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STRATIGRAPHY, SEDIMENTOLOGY, AND TAPHONOMY OF A SAUROPOD QUARRY FROM THE UPPER MORRISON FORMATION OF THERMOPOLIS, CENTRAL WYOMING

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Abstract—We describe the lithology, stratigraphy and fossils from the Upper Morrison Formation of the Beside Sauropod (BS) Quarry on the Warm Springs Ranch near Thermopolis, Wyoming. Among vertebrate and invertebrate fossils, sauropod skeletal remains dominate from the quarry, including one large *Apatosaurus* and two fully-grown *Camarasaurus*. The fairly complete three skeletons are disarticulated, although they are well-preserved. No other vertebrate fossils are found with exception of at least 29 shed theropod teeth, indicating possible scavenging activity. All sauropod bones are found in a carbonate mudstone layer, which also contains abundant lignitic fragments and some siliceous tree-trunks. We think burial took place in a poorly-drained floodplain near a palustrine or lacustrine system. Although mudstone, sandstone, and siltstone are the three most common types of rocks in the upper Morrison Formation, the sequence and thickness of each layer varies between the BS Quarry and other dinosaur quarries on the Warm Springs Ranch. Differences are also discernable in sediments of the original bone bearing layers in the relatively small area, indicating complex fluvial and lacustrine systems, such as anastomosing river channels, may have been present in central Wyoming in the early Tithonian time.

INTRODUCTION

The Morrison Formation consists of fluvial and lacustrine deposits generally characterized by thick layers of multi-colored mudstone in the Rocky Mountain region. Facies changes are found through the initial sequence of the formation due to discontinuous sediments of heterolithic sandstone, siltstone, and mudstone; for example, 12 lithofacies are found in a small area of central Wyoming (Jennings, 2005). Lithology and overall thickness also vary in the Morrison Formation (Mirsky, 1962; Furher, 1970; Lawton, 1994; Peterson, 1994; Turner and Peterson, 1999, 2004; Rees et al., 2004). Significant questions still remain with regard to the stratigraphic correlation and interpretation of the depositional environment in the Morrison Formation among most sub-basins and/or ranges (Trujillo, 2002; Ikejiri, 2005). Therefore, detailed descriptions of lithology and stratigraphy on a local scale are needed to ascertain geologic information on a larger scale in the Morrison Formation.

Since 1994, the Wyoming Dinosaur Center (WDC) has been excavating over a dozen individual fossil sites in the upper Morrison Formation on about 1.6 km^2 (400 acres) of the Warm Springs Ranch, which is about 1.5 km southeast of Thermopolis near the southern edge of the Big Horn Basin in central Wyoming (Fig. 1). Multiple dinosaur skeletons have been excavated from three major quarries: Bone Bed (BB), Beside Sauropod (BS), and Something Interesting (SI) (Fig. 2). Isolated dinosaur bones have also been recovered from over a dozen other sites on the ranch (Watkins et al., 2005). Sauropod remains dominate the vertebrate fossils from the ranch. In the BS Quarry the majority of the bones belong to three large sauropod skeletons. These remains consist of one *Apatosaurus* (NSMT-PV 20375; Upchurch et al., 2004) and two fully-grown *Camarasaurus lentus* (WDC A, B) (Ikejiri, 2004; Ikejiri et al., 2005). Aside from sauropod remains, theropod shed teeth are the only vertebrate fossils found in the BS Quarry, which is possibly significant for interpretation of taphonomic events.

We describe the sedimentology, stratigraphy and fossils found at the BS Quarry. Based on this information, we discuss taphonomic processes associated with these sauropod skeletons. Additionally, lithology and stratigraphy are compared among the three major quarries on the Warm Springs Ranch. Hopefully, our study will provide a small piece of the puzzle to better understand the paleoenvironment of the Rocky Mountain region in the Late Jurassic.

Abbreviations for quarries: **AM**, Accurately Measured; **BB**, Bone Bed; **BS**, Beside Sauropod; **CB**, Cheryl's Blind; **FS**, Foot Site; **LA**, Large Apatosaur; **PM**, Possible Megalosaur; **S**, Sauropod; **SD**, Schencks' Dinosaur; **SI**, Something Interesting; **TH**, Ty's Humerus; **TYA**, There You Are.

Abbreviations for institutions: **NSMT-PV**, National Science Museum, Tokyo; **WDC**, Wyoming Dinosaur Center, Thermopolis, WY.

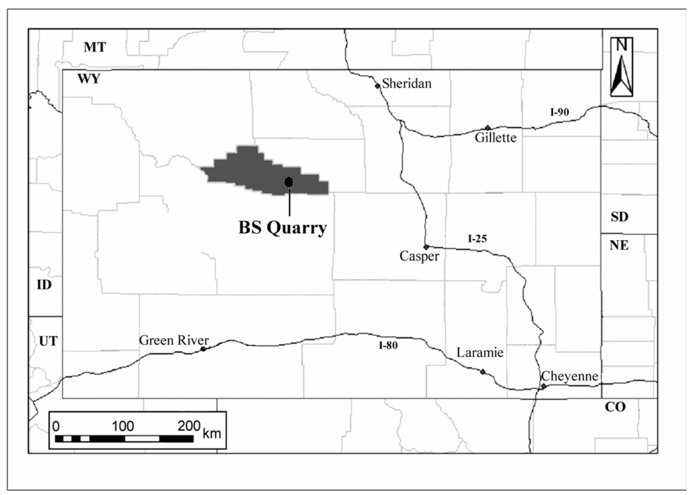

FIGURE 1. Location of the Beside Sauropod (BS) Quarry near Thermopolis, Wyoming. Hot Springs County is denoted by gray.

DISCOVERY AND EXCAVATION OF THE BS QUARRY

After the first dinosaur remains were found at the BS Quarry in the summer of 1993, the WDC soon recognized the site potentially contained abundant sauropod bones. In 1994, excavation began in the southwestern section of the BS Quarry, and extensive excavations were made from 1994 to 1997 and from 2000 to 2005 mostly under the direction of Pamela Watkins. The quarry was extended to the northeast and three sauropod skeletons, two *Camarasaurus* and one *Apatosaurus*, were found. Most elements of the *Apatosaurus* were collected from the southwestern part of the site, formerly referred to as the S Quarry (Upchurch et al., 2004). The majority of skeletal remains of *Camarasaurus* tend to be concentrated in the central and the northeastern areas of the BS Quarry (Fig. 3) (Upchurch et al., 2004).

Most bones of the *Apatosaurus* (NSMT-PV 20375) were excavated by 1997 in the S Quarry and this specimen was sent to the NSMT. Some cranial elements of *Camarasaurus* were also sent to Japan with the skel-

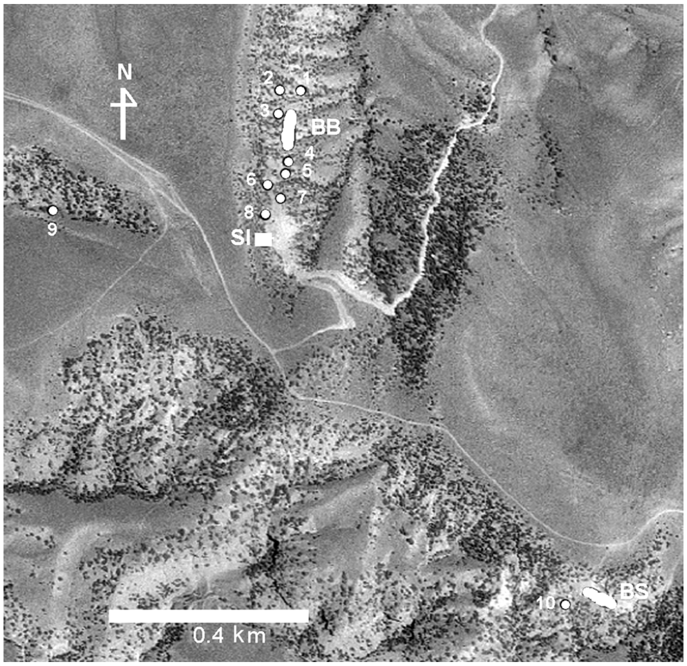

FIGURE 2. Aerial photo of the partial Warm Springs Ranch in central Wyoming, showing location of the BB, BS, and SI quarries. Symbols for other quarries are: **1**, FS, **2**, AM, **3**, LA, **4**, SD, **5**, TYA, **6**, TH, **7**, CB and **8**, PM.

eton of *Apatosaurus*. After preparation in Germany, the skeleton of *Apatosaurus* was mounted at the NSMT in the winter of 2000. Fossil remains of *Camarasaurus* from the BS Quarry were prepared, and in 2000, David Trexler mounted a composite skeleton of *Camarasaurus* (WDC A, B) at the WDC. Many of the remaining elements associated with WDC A and B are also on display in another section of the museum. In the fall of 2005, Mike Grissom skillfully re-mounted the original skeleton (mostly WDC A) at the museum, and another skeleton (WDC B) is scheduled to be mounted in 2006. Excavation is still ongoing since potentially some remains of the three sauropods are still covered in the quarry.

GEOLOGIC SETTING

Overview and Stratigraphy of the Warm Springs Ranch Dinosaur Quarries

A number of excellent dinosaur quarries are known from the Morrison Formation near the Bighorn Basin, north central Wyoming, such as the Greybull-Shell (e.g., Howe Ranch quarries, Smithsonian quarries), Kaycee (e.g., Red Fork Powder River quarries), and Buffalo (e.g., Poison Creek quarries) areas. The southern region of the basin seems to be less productive with only the Warm Springs Ranch known to contain major dinosaur quarries. There are over a dozen dinosaur quarries on the Ranch (AM, CB, FS, LA, PM, SD, TH, and TYA quarries) and most are clustered near each other in a small area on the east side of the hill (Watkins et al., 2005) (Fig. 2). The BS Quarry is located on the south side of the hill approximately 800 m to the southeast.

The stratigraphy and lithology of the Morrison Formation on the Warm Springs Ranch have been studied by several authors (e.g., Bjoraker, 1995; Bjoraker and Naus, 1996; Carson, 2000; Jennings, 2005). Small-scaled facies changes, involving sandstone, siltstone, red mudstone, olive mudstone and greenish gray mudstone lithologies (Jennings, 2005), often occur near the bone beds in the quarries due to the transition between fluvial and lacustrine deposits (Bjoraker, 1995; Bjoraker and Naus, 1996; Jennings, 2005**)**. Seemingly, no consistent regional isochronous marker bed has widely accepted in the entire geographical area of the Morrison Formation, although a few ideas have been proposed (Owen et al., 1989; Fishman et al., 1995; Demko et al. 1996; Turner and Peterson, 1999). Therefore, correlation of the Warm Springs Ranch dinosaur quarries in the upper Morrison Formation is difficult, and, hopefully, more detailed studies of sedimentology and lithology of each quarry will aid in clarification.

Dinosaurs are the most abundant vertebrate fossils from the upper Morrison Formation and, biostratigraphically, some taxa are potentially useful for identification on broad stratigraphic level (e.g., Turner and Peterson, 1999; Foster, 2003; Ikejiri, 2005). Based on five biozones of *Camarasaurus* established by Ikejiri (2004, 2005), the BS Quarry is thought to occur in Transitional Zone, which is slightly above the Kimmeridgian/Tithonian boundary.

The Cloverly Formation (early Cretaceous) comprises the uppermost layer near the BS Quarry and is characterized by slightly silty, medium to coarse sandstone and granular chert to pebbly conglomerate (Fig. 4). No fossil remains of vertebrates have been found in the Cloverly Formation on the ranch (Burkhard Pohl, personal communication). No evidence of the Sykes Mountain Formation, which supposedly overlies the Cloverly Formation in the area, is present at the quarry. Vertically, the quarry is placed about 9.5-10 m below the J/K boundary in the upper Morrison Formation, and Turner and Peterson (1999) interpreted the vertical position as approximately just below the Tithonian/Kimmeridgian boundary. The thick marine Sundance Formation underlies the Morrison Formation.

Sedimentology of the BS Quarry

Laterally, the BS Quarry comprises an elongate area, 50 m x 15 m, running from west to east. The strata in the quarry dip 7° towards north. Because the quarry is located on a step or bench along the hill, a vertical cross section can be observed. Most dinosaur remains occur within a vertical thickness (about 1.0 m) of the bone bearing layer.

The bone bed consists of dark green or gray mudstone, containing abundant illite, (Jennings, 2005). The dark mudstone is very crumbly with a sharp edge when dry, which is commonly found in the upper portion of the formation from Como Bluff, Wyoming to Morrison, Colorado (Turner and Peterson, 2004). Very hard silty carbonate nodules are fairly common in the upper half of the bone layer at the BS Quarry (Fig. 4). Nodules range up to 0.15 m in a diameter and are variable in shape (circular to oval) with rounded smooth surfaces. Above the bone layer, thin layers (up to 0.2 m in thickness) of similar hard carbonate rock exist. Those layers are pinched out and do not extend to the SI or BB Quarry on the east side of the hill.

Dinosaur bones are concentrated near the bottom half of the mudstone layer although some large elements are also common in the mid-section (Fig. 4). In the lower layer of the bone bed abundant lignite fragments are present, as well as large pieces of siliceous tree-trunks. Only small skeletal fragments occur in the upper 25 % of the bone bed even though the same type of mudstone is present. A thin sandstone layer (about 0.4 m in vertical thickness) underlies the bone bed and is quite distinctive from the mudstone. No fossils have been found in this fine sandstone bed, but some large bones were almost lying on top of the layer.

About 1 m above the bottom of the bone bed, several thin layers (from 0.1 to 0.3 m thickness) of carbonate rocks and much thicker mudstone alternate in a random sequence. The hard carbonate layers are light gray or dark yellow (when dry), lack fossils, and pinch out in a relatively short distance, less than10 m, near the BS Quarry (Fig. 4). Other Warm Springs' quarries, such as the SI Quarry, exhibit fewer and thinner layers characterized by limey mud with microscopic bioclasts and the presence of ostracods and lacustrine mollusks (Jennings, 2005). In addition, the SI Quarry has horizontal carbonate concretionary fills and in some places, vertical ones, which infill desiccation cracks (Jennings, 2005), but such vertical carbonate mudstone or limestone is absent in the BS Quarry.

About 10 m above the bone bed near the BS Quarry outcrops a random vertical sequence of three different facies with a total thickness of about 5 m. The three facies are characterized by a greenish gray claystone, a light grayish mudstone, and a dark greenish mudstone with purple mottles (Fig. 4), and each facies is less than 0.5 m in vertical thickness. The profile represented by these three types of facies is also commonly found at the BB and SI quarries on the Warm Springs Ranch (Watkins et al., 2005).

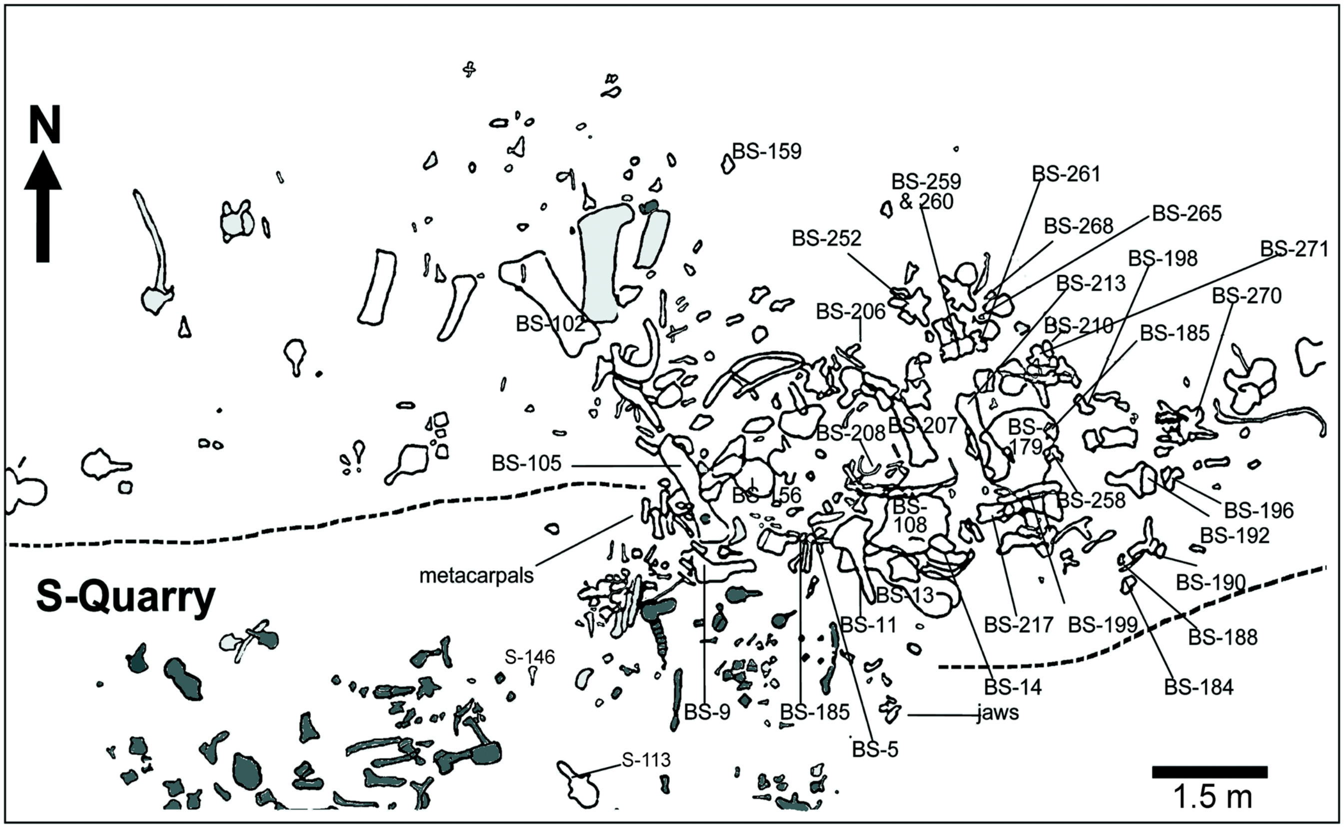

FIGURE 3. Partial map of the Beside Sauropod (BS) Quarry in central Wyoming. Identical bones of *Camarasaurus* (either WDC A or B) are white and dark gray for *Apatosaurus* (NSMT-PV 20375). Lighter gray indicates indeterminate taxon. Note most bones of three skeletons are disarticulated and physically overlap (Modified from Ikejiri et al., 2005).

With regard to a stratigraphic correlation between the BS and SI or BB quarries, we suggest that the sandstone layer placed just below the bone bed of the BS Quarry is a useful marker unit (Fig. 4). Although the BS Quarry is located about 0.8 km from the SI Quarry and vegetation covers the hill (Fig. 2), the angle and direction of the dip of the layers are similar among the quarries. Additionally, the thickness between the sandstone layer and the J/K boundary is close in the two different sites. Stratigraphically, the BS Quarry is estimated to be lower than the BB Quarry and higher than the SI Quarry (Fig. 4).

Dinosaurs from the Warm Springs Ranch

Eight genera of dinosaurs were reported from the WDC dinosaur quarries, including theropod (*Allosaurus*), sauropods (*Apatosaurus*, *Camarasaurus*, *Diplodocus* and *Brachiosaurus*) and ornithishcians (*Iguanodon*, *Stegosaurus*, and *Camptosaurus*) (Bjoraker and Naus, 1996; Turner and Peterson, 1999). However, some taxa seem to be misidentified from fragmentary elements. We think that the only first four genera are reasonably identified based on diagnostic elements (Watkins et al., 2005).

Three large fairly complete sauropod skeletons were found from the BS Quarry. Most bones of the large *Apatosaurus* (NSMT-PV 20375) were distributed in the southwestern area of the quarry (Fig. 3). However, it should be noted that some bones of *Camarasaurus* were also recovered near elements of *Apatosaurus* (Fig. 5G-J) that are though to belong to NSMT-PV 20375. Based on a minimum number of elements, the BS Quarry produced two skeletons of *Camarasaurus* (WDC A, B) (Fig. 5A-F) with approximately an 8 % size difference between the smaller WDC A and larger WDC B (Ikejiri, 2004; Ikejiri et al., 2005). The specimens are assigned to *C. lentus* based on the short massive neural arches occurring from the anterior to mid-dorsal vertebrae (Fig. 5B) and absence of T-shaped neural spines in the anterior caudal vertebrae (Ikejiri, 2004, 2005; Ikejiri et al., 2005).

TAPHONOMY OF THE BS QUARRY

Burial Condition

An important question to consider in the taphonomic process is whether or not the three sauropod skeletons were buried by a rapid flood event or multiple events over a relatively long period. Some bones of the three sauropods physically overlie suggesting that after death, possibly they were piled on each other in a single flood event. Some bones of the three sauropods were found in the same unit with no clear separation, which leads to the interpretation that the carcasses of the three sauropods were deposited about the same time.

Two distinct degrees of preservation of the sauropod skeletons may give us another clue for understanding the taphonomic process. Although all bones are placed in the same type of dark grayish mudstone with no strong evidence of paleosols [e.g., invertebrate trace fossils and plant rooting trace in the upper formation as described by Demko et al. (2004)], the lower half of the bone bearing layer has much better preserved elements (weathering stages 0 to 1 or 2 in Behrensmeyer, 1978). These bones are coated with a relatively thin carbonate rind; in contrast, all sauropod elements have weathered surfaces in the upper half of the bone bearing layer (30-50 cm interval). For the most part they are too fragmentary to be identified individual bones (Behrensmeyer's weathering stage 3-5). Higher quality of bone preservation seems to be a function of burial depth as the larger and heavier bones, such as the shoulder girdles, sacrum, and large limb bones, are found in the lower level.

Perhaps, the three sauropods were buried in low energy environment. Well-preserved and disarticulated skull (e.g., quadrates, fragmentary

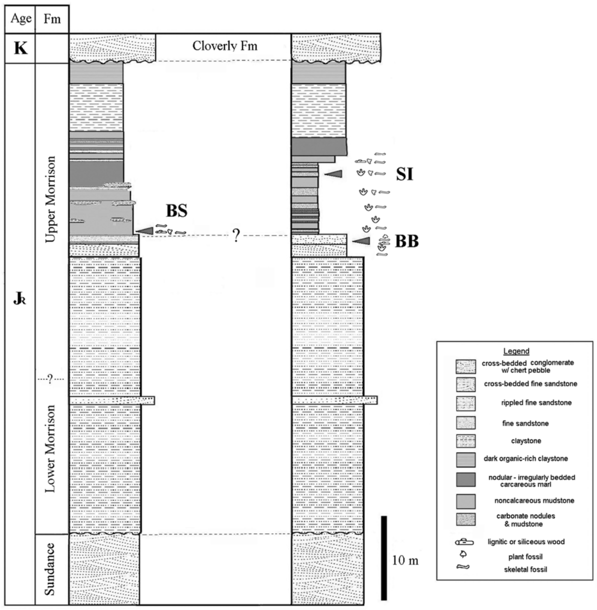

FIGURE 4. Stratigraphic section and lithology at the BS, BB, and SI quarries from the Upper Morrison Formation of central Wyoming. Modified from Ikejiri (2004), Jennings (2005), and Watkins et al (2005).

skull roof bones), jaw elements and isolated teeth of *Camarasaurus* are found throughout the entire quarry. Also, based on recent excavation (from 2002 to 2005), several long limb bones, both shoulder girdles, and several dorsal vertebrae belonging to WDC B are semi-articulated in the northeast area of the BS Quarry. Such small fragile bones preserved in the quarry and the skeletal association are possibly indicators of low energy environment.

Paleocurrent

The only possible evidence of a paleocurrent is that the three skeletons are largely disarticulated and the majority of the bones are relatively separated. Most remains of *Apatosaurus* came from the southwestern area of the BS Quarry, and bones from the northeastern part of the quarry tend to belong to the larger *Camarasaurus* (WDC B). However, some bones of the smaller *Camarasaurus* (WDC A) physically overlap the two other skeletons (Fig. 3). Such disarticulation and separation may be due to scavenging activity by carnivorous dinosaurs. Long limb bones and rib fragments show no particular orientation due to paleocurrent, and some bones of the three sauropods overlap each other as some jaw elements and caudal vertebrae of *Camarasaurus* are found with the skeleton of *Apatosaurus* (Fig. 3).

Most large sauropod bones, especially elongate limb and rib bones are deposited horizontally in the quarry. Relatively small bones (e.g., a metacarpal, limb and rib fragments) are deposited vertically. The latter type of deposition is much less common in the quarry; therefore, we suggest that the sauropod skeletons were buried under a relatively low energy environment, such as a lacustrine or palustrine system.

Scavenging Activity

At least 29 theropod shed teeth have been found from the BS Quarry. They range in size from 9.1 to 52.5 mm in the crown height (Table 1), implying the teeth belong to more than one theropod. Based on overall shape, the teeth can be classified as two morphotypes. Morphologically, most teeth are relatively long and transversely robust (Fig. 6A, B) indicating *Allosaurus* (Madsen, 1976; Bakker and Bir, 2004). In contrast, three teeth (WDC BS-641, 885, 889) are much smaller than those teeth of *Allosaurus* and also display a number of significant morphological differences, such as a stronger hook at the tooth tip, transversely compressed overall shape and relatively larger serrations, especially on the posterior carina. WDC BS-641 (Fig. 6C) shows well-serrated posterior carinae; in contrast finer serrations are only exhibited on about the 1/5 apical of the anterior carina. These small teeth have a smooth surface, which also differs from another common theropod from the Morrison Formation, *Ceratosaurus*, characterized by distinctive longitudinal groves (Madsen and Welles, 2000). Although a few indeterminate maniraptoran taxa are reported from the Morrison, such as *Coelurus*, *Tanycolagreus*, and *Ornitholestes* from the Morrison Formation (e.g., Carpenter et al., 2005a, b), no well-preserved teeth have been known in the first two taxa and the last taxon tend to have much larger overall size, which can be distinguished from the small distinctive hooked teeth from the BS Quarry (J.R. Foster, personal commun. 2006). Interestingly, the apically pointed tooth tip and the asymmetrical denticle development between the anterior and posterior proportions found in the three teeth from the BS Quarry are known in dromaeosaurids (Currie et al., 1990; Ostrom, 1990). Thus, it is possible that the three teeth infer a possible occurrence of a basal deinonychosaurid in the late Jurassic of North America (D.J. Varricchio, personal commun. 2005). However, remains of those small-bodied theropods are too fragmentary and taxonomic assignment is difficult based on isolated teeth.

Most shed teeth are well-preserved and recovered from the upper half of the bone bed layer in the BS Quarry. Because some teeth are found near large sauropod bones, it is possible that, at least, one of the sauropods was scavenged. However, it should be noted that after examining over a hundred rib pieces, 25 long limb and girdle bones and 21 chevrons, none of the elements exhibits clear bite marks or tips of shed teeth.

Additionally, in most other Warm Springs Ranch quarries, over a hundred shed theropod teeth have been recovered from the SI Quarry, indicating a possibly theropod feeding site (Jennings, 2005). Therefore, possibly, the sauropod carcasses were scavenged by theropod(s) near the BS Quarry. Such scavenging might be one explanation for the largely disarticulated sauropod skeletons in the quarry.

DEPOSITIONAL ENVIRONMENT OF THE BS QUARRY

Table 2 shows comparisons of paleoenvironmental factors at the BS Quarry with the BB and SI quarries. It should be noted that even in a relatively small area the bone bearing layers of BB, BS and SI quarries show different facies (Watkins et al., 2005). For example, the three sauropod skeletons are deposited in the illite-rich mudstone at the BS Quarry, and all sauropod bones are found in greenish gray carbonate or silty mudstone layers containing barite at the SI Quarry (Jennings, 2005). Such mudstone facies bearing sauropod skeletons in the BS and SI quarries seem to indicate either a lacustrine or palustrine system. In contrast, all skeletal remains of dinosaurs and plant fossils are found in light brownish or yellowish fine sandstone layers in the BB Quarry (Watkins et al., 2005). This facies is similar to fluvial/overbank floodplain deposits, as commonly reported in the lower and upper Morrison Formation (Demko et al., 2004).

Jennings (2005) suggested that two partial sauropod skeletons are deposited in two different facies at the SI Quarry although the vertical distance between the upper (containing a partially articulated diplodocid skeleton) and the lower (at least one disarticulated juvenile skeleton of *Camarasaurus*) units is less than 1 m. However, in the BS Quarry the three sauropod remains are found in the single thick mudstone layer with no significant facies changes, indicating that a single depositional event buried the three skeletons. In the BB Quarry 1370 dinosaur bones are physically laying on the cross-bedded sandstone layer (Watkins et al., 2005). The bone bearing layer of the BB Quarry is much thinner (about 50 cm) than that of the BS and SI quarries.

It is of interest that no small vertebrate fossils like crocodilian teeth, turtle scutes or fish bones are found on the Warm Springs Ranch even though they are often found in other major Morrison dinosaur quarries, such as the Dry Mesa Quarry, Dinosaur National Monument, Como Bluff and Garden Park (Foster, 2003). In the upper Morrison Formation, crocodilians and turtles are not known from the Bighorn Basin although some fragmentary elements are found in southern Montana and western South Dakota (J.R. Foster, personal commun. 2005).

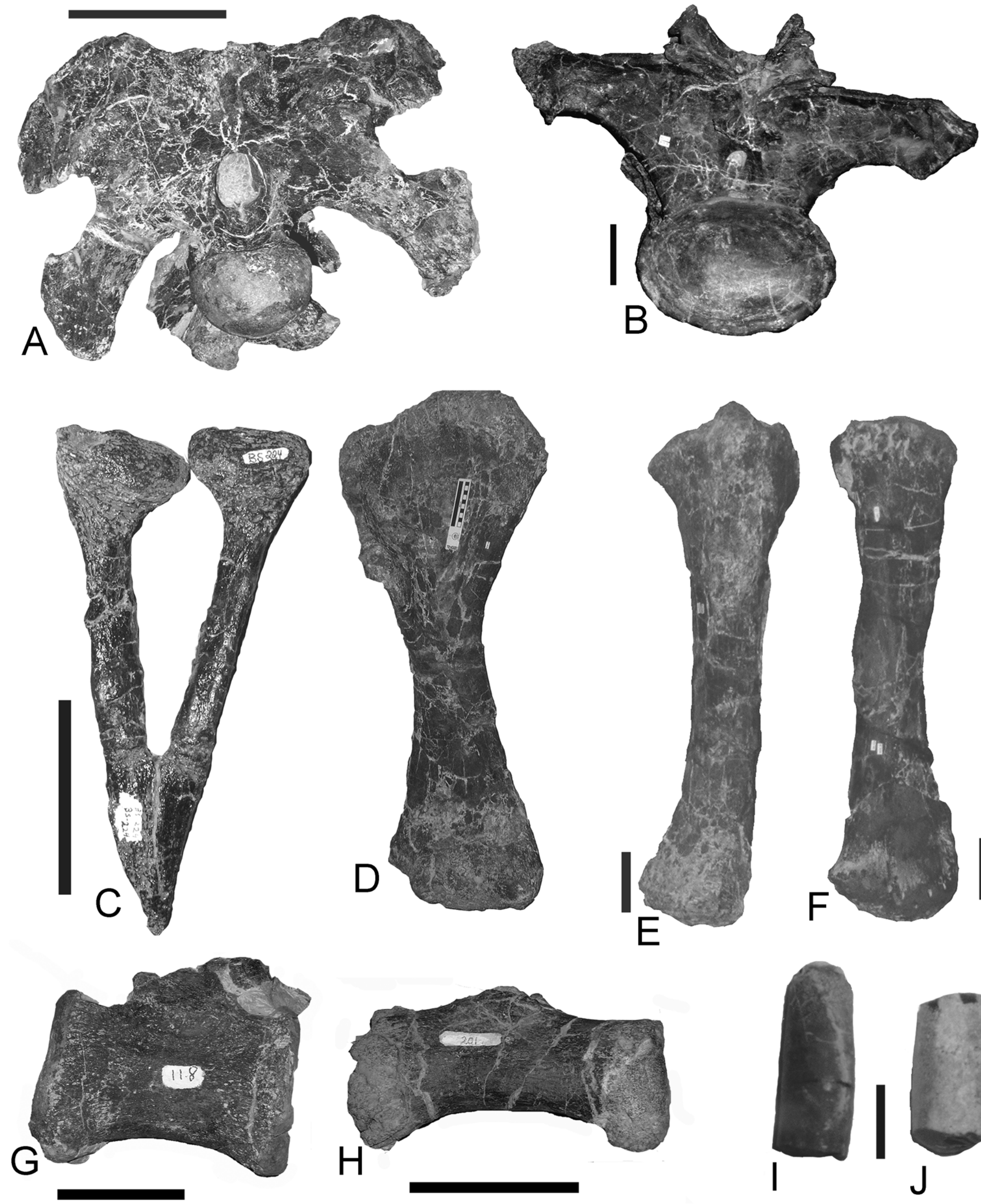

FIGURE 5. Selected sauropod bones from the BS Quarry in central Wyoming. *Camarasaurus lentus*, **A**, braincase (WDC B:BS-388), **B**, anterior dorsal vertebra (WDC B:BS-178), **C**, first chevron (WDC A?:BS-224), **D**, right humerus (WDC B:BS-724) **E**, left ulna (WDC B:BS-312) and **F**, left radius (WDC B:BS-315). *Apatosaurus*, **G**, distal caudal vertebra (WDC:S-118 = BS-425), **H**, distal caudal vertebrae (WDC:S-201), **I**, isolated tooth (WDC:BS-740) and **J**, isolated tooth (WDC:BS-713). **A-C**, posterior view. **D-F**, anterior view. **G** and **H**, left lateral view. Scale bars equal 10 cm in **A-H** and 1 cm in **I** and **J**.

The fossil distributions of crocodilians and turtles may indicate significantly different paleoenvironments. During the Tithonian time Western South Dakota is thought to be associated with stream deposits rather than lacustrine or pond deposits that were more preferable environments for crocodilians and turtles (Turner and Peterson, 2004). Thus, they might avoid living in those lacustrine environments in the Bighorn Basin area (J.R. Foster, personal commun. 2006). Another explanation could be that although these animals were present in the area, preservation was poor because the sediment water interface was oxidized and smaller skeletons might be destroyed by the decay process.

Non-vertebrate fossils are also found from the BS Quarry. A few indeterminate ostracods were collected from the bone bearing layer in the BS Quarry (Fig. 7) although no other microfossils are found. Small lignitic fragments are very common in the lower bone bed of the BS Quarry, which is similar to abundant plant remains in the BB Quarry. Also, siliceous tree-trunks are known from the BS Quarry, but such siliceous plant fossils are absent in the SI Quarry.

In summary, lignite suggests that reducing conditions existed at least some of the time. The combination of carbonate mudstone, ostracods, plant fossils and well-preserved bone (except at the top of the quarry) suggests that this is a marshy area associated with a floodplain lake or pond environment as classified by Turner and Peterson (2004).

TABLE 1. Size of selected theropod shed teeth from the Beside Sauropod Quarry in central Wyoming. All measurements are in mm. <> indicates incomplete measurements.

WDC number	CH	CBL	CW	Taxon
BS-618	<23.0>	<8.5>	<6.0>	*Allosaurus*
BS-621	<11.5>	<8.0>	<8.0>	*Allosaurus*
BS-643	<11.5>	8.0	?	*Allosaurus*
BS-691	<14.0>	<5.5>	<2.5>	*Allosaurus*
BS-700	36.6	16.0	14.0	*Allosaurus*
BS-715	<16.0>	<10.7>	<6.0>	*Allosaurus*
BS-716	<10.5>	<6.0>	<3.0>	*Allosaurus*
BS-725	<17.5>	<8.0>	<4.5>	*Allosaurus*
BS-749	32.8	15.6	12.3	*Allosaurus*
BS-798	<52.5>	<18.0>	<12.0>	*Allosaurus*
BS-820	<19.5>	?	?	*Allosaurus*
BS-835	<5.0>	<3.5>	?	*Allosaurus*
BS-836	<10.0>	<13.0>	<11.0>	*Allosaurus*
BS-837	<17.0>	<7.5>	?	*Allosaurus*
BS-846	<22.0>	<6.0>	<6.0>	*Allosaurus*
BS-915	<9.5>	<3.0>	<4.0>	*Allosaurus*
BS-641	9.1	9.2	4.2	deinonychosaurid(?)
BS-885	12.6	8.3	3.6	deinonychosaurid(?)
BS-889	12.2	7.0	3.2	deinonychosaurid(?)

Abbreviations for measurements: **CBL**, fore-aft basal length; **CH**, total crown height; **CW**, crown base width. See explanations for measurements in Smith (2005). Note: fragmental elements are excluded from this list.

INTERPRETATION OF PALEOENVIRONMENT IN CENTRAL WYOMING

Among vertebrate fauna, sauropod remains dominate from the Warm Springs' dinosaur quarries, and the high concentration of sauropods is possibly significant for understanding the paleoenvironment of central Wyoming during the ages. Based on limited information, we suggest the following interpretation for this feature. The sedimentological data from the BS Quarry indicates a high degree of alkalinity and low precipitation. The high density of sauropod remains in this area seem to correlate with lush vegetation, and abundant plant fossils support this scenario. Today we see large-bodied herbivorous vertebrates such as African elephants live in highly-vegetated environments (e.g., tropical semi-arid areas in Kenya; Behrensmeyer, 1975).

Abundant lignite can indicate "…eutrophic lake-margin marshes analogous to the interdistributary bays of a delta front environment" (Reading, 1986, p. 82). Portions of some pieces of petrified wood possibly indicate that the area was relatively humid, which perhaps imply regular rainy seasons rather than a lacustrine environment. The deposits include the continual recycling of carbonate, including nodularization. The deposits with abundant lignite can be interpreted as a prograding lacustrine delta because of evidence of facies geometry and lack of exposed features, and, possibly the BS deposits originated in similar environments.

Aanastomosing rivers might have been present in the Thermopolis area during this age. This type of rivers can explain why the sequence of sediments in the BS Quarry differs from other Warm Springs' dinosaur quarries. Anastomosing rivers are defined by large areas of flood plain, multiple channels, and lateral stability of channels, such as the recent Tonlé Sap River in central Cambodia (Makaske, 2001). The BS Quarry, as well as other dinosaur quarries on the Warm Springs Ranch, exhibits evidence of regular large flood plains based on low angle cross-bedding, the periodic sequence between mudstone and sandstone beds, and abundant plant materials. A large flood could bury carcasses of the three large sauropods in a

TABLE 2. Paleoenvironmental indicators at three major dinosaur quarries from the upper Morrison Formation of the Warm Springs Ranch, central Wyoming.

Quarry	Type**	Depositional environment	Lithologies and fossils	Tahonomic features
BS	Poorly drained flood plain	Palustrine or lacustrine wetland; marshy land	Gray carbonate mudstone; hard carbonate rocks; lignite and siliceous woods; sauropod skeletons; shed theropod teeth, ostracods	Low energy; not far removed from death site; low probability of scavenging; disarticulated sauropod skeletons
BB	Overbank sand	Riparian environment***	Tan to yellow fine grained sandstone; thin interbedded mudstone layers abundant lignite & plant material; sauropod bones	Mostly isolated sauropod bones; relatively rapid burial; bones encompassing a large depositional area
SI*	Poorly drained floodplain	Shallow water; palustrine-lacustrine setting	Carbonate mudstone underlying poorly cemented silty mudstone; barite nodules; sauropod skeletons; shed teeth; sauropod and theropod foot prints(?); ostracods	Seasonal lake; annual rain/dry season; theropod feeding site; semi-articulated sauropod skeletons; sauropod track ways (?)

*Data from Jennings (2005) and Watkins et al (2005).
**Based on Foster (2003).
***See explanation in Turner and Peterson (2004).

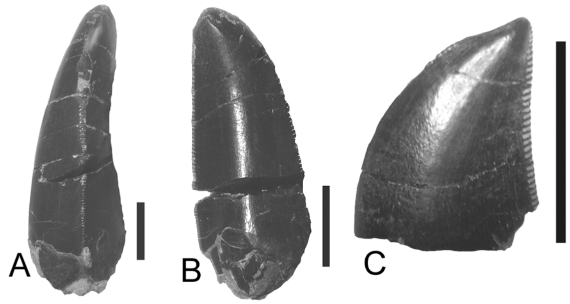

FIGURE 6. Theropod teeth from the BS Quarry in central Wyoming. **A**, *Allosaurus* sp. (BS-700), mesial view. **B**, *Allosaurus* sp. (WDC BS-749), lingual view. **C**, indeterminate small theropod (deinonychosaurid?) (WDC BS-641), lingual or labial view. Scale bars equal 10 mm.

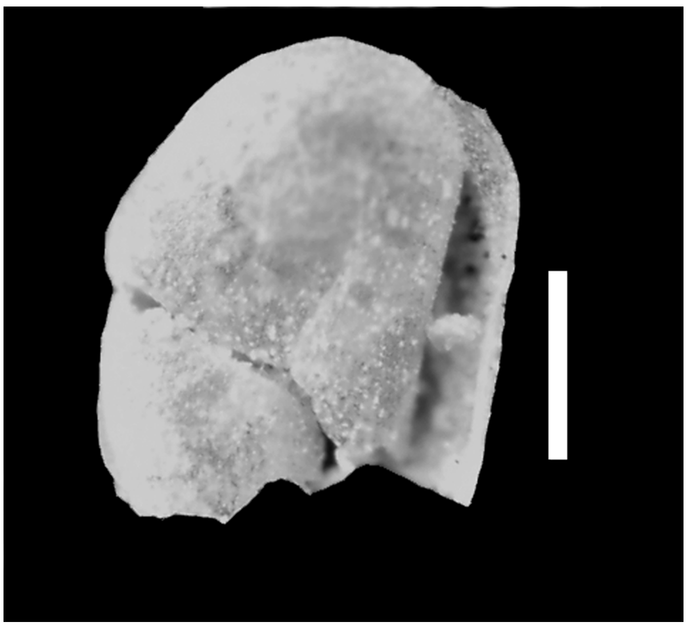

FIGURE 7. Indeterminate ostracod from the BS Quarry in central Wyoming. Scale bar equals 20 µm. Picture courtesy by Debra Jennings.

short period and explain why the skeletons are well-preserved without scavenging marks. Moreover, streams might erode some bones that were stacked above the mud surface and/or weathered. Makaske (2001, p. 189) listed other diagnostic features for this environment, such as (1) laterally connected channel sandstone bodies, (2) laterally extensive, thick lenses of lithologically heterogeneous, fine-grained avulsion deposits, (3) sandstone that pass abruptly into overlying mudrock, and (4) occurrences of lacustrine deposits and coal. Because the BS Quarry exhibits the last two characters, the sauropod skeletons may have been deposited under the anastomosing river-type of environment.

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