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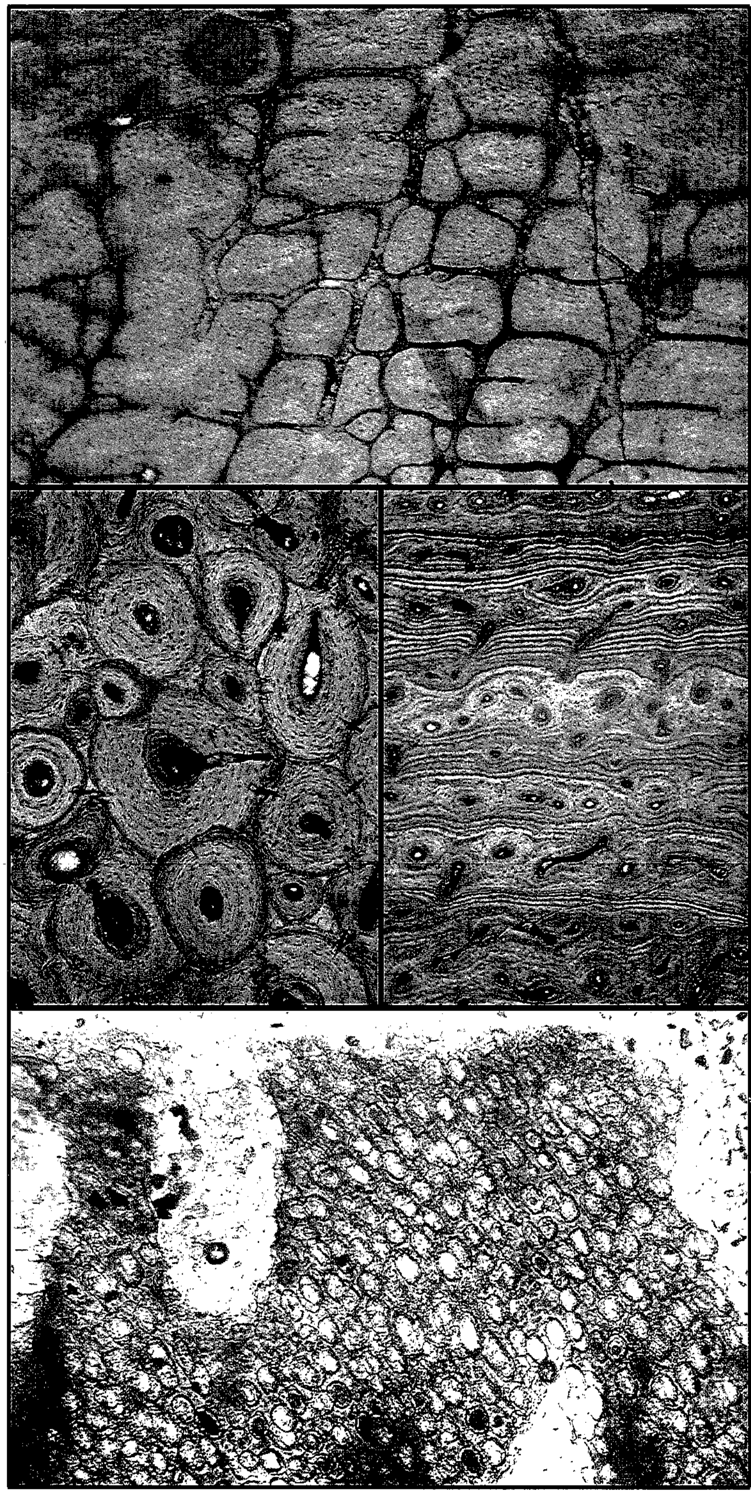

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Cover: Fossil tissues from Cleveland-Lloyd allosaurs.

Top: Uniform periosteal bone with reticulating primary vascular canals, some of which are aligned longitudinally (left to right) and radially. Caudal vertebra, centrum; longitudinal section; C-LQ 087.

Middle left: Vascular zonal bone with lamellated annuli and non-lamellated zones. Local development in a right radius; transverse section; C-LQ 109.

Middle right: Dense Haversian bone showing secondary osteons, secondary vascular canals at their centers, and the concentric arrangement of osteocyte lacunae (small dark bodies) around them. Dorsal rib; transverse section; C-LQ 106.

Bottom: Calcified cartilage showing the rounded form of the spaces (lacunae) once occupied by chondrocytes. Proximal end of a fibula; longitudinal section; C-LQ 014.

In all sections the direction of the external surface is upward.

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Sedimentology of a *Ceratosaurus* Site in the San Rafael Swell, Emery County, Utah

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ABSTRACT

An incomplete *Ceratosaurus nasicornis* skeleton was excavated from the Upper Jurassic Morrison Formation in the San Rafael Swell, Utah. The specimen is the seventh known occurrence of the genus in North America. The *C. nasicornis* skeletal material was excavated from a thin Stage I splay sandstone bed within the lower Brushy Basin Member. The splay is interpreted to have been derived from a fluvial channel sandstone bed approximately 40 m to the east. The channel sandstone is a very coarse-grained, poorly sorted, pebble-rich lithic arenite. The thin ceratosaur-bearing splay sandstone bed is a coarse- to fine-grained, very poorly to moderately sorted sublitharenite. The splay sandstone exhibits rapid granulometric and petrologic change westward. According to the bone volume-flow velocity equation (Behrensmeyer, 1975; Richmond and Morris, in press), the paleoflow velocity for the exposed proximal portion (i.e., nearest the channel) of the splay was approximately 120 cm/sec. Paleoflow velocity of the exposed distal portion of the bed was less than 50 cm/sec. The Stage I splay did not result in a thick sandstone deposit or avulsion of the channel.

INTRODUCTION

An incomplete specimen of a *Ceratosaurus nasicornis* (BYUVP 12893) was excavated from the lower Brushy Basin Member of the Upper Jurassic Morrison Formation. The ceratosaur was found in the San Rafael Swell desert approximately 24 km (15 miles) southeast of the town of Moore and 1.6 km (1 mile) north of Interstate 70 (Fig. 1). The partially articulated skeleton is the seventh known occurrence of the genus in North America and is one of the most complete ceratosaur specimens yet found (Britt and others, 1991). The extremely rare uncrushed partially articulated skull and postcranial skeletal elements of the ceratosaur clarify some important and previously unknown *C. nasicornis* features (Britt, pers. comm., 1995).

The purpose of this paper is fourfold:

1. To document the stratigraphic position of the specimen to determine the age range of *C. nasicornis* in the Late Jurassic.

2. To determine the depositional facies inhabited by the ceratosaur in the Late Jurassic. This information may increase understanding of the terrestrial environments inhabited by *C. nasicornis* and therefore contribute paleoecological information (see Dodson and others, 1980) about this relatively obscure dinosaur.

3. To facilitate the search for missing portions of the specimen. The endangered cactus *Pediocactus despainii* is under environmental protection throughout much of Emery County.

In 1988, under an investigation permit, the Brigham Young University Earth Science Museum collected some exposed dorsal vertebrae of the ceratosaur. Four years later, after the Bureau of Land Management conducted an environmental impact survey concerning the protection of the cactus, a limited excavation permit was issued. Determining the depositional system that led to the preservation of the ceratosaur may give insight as to where more material of this specimen may be recovered with limited surface disturbance.

4. The stratigraphic horizon in which the ceratosaur was found is replete with dinosaur bone fragments. Therefore, an understanding of the depositional systems within this stratigraphic horizon may aid in finding other dinosaur specimens within the surrounding area.

METHODS

Stratigraphic measurement of the Brushy Basin Member was made with a Jacob's staff. The thin sandstone beds at the excavation site were measured with a tape measure. To determine illite/smectite ratios of mudstone units, clay samples were prepared and X-ray diffraction was performed as prescribed by Moore and Reynolds (1989). Sandstone samples were collected, and a 300-point count

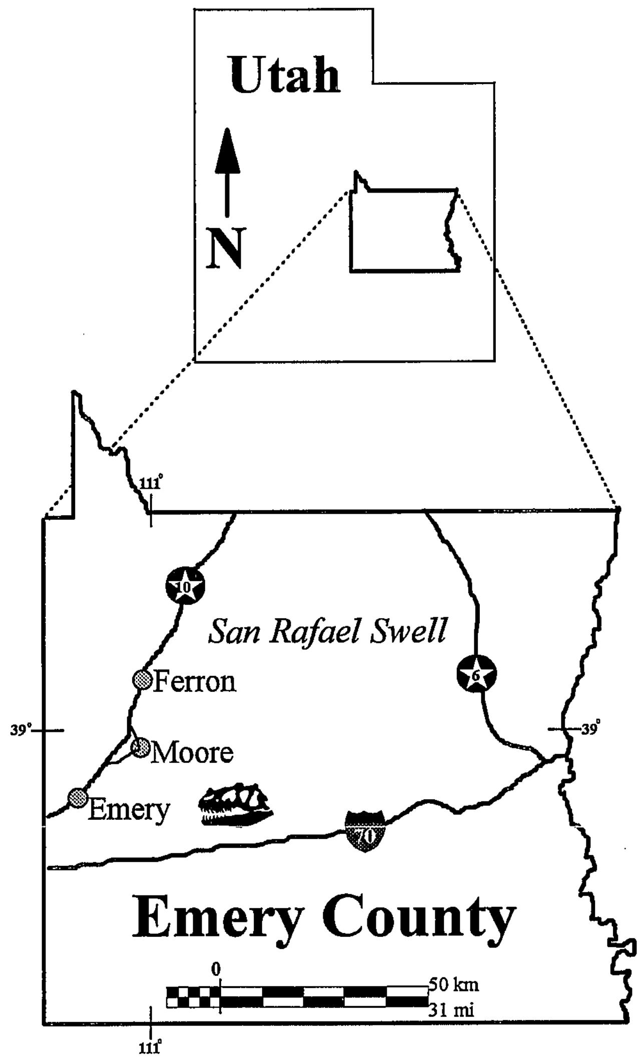

Figure 1. Index map of the Ceratosaurus *excavation site in south central Utah. The site is in the San Rafael desert approximately 24 km southeast of the town of Moore and 1.6 km north of Interstate 70.*

analysis was performed (Van Der Plas and Tobi, 1965) on each oriented sandstone thin section. The point count method is ± 5% accurate at the 95th confidence interval for framework grain abundances between 20% and 80%. The values obtained were used for the petrographic classification of the sandstone units at the site (Pettijohn and others, 1978). A framework grain ratio of quartz to lithic grain percentages was determined to show changes in sandstone petrology westward along the sandstone bed exposure. Quartz percentage includes all monocrystalline, polycrystalline, and microcrystalline quartz grains. Lithic percentage includes all lithic and spicule chert grains. Feldspars were not included because they constitute < 3% of the framework grains for all samples. A second 300-point count analysis of apparent grain elongation of the sandstone thin sections was performed to determine a calculated mean grain size for each sandstone sample. The procedure results are within the 99th confidence interval for sieve analysis (Friedman, 1958; Harrell and Eriksson, 1979).

STRATIGRAPHY

Three members of the Morrison Formation are present in the San Rafael Swell. In ascending order they are the Tidwell Member (Peterson, 1988), the Salt Wash Member (Lupton, 1914), and the Brushy Basin Member (Gregory, 1938). The Tidwell Member consists of interbeds of red mudstone and gypsum and closely resembles the underlying Summerville Formation. The Salt Wash Member consists of interstratified mudstone and sandstone beds. The upper portion of the Salt Wash Member in the San Rafael Swell is characterized by two pebble-rich, fluvial sandstone beds that are separated stratigraphically by a few meters (Trimble and Doelling, 1978). In the study area, both sandstone beds are present. The upper 2 m of the Salt Wash Member is a pebble-rich sandstone bed that is considered to be the upper contact bed of the member (Trimble and Doelling, 1978; Crooks, 1986).

The Brushy Basin Member in the San Rafael Swell is recognizable by a thick sequence (approximately 92 m [300 ft] thick; Craig and others, 1955; Crooks, 1986) of variegated mudstone units (Fig. 2). The boundary between the lower and upper intervals of the Brushy Basin Member is defined by a change from illitic (in the study area about 70%) to smectitic (80%) clay (Turner and Fishman, 1991). This boundary is discernable in the field area as an abrupt vertical change in the mudstone weathering pattern (Fig. 3). The collection site is 3.5 m below the illite/smectite clay change and so is within the lower Brushy Basin Member (Fig. 4). The mudstone units of the upper Brushy Basin Member are sparsely interstratified with fine-grained sandstone and pebble-rich, conglomeratic sandstone beds.

Stratigraphically above the Brushy Basin Member of the Morrison Formation is the Buckhorn Conglomerate, the basal member of the Lower Cretaceous Cedar Mountain Formation. In the study area, the Buckhorn Conglomerate is a pebble-rich fluvial sandstone bed (Harris, 1980; Crooks, 1986). In other areas of the San Rafael Swell the member is more conglomeratic (Crooks, 1986). The collection site is approximately 7 m above the Salt Wash Member and 85 m below the Buckhorn Conglomerate Member of the Cedar Mountain Formation (Fig. 4).

SPLAY DEPOSITION

A crevasse splay occurs when floodwaters breech a natural channel levee. A sediment point source may develop

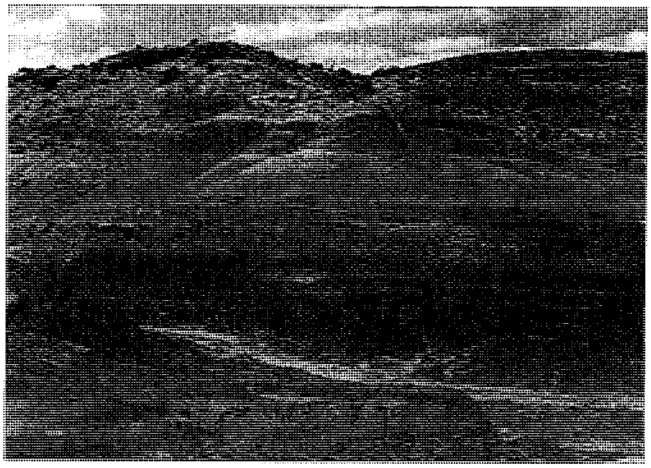

Figure 2. In the San Rafael Swell the Brushy Basin Member of the Morrison Formation is recognizable by its thick sequence of variegated mudstone units.

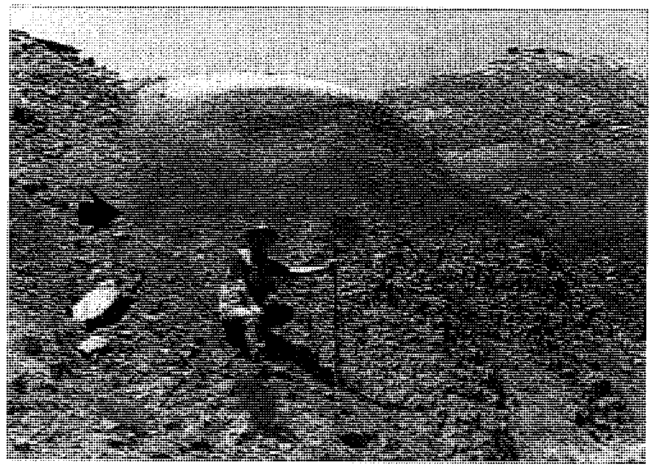

Figure 3. Clay change from illitic to smectitic mudstone 3.5 m above the splay sandstone bed. Notice the differing weathering patterns of the two mudstone types (arrow). The illitic nature of the lower mudstone unit indicates that the ceratosaur-bearing sandstone bed is within the lower Brushy Basin Member of Turner and Fishman (1991).

at the levee break as floodwater is discharged from the fluvial channel. Water and sediment expand onto the floodplain in sheetlike and/or fanlike patterns (Collison, 1978) that wane in the flow direction. Channeling of flow through the levee causes scouring and deepening of crevasse channels, allowing large volumes of water and sediment to enter onto the floodplain (Galloway and Hobday, 1983; O'Brien and Wells, 1986). Typically coarse-grained sediment is deposited near the fluvial channel, and fine-grained sediment is deposited farther out on the floodplain. Sorting increases distally. At the onset of flooding, clay and silt may be deposited first as the basal portion of a coarsening-upward sequence (Smith and others, 1989). Coarsening-upward sequences are also the product of subsequent flood events. These floods may cause aggradation and progradation of the splay (Tyler and Etheridge, 1983). If progradation is rapid, fluid escape structures may form in the underlying water-saturated sediment.

Crevasse splays can also fine-upward (Bridge, 1984), depending on the depositional conditions and locale of the splay. Fining-upward sequences can be caused by the abandonment of an individual crevasse channel or complete abandonment of the splay. Abandonment of a splay can occur at any stage of splay development due to the crevasse becoming plugged with sediment, the elimination of the gradient between the fixed channel and the floodplain, or abandonment of the fluvial system in the area (Smith and others, 1989). Splay deposits range in thickness from centimeters to tens of meters and are the product of one or several discrete flood events.

Smith and others (1989) have divided splay aggradation and progradation into stages of development. Stage I begins with initial deposition by sheet flow forming unstable splay channels. Wide, shallow channels quickly develop as the lobate splay enlarges. Channelization becomes more pronounced as bedload sediment is fractionated through distributary channels. In Stage I, a general coarsening-upward sequence in the proximal portion of the splay and in the distributary channels is common. A Stage I splay is short-lived and limited in size.

Stage II involves enlargement of the splay by the elongation and coalescing of channels and/or two or more smaller splays. In the proximal portion of the splay(s), older channels are abandoned and stabilized by vegetation. Flow is concentrated to a few relatively stable narrow channels. Small islands of interchannel deposits may develop. The channel facies geometries are more complex than in Stage I and include complexes of interconnected channels.

A Stage III crevasse splay is characterized by aggradation and progradation of a Stage I or Stage II splay. The flow becomes more localized as Stage II channels coalesce and concentrate flow into narrow anastomosed channels separated by large islands of interchannel deposits. Stage III morphologies commonly occur where the splay progrades into a shallow pond or lake and could be regarded as a delta.

CERATOSAUR SPLAY

Associated with the ceratosaur-bearing sandstone bed is a fluvial channel sandstone bed approximately 40 m (130 ft) east of the excavation site. Although the area

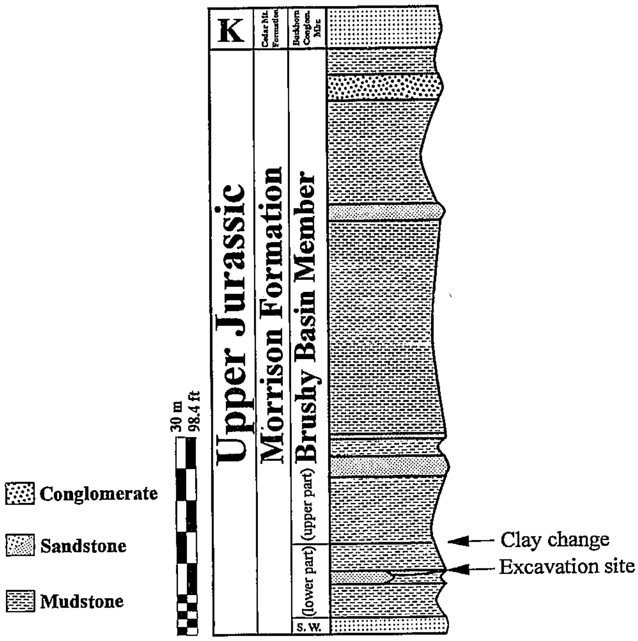

Figure 4. Measured stratigraphic section of the Brushy Basin Member at the Ceratosaurus *excavation site. Note the division of the lower and upper Brushy Basin Member of the Morrison Formation and the position of the splay sandstone bed. See discussion in text for additional documentation of the stratigraphic position of the quarry within the Brushy Basin Member.*

Figure 5. The thin splay sandstone bed from which the Ceratosaurus *was excavated has a limited exposure. "A" is the exposed proximal portion of the bed, whereas "B" is the exposed distal portion of the bed.*

between the fluvial channel bed and the ceratosaur-bearing sandstone bed is covered by alluvium, both beds are interpreted to be within the same stratigraphic horizon. The channel is the apparent sediment source for the ceratosaur-bearing sandstone. The fluvial channel sandstone is a very coarse-grained (mean -0.4ϕ), poorly sorted (1.03ϕ), pebble-rich lithic arenite. Trough cross-beds (10 measurements) indicate that paleoflow direction of the channel was north-northeast (see Derr, 1974).

The thin ceratosaur-bearing sandstone bed has a limited 6 m (18 ft) horizontal exposure. Along the length of the exposure the bed has a consistent thickness of approximately 10 cm (4 in) (Fig. 5). Bedforms were not observed in the bed. Therefore, the typical relationship between grain size, bedforms, and flow velocity (Harms and others, 1982; Southard and Boguchwal, 1990) could not be investigated. The lack of bedforms also precluded determining the paleoflow direction for the bed.

Dinosaur bones can be used to approximate the paleoflow velocity in unidirectional depositional systems. Behrensmeyer (1975) derived equations to equate the volume of an irregularly shaped mammal bone to the entrainment velocity of a spherical quartz diameter. Using her equations for nominal diameter and calculated quartz equivalence, together with a modification of the Nivan-Hjülstrom velocity equation (Malde, 1968), a minimum entrainment velocity can be determined for any given dinosaur bone volume.

The formulas are:

Nominal Diameter of Bone:

$$d_b = (1.91 \times \text{Bone Volume})^{1/3}$$

Calculated Quartz Diameter:

$$d_q = (p_b - 1) \times d_b/1.65 \text{ (Behrensmeyer, 1975)}$$

Flow Velocity Equation:

$$V = 304.8(.03281 d_q)^{1/2.6} \text{ (Malde, 1968)}$$

where bone density (p_b) is 1.47 g/cm^3 (Richmond and Morris, in press).

Two isolated *Camarasaurus* posterior caudal vertebrae were deposited at the base of the eastern edge of the exposure (i.e., nearest the channel) of the ceratosaur-bearing sandstone bed and are interpreted to have been transported by the flood. The most complete of these caudal vertebrae was used to approximate the paleoflow velocity. The bone volumes of elements from the *C. nasicornis* were not used to determine flow velocity because it was difficult to establish whether the collected material had been transported any significant distance (see Voorhies, 1969; Richmond and Morris, in press). The external bone volume (Richmond, 1994) of the extracted *Camarasaurus* caudal vertebrae was measured at 500 cc. This yields a quartz grain equivalent of 2.8 mm. This calculation directly correlates with the mean grain size (2.8 mm) determined by granulometric procedures for the same horizontal position within the bed. The resulting paleoflow velocity for the deposit is approximately 120 cm/sec. The mean grain size (2.8 mm) and the Hjülstrom diagram (Sundborg, 1956) can be used to determine the minimum critical current velocity required to entrain quartz grains. The paleoflow velocity determined by grain size confirms the paleoflow velocity approximated by the calculated quartz grain equivalent.

The mean grain size (0.130 mm) was used to approximate the paleoflow velocity in the distal portion of the bed. The minimum critical current velocity necessary for entrainment of a 0.130 mm grain is approximately 50 cm/sec (Sundborg, 1956). Deposition, therefore, occurred when the flow velocity fell below 50 cm/sec. The two differing calculated paleoflow velocities indicate a reduction in the paleoflow velocity during deposition of the ceratosaur-bearing sandstone bed.

A reduction in the paleoflow direction along the exposure is indicated also by a decrease in mean grain size from 0.9ϕ at the eastern edge of the exposure to 2.8ϕ at the western edge. Also associated with the westward granulometric changes (decrease in grain size) is a petrologic contrast between the channel sandstone bed (lithic arenite) and the ceratosaur-bearing sandstone bed (sublitharenite). The channel sandstone bed has a quartz-lithic grain ratio of 2:7. At the exposed eastern portion of the ceratosaur-bearing sandstone bed (i.e., nearest to the channel, 40 m westward), the quartz-lithic grain ratio increases to 3:1. Six meters westward this ratio increases to 7:1 (Fig. 6). A possible explanation for the petrologic change is the winnowing of larger, more durable grains during deposition.

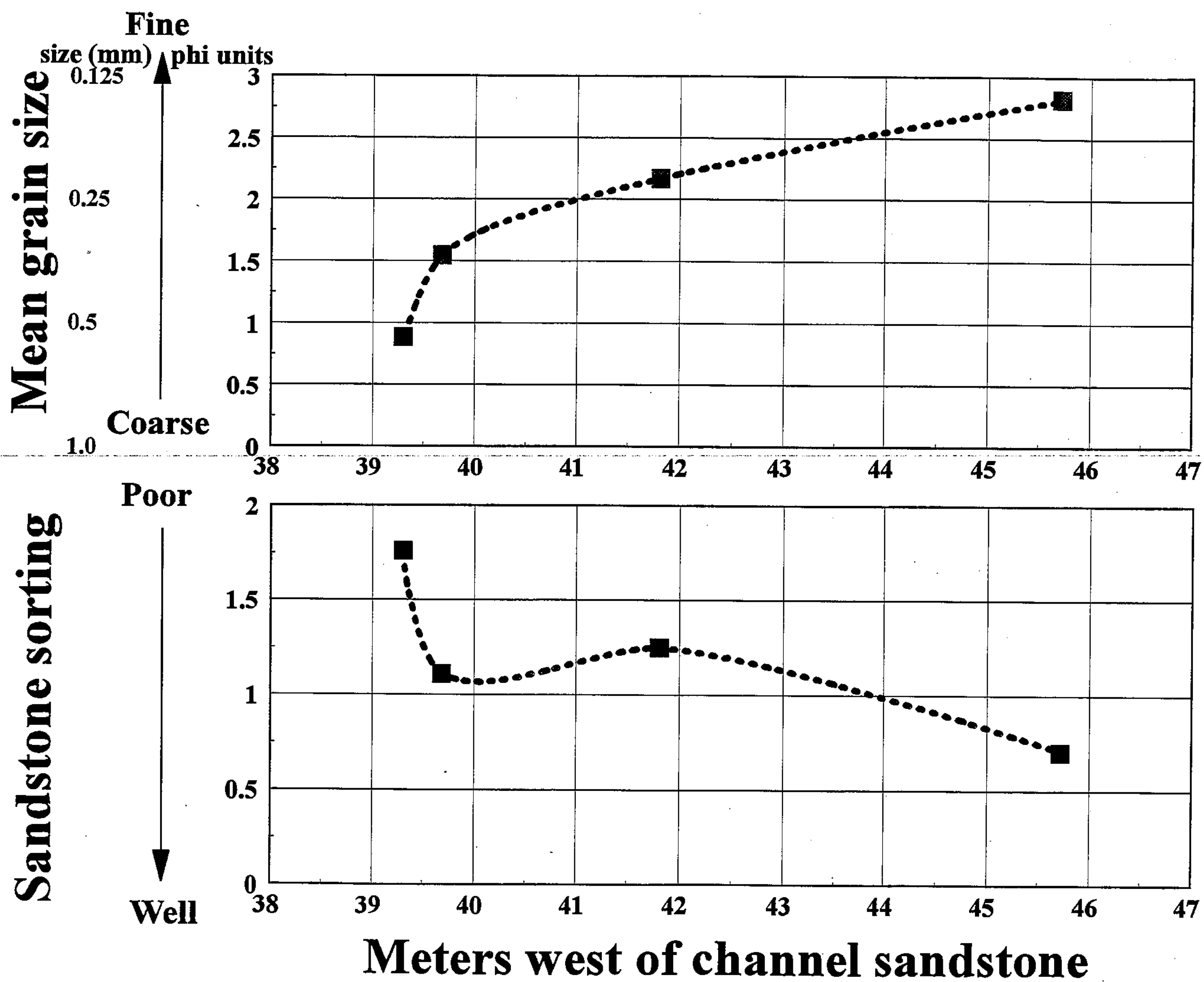

Figure 6. The graphical relationship showing the change in mean grain size and grain sorting along the exposure of the thin sandstone bed. The graphical representation is interpreted to indicate waning fluid flow and competence over the distance of 6 m.

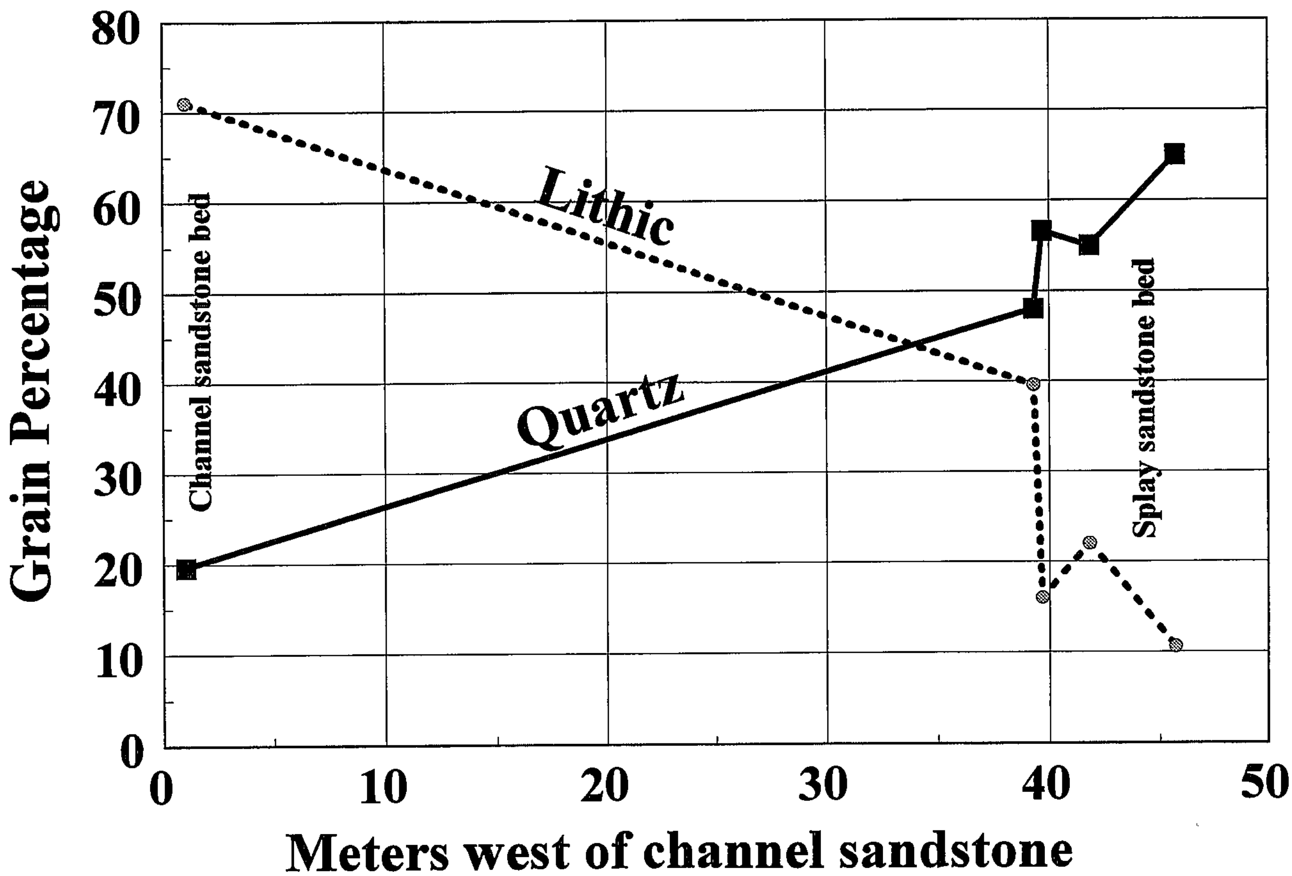

Figure 7. Quartz-lithic grain ratio of the channel sandstone bed and the thin sandstone bed. The 40 m between the two sandstone beds is covered by alluvium. The quartz-lithic grain ratio increases rapidly westward along the thin sandstone bed, suggesting a decrease in flow velocity and thus a decrease in the fluid flow competence. The fluid flow competence was such that it was less able to transport the larger and mechanically more durable lithic grains.

Sorting increases from 2.0ϕ to 0.7ϕ in a westward direction (Fig. 7). Harrell and Blatt (1978) demonstrated that the mechanical durability of polycrystalline and microcrystalline quartz grains is about 20% greater than monocrystalline quartz grains. Monocrystalline quartz grains were evidently abraded during transport within the fluvial channel prior to deposition onto the floodplain. The waning fluid flow during deposition of the bed resulted in a reduction of fluid competence. The rapidly diminishing fluid competence may have differentiated the larger, more durable polycrystalline and microcrystalline quartz grains (lithic grains) from the smaller, less durable monocrystalline quartz grains. The distal western portion of the ceratosaur-bearing sandstone bed is dominated by moderately well-sorted, fine-grained monocrystalline quartz sediment. This westward change of granulometric and petrologic characteristics suggests the sediment was derived from the east and that the flow waned westward.

The thinness of the sandstone bed containing the *C. nasicornis* suggests that the flooding was short-lived. The westward decrease in flow velocity and grain size and the westward increase in sorting along the exposure suggest a point source to the east. The bed is interpreted to be a Stage I crevasse splay.

A very thin (2 cm), coarse-grained sandstone bed overlies the fine-grained distal western portion of the ceratosaur-bearing sandstone bed, suggesting progradation of the splay during deposition. Twenty-eight centimeters (11 in) beneath the ceratosaur-bearing sandstone bed is a poorly sorted (1.9ϕ), coarse-grained (0.98ϕ) lithic arenite. The bed is 20 cm (8 in) thick. A mudstone unit is present between this lower sandstone bed and the upper ceratosaur-bearing sandstone bed. The lower sandstone bed is also interpreted to be a crevasse splay deposit. The association of the beds may indicate seasonal flooding of the channel.

A possible taphonomic interpretation for the specimen is that the *Ceratosaurus* died on the floodplain relatively close to the excavation site (the site is < 2.0 meters in diameter). After partial disarticulation, water and sediment discharged from the channel entrained, transported, and deposited the more mobile elements of the skeleton (see Voorhies, 1969). Missing skeletal elements may have been deposited west of the excavation site and are now covered by a thick mudstone unit and alluvium. There remains the possibility, of course, that the missing fossil material was scavenged prior to burial or that it was destroyed by exposure.

CONCLUSIONS

The fossil skeletal material of a *Ceratosaurus nasicornis* was deposited by a Stage I crevasse splay. The flood event formed a thin sandstone bed in the lower interval of the Brushy Basin Member of the Morrison Formation. Within the measured splay exposure, the paleoflow velocity decreased rapidly from approximately 120 cm/sec in the exposed proximal eastern portion to less than 50 cm/sec in the exposed distal western portion of the bed. Granulometric and petrologic relationships of the splay sandstone bed suggest that it was derived from a fluvial channel 40 m east of the site. The waning fluid flow along the exposure suggests that the remaining *Ceratosaurus* skeletal elements were probably deposited farther west of the excavation site and may be recoverable.

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