statistical significane of clustered orientation data on a sphere: an empirical derivation: Journal of Geology, v. 96, p. 591-599.

Kauffman, E. G., 1977, Geological and biological overview: Western Interior Cretaceous Basin: Mountain Geologist, v. 14, p. 75-99.

Kauffman, E. G., and Caldwell, W. G. E., 1993, The western interior basin in space and time, *in* Caldwell, W. G. E. a. K., E. G., ed., Evolution of the Western Interior Basin, Geological Association of Canada, Special Paper 39, p. 1-30.

Knechtel, M. M., and Patterson, S. H., 1956, Bentonite deposits in marine Cretaceous formations of Hardin District, Montana and Wyoming, United States Geological Survey Bulletin, 116 p.

Koster, E. H., and Currie, P. J., 1987, Upper Cretaceous coastal plain sediments at Dinosaur Provincial Park, southeast Alberta: Geological Society of America Centenial Field Guide, Rocky Mountain Section, v. 2, p. 9-14.

Leckie, D. A., and Walker, R. G., 1982, Storm and tide dominated shorelines in Cretaceous Moosebar-Lower Gates interval - outcrop equivelants of deep basin gas traps in Western Canada: American Association of Petrolium Geology Bulletin, v. 18, p. 138-157.

Leeder, M. R., 1973, Fluviatile fining-upwards cycles and the magnitude of palaeochannels: Geology Magazine, v. 110, p. 265-276.

Leidy, J., 1856, Notice of remains of extinct reptiles and fishes, discovered by Dr. F.V. Hayden in the badlands of the Judith River, Nebraska Territory: Proceedings of the Academy of Natural Sciences of Philidelphia, v. 8, p. 72-73.

Martel, A. T., and Gibling, M. R., 1991, Wave-dominated lacustrine faceis and tectonically controlled cyclicity in the Lower Carboniferous Horton Bluff Formation, Nova Scotia, Canada, *in* Anadon, P., Ll. Cabrera, and K. Kelts, ed., Lacustrine Facies Analysis: Special Publication of the International Associations of Sedimentologists, p. 223-244.

Maxwell, W. D., and Ostrom, J. H., 1995, Taphonomy and paleobiological implications of *Tenontosaurus-Deinonychus* associations: Journal of Vertebrate Paleontology, v. 15, p. 707-712.

Miall, 1977, A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1-62.

Miall, 1996, The Geology of Fluvial Deposits: New York, Springer, 582 p.

Ostrom, J. H., 1969, Osteology of *Deinonychus antirrhopus*, an unusual theropod from the Lower Cretaceous of Montana: Bulletin of the Peabody Museum of Natural History, v. 30, p. 1-165.

Reineck, H. E., and Singh, I. B., 1973, Depositional Sedimentary Environments: New York, Springer-Verlag, 439 p.

Rogers, R. R., 1990, Taphonomy of three dinosaur bone beds in the Upper Cretaceous Two Medicine Formation of northwest Montana: Evidence for drought related mortality: Palaios, v. 5, p. 394-413.

Rogers, R. R., 1993, Systematic patterns of time-averaging in the terrestrial vertebrate record: A Cretaceous case study, *in* Kidwell, S. M., and Behrensmeyer, A. K., ed., Taphonomic Approaches to Time Resolution in Fossil Assemblages: Short Courses in Paleontology: Knoxville, tennessee, The Paleontological Society, p. 228-249.

Rogers, R. R., 1995, Sequence stratigraphy and vertebrate taphonomy of the Upper Cretaceous Two Medicine and judith River Formations, Montana [Dissertation thesis]: University of Chicago, 216 p.

Rogers, R. R., 1998, Sequence analysis of the Upper Cretaceous Two Medicine and Judith River Formations, Montana: Nonmarine responses to the Clagget and Bearpaw marine cycles: Journal of Sedimentary research, v. 68, p. 615-631.

Rust, B. R., 1978, Depositional models for braided alluvium, *in* Miall, A. D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir, Canadian Society of Petroleum Geologists, p. 605-625.

Sahni, A., 1972, The vertebrate fauna of the Judith River Formation, Montana: American Museum of Natural History Museum Bulletin, v. 147, p. 321-412.

Schmitt, J. G., Horner, J. R., Laws, R. R., and Jackson, F., 1998, Debris flow deposition of a hadrosaur-bearing bone bed, Upper Cretaceous Two Medicine Formation, northwest Montana: Journal of Vertebrate Paleontology, v. 18, sup. no. 3, p. 76.

Schwartz, H. L., and Gillette, D. D., 1994, Geology and taphonomy of the Coelophysis quarry Upper Triassic Chinle Formation, Ghost Ranch, New Mexico: Journal Of Paleontology, v. 68, p. 1118-1130.

Toots, H., 1965, Sequence of disarticulation in mammalian skeletons: Contributions to Geology, University of Wyoming, v. 4, p. 37-39.

Varricchio, D. J., 1995, Taphonomy of Jack's Birthday Site, a diverse dinosaur bone bed from the Upper Cretaceous Two Medicine Formation of Montana: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 114, p. 297-323.

Varricchio, D. J., and Horner, J. R., 1993, Hadrosaurid and lambeosaurid bone beds from the Upper Cretaceous Two Medicine Formation of Montana: Taphonomic and biologic implications: Canadian Journal of Earth Science, v. 1993, p. 997-1006.

Voorhies, M. R., 1969, Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox county, Nebraska: Contributions to Geology, University of Wyoming, Special Paper Number One, p. 68.

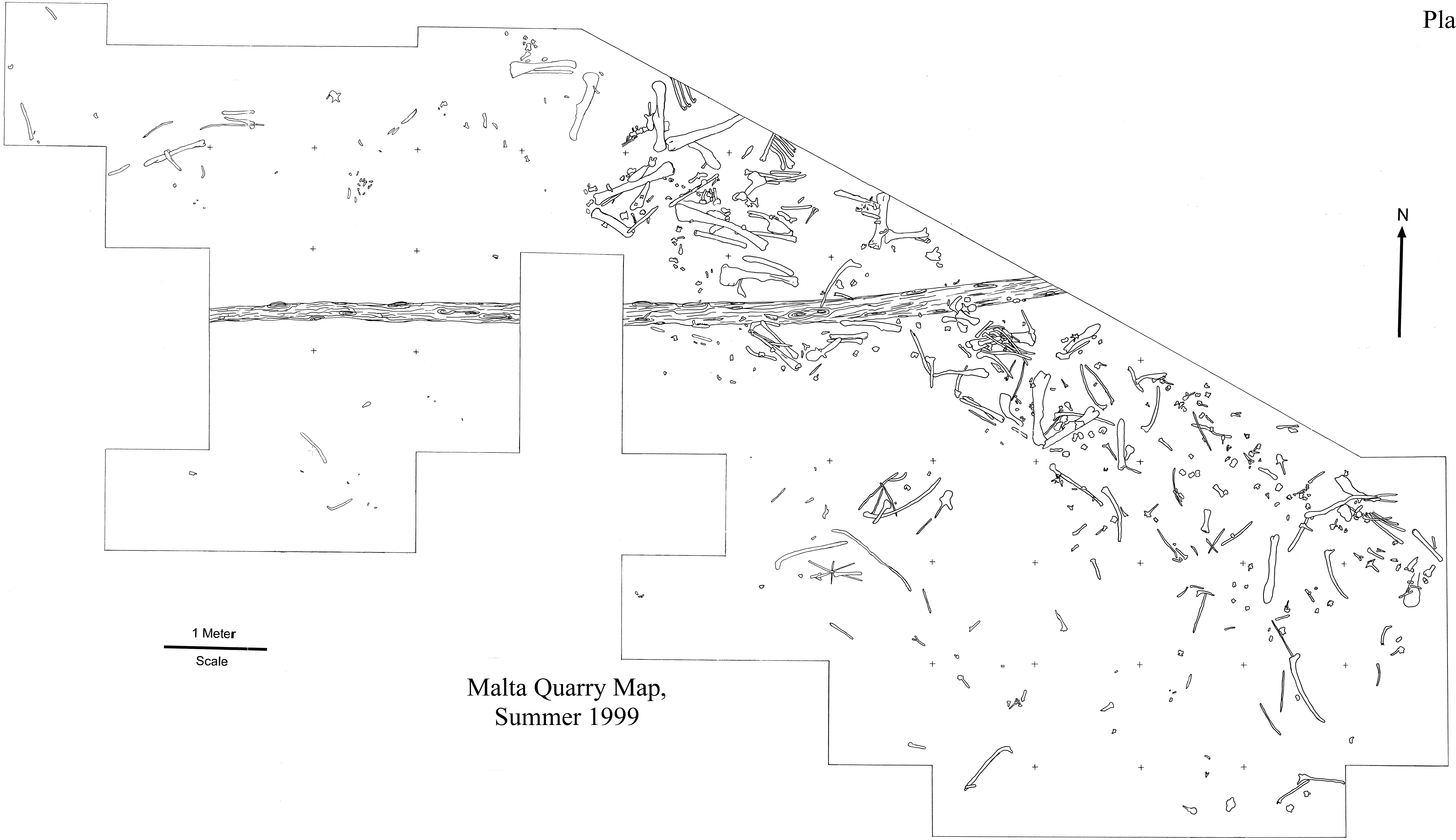
Voorhies, M. R., 1985, A Miocene rhinoceros herd buried in volcanic ash.: National Geographic Research Report Projects, v. 1978, p. 671-688.

Walker, G. W., and Bergman, K. M., 1993, Shannon Sandstone in Wyoming: A shelf-ridge complex reinterpreted as lowstand shoreface deposits: Journal of Sedimentary Petrology, v. 63, p. 839-851.

Weigelt, J., 1989, Recent Vertebrate Cracasses and their Paleobiological Implications: Chicago, University of Chicago Press, 188 p.

Wood, J. M., Thomas, R. G., and Visser, J., 1988, Fluvial processes and vertebrate taphonomy: The Upper Cretaceous Judith River Formation, south-central Dinosaur Provincial Park, Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 66, p. 127-143.

Plate 1



Malta Quarry Map,
Summer 1999