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Late Albian Dinosaur Tracks from the Cratonic (Eastern) Margin of the Western Interior Seaway, Nebraska, USA

R. M. Joeckel
Conservation and Survey Division, School of Natural Resources, IANR, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

J. M. Cunningham
Burlington Northern Santa Fe Railway, Environmental Operations, Kansas City, Kansas, USA

R. G. Corner and G. W. Brown
University of Nebraska State Museum, Lincoln, Nebraska, USA

P. L. Phillips
Geology and Geography Program, University of North Carolina-Pembroke, Pembroke, North Carolina, USA

G. A. Ludvigson
Iowa Department of Natural Resources, Geological Survey Bureau, Iowa City, Iowa, USA

At least 22 tridactyl dinosaur tracks, poorly preserved in various degrees of expression, have recently been found at an exposure in the Dakota Formation (Lower Cretaceous, Albian) in Jefferson County, Nebraska. These tracks generally have broad, blunt digits and a broad posterior margin. The largest of the tracks measures 57 cm in length and 58 cm in width. All of the tracks lie within a stratigraphic horizon of 40 cm or less, but they do not form a single trackway. We interpret the trackmakers to have been ornithopods.

The Jefferson County tracks are in a well-cemented sandstone with oscillation ripples, at a stratigraphic level between two well-established sequence boundaries. Channel forms and lateral accretion units are common in the stratigraphic interval enclosing the tracks, and the site is interpreted as a bar or sand flat in a tidally influenced river.

The Jefferson County tracks are only the second known occurrence of large Mesozoic tetrapod tracks east of the Rocky Mountain Front-High Plains Margin, including the Black Hills of South Dakota, west of the Atlantic Coastal Plain, and north of the Gulf Coastal Plain. Further, this paper is the first documentation of *in situ* dinosaur fossils from the Nebraska-Iowa area.

Keywords Tracksite, dinosaur, Albian, Dakota Formation, Nebraska

Address correspondence to R. M. Joeckel, Conservation and Survey Division, School of Natural Resources, IANR, University of Nebraska-Lincoln, Lincoln, NE 68588-0517, USA. E-mail: rjoeckel3@unl.edu

INTRODUCTION

A tracksite recently discovered in the middle Dakota Formation in southern Jefferson County, Nebraska (Figs. 1, 2) is the first *in situ* occurrence of large continental vertebrate fossils to be described from Cretaceous strata in that state. To our knowledge, the tracksite is only the second occurrence of large Cretaceous (and, for that matter, Mesozoic) tetrapod tracks east of the Rocky Mountain Front-High Plains Margin-Black Hills, west of the Atlantic Coastal Plain, and north of the Gulf Coastal Plain (Lucas and Hunt, 1989; Pittman, 1989; Lockley et al., 1994; Lucas et al., 2000). Thus, the Jefferson County tracks are very important in terms of regional biogeography, biostratigraphy, and paleoecology.

Exceedingly few vertebrate fossils have been collected from nonmarine Cretaceous sediments at the eastern cratonic margin of the Western Interior Seaway. The Albian-Cenomanian Dakota Formation constitutes most of the nonmarine sedimentary record along the cratonic margin of the seaway in the midcontinental United States, particularly western Iowa, eastern Nebraska, and central Kansas. It is dominated by fluvial and tidal estuarine deposits (Brenner et al., 2000; Joeckel et al., in press) and has yielded a famous assemblage of early angiosperm macrofossils. It appears to be overwhelmingly barren, however, with respect to vertebrate macrofossils.

Vertebrate fossils that can be strictly documented to have come from the Dakota Formation on the eastern margin of the

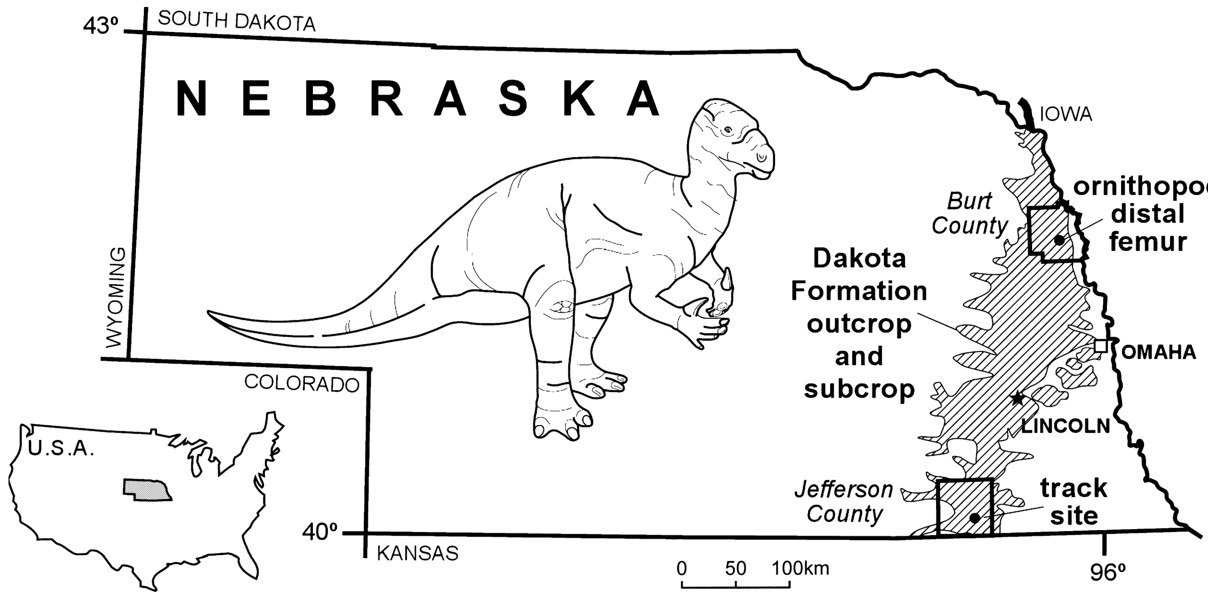

FIG. 1. Map showing Dakota Formation outcrop and subcrop in Nebraska, probable location of earlier, poorly documented find of ornithopod distal femur (Burt County), and dinosaur tracksite (southern Jefferson County). Exact locality information is being withheld to preserve site and protect private landowners.

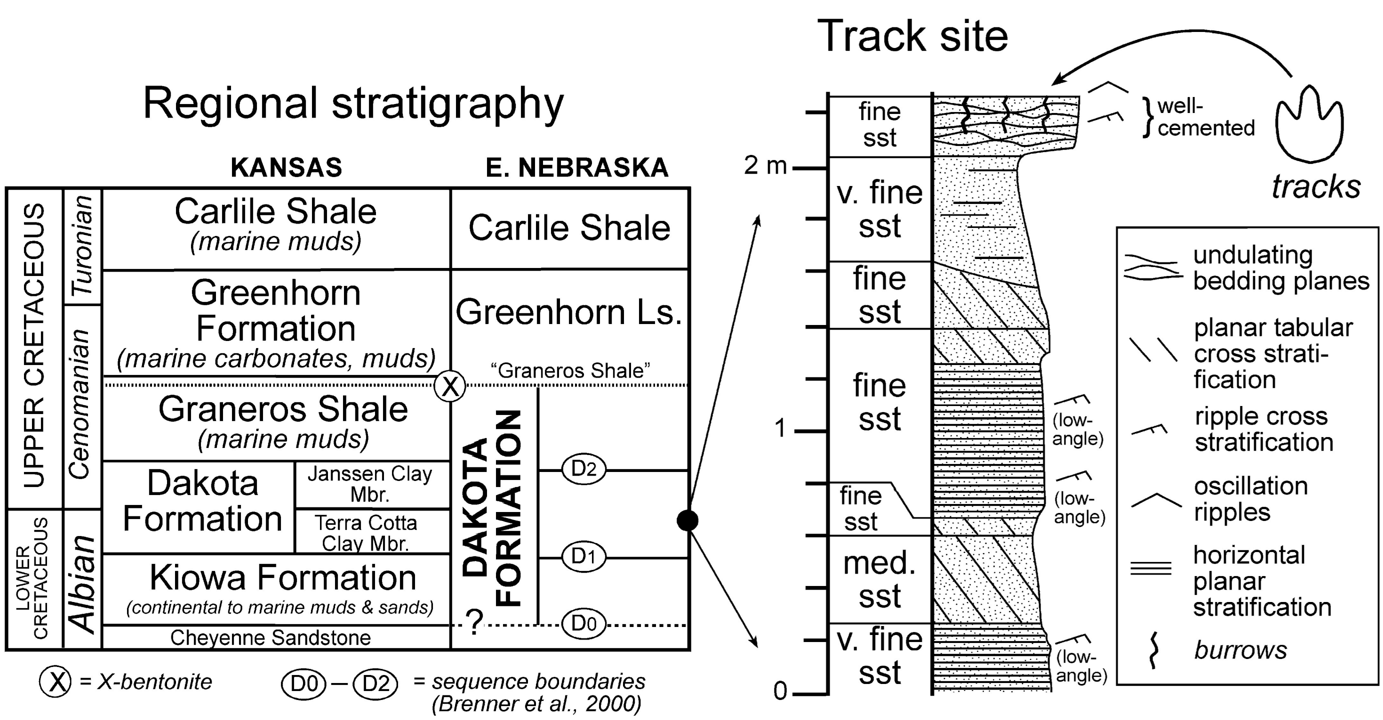

FIG. 2. Dakota Formation stratigraphy in Kansas and eastern Nebraska (left) and stratigraphy of dinosaur tracksite (right). Tracksite lies near middle of Dakota Formation between sequence boundaries D_1 and D_2 of Brenner et al. (2000).

seaway are limited to a few isolated crocodilian and turtle skeletal remains, and probable bird and dinosaur tracks from Kansas (Stanton, 1922; Mehl, 1931; Eaton, 1960; McAllister, 1989, Nelson, 1989; Lund and Nelson, 1990). The distal end of an ornithopod femur (Barbour 1931; Galton and Jensen, 1978) was almost certainly collected from the Dakota Formation in Burt County, Nebraska, but exact locality and stratigraphic information are lacking.

GEOLOGIC SETTING

Regional Dakota Formation Stratigraphy

The Dakota Formation on the cratonic eastern margin of the Western Interior Seaway is characterized by major lateral facies changes within mere tens to hundreds of meters, and the few large (>100 m) outcrops available for study frequently exhibit varying complexities of cut-and-fill. In the past decade, Dakota Formation deposits in southeastern Nebraska and western Iowa have been reinterpreted as fluvial to estuarine. Tidal influence on Dakota Formation fluvial systems and the filling of pre-Dakota-Formation bedrock valleys by transgressive system tracts are two particularly important motifs that have emerged from recent research (Brenner et al., 2000; Joeckel et al., in press). Mottled, hydromorphic paleosols are common in the Dakota Formation, as are very thin, discontinuous lignites and carbonaceous mudstones (Brenner et al., 2000; Joeckel et al., in press).

Terrestrial palynomorphs as well as marine dinoflagellates and acritarchs have been used to construct a biostratigraphic framework, which has aided the recognition of three sedimentary sequences within the Dakota Formation (Brenner et al., 2000; Joeckel et al., in press). In southeastern Nebraska and western Iowa, the basal, gravel-bearing part of the Dakota Formation (lower sequence bounded at its top by sequence boundary D_0 of Brenner et al., 2000) records the Late Albian Kiowa-Skull Creek marine transgression of a coastal plain crossed by large fluvial systems and their estuaries, which flowed through incised bedrock valleys (Joeckel et al., in press). A middle sequence, bounded by sequence boundaries D_1 and D_2 of Brenner et al. (2000), includes the track bed and consists of a combination of mudstones and sandstones; it is also dominantly fluvial to estuarine in origin. Uppermost Dakota Formation strata (upper sequence bounded below by sequence boundary D_2 of Brenner et al., 2000) in Iowa and Nebraska, which include transitional marine facies, record the initial stages of transgression at the onset of the "Greenhorn marine cycle" in the early Cenomanian. Consult Brenner et al. (2000) for a complete discussion of Dakota Formation facies, palynostratigraphy, and sequence stratigraphy, including a composite section of the Dakota Formation in Jefferson County, Nebraska. The track level correlates to the top of a sandstone bed approximately halfway up into the middle sequence (Brenner et al., 2000, Fig. 5). The track bed is also 25 m below the level of the famous Rose Creek paleobotanical site, from which 20 species of mid-Cretaceous angiosperm megafossils have been described (Upchurch and Dilcher, 1990).

Track Bed

The track bed is a conspicuously well-cemented, well-sorted quartz arenite, which caps more friable sandstones immediately below it in a 2 to 3 m high bench (Fig. 2). Variability in cementation within narrow stratigraphic intervals is typical of the Dakota Formation. The track bed contains blocky, poikilotopic, calcite cements, and secondary porosity is common within 0.5 m below the level of the tracks; minus-cement porosity in the track bed is approximately 35%. These preliminary petrographic data indicate that the track-bearing sandstone was cemented with calcite and minor pyrite and siderite relatively shortly after deposition. The serendipitous occurrence of early cementation at the top of the bench promoted both the preservation of the tracks and their eventual bedding-plane-parallel exposure. Cross-stratified sandstones indicating unidirectional flow with a strong westerly component underlie the track level, and the entire package of sandstones at the tracksite appears to correlate with part of a tidally-influenced fluvial channel fill exposed several kilometers northward.

Within the track bed, small-scale ripple cross-stratification is visible in on the unweathered undersides of collapsed sandstone blocks. Oscillation ripples with crests striking almost exactly NE-SW appear on one small part of the upper surface of the bed, and within the same narrow stratigraphic interval as the tracks (Figs. 2, 3A). The track bed consists of several thick laminae to thin beds 0.5 to 7 cm in thickness, separated by gently undulating bedding planes that verge on lenticular bedding.

Skolithos-like and *Rosselia*-like burrows extend downward from the upper surface of the track bed, but these invertebrate traces are poorly preserved. Body fossils of marine organisms have not been found within several meters both below and above the level of the tracks. On the other hand, large-scale channel forms and lateral accretion units are common in the same enclosing interval, indicating a dominance of fluvial processes. Marine bivalves occasionally are found near the top of the Dakota Formation in Jefferson County, but at stratigraphic positions at least 25 m above that of the tracksite.

In the context of an overall understanding of Dakota Formation depositional environments, these observations suggest that the tracksite was an emergent bar or sand flat in a tidally-influenced river (Brenner et al., 2000; Joeckel et al., in press).

The track bed is heavily weathered and ferruginized from extensive exposure to the elements on a high terrace of a small stream. Before exposure, it was also at the base of a shallow soil profile, which still covers part of the site. The weathering of carbonate cements, production of surficial ferric hydroxide crusts and case hardening, attack by plant roots and lichens, rainfall, runoff, and human and animal traffic have eroded the tracks considerably. A hog barn had once existed atop the

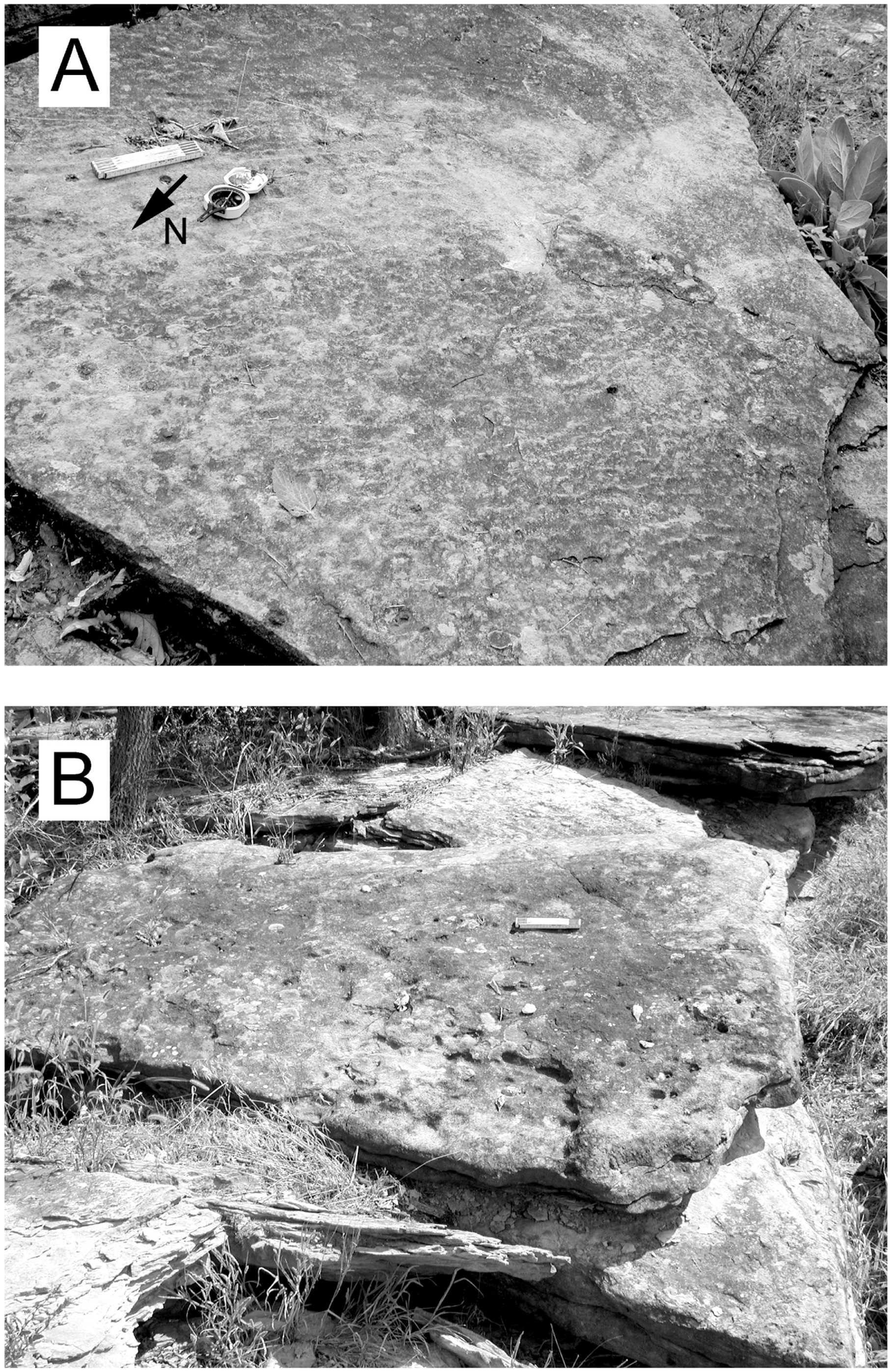

FIG. 3. **A,** Upper surface of collapsed sandstone block with oscillation ripples, from same level as tracks. **B,** Upper surface of second sandstone block, also from same level as tracks, with many, indistinct impressions that may record wholesale bioturbation by large, walking vertebrates. Scale in both photographs is 20 cm long.

tracksite more than 20 years ago, and small trees have since colonized the area.

DESCRIPTION OF TRACKS

There are at least 22 separate tracks in various degrees of expression at the Jefferson County, Nebraska site (Figs. 4–6; Table 1). Together, the tracks do not appear to form a single trackway (numbers 3 and 4 appear to be aligned: Fig. 6B; see also Table 1), and even though all of the tracks lie within a stratigraphic horizon 40 cm or less in thickness, the tracks definitely lie on more than one very thin bedding plane within that interval. Additional tracks doubtless underlie the exposed surface of the sandstone bench at the site. In addition to distinct tracks, parts of this surface are covered with overlapping, shallow,

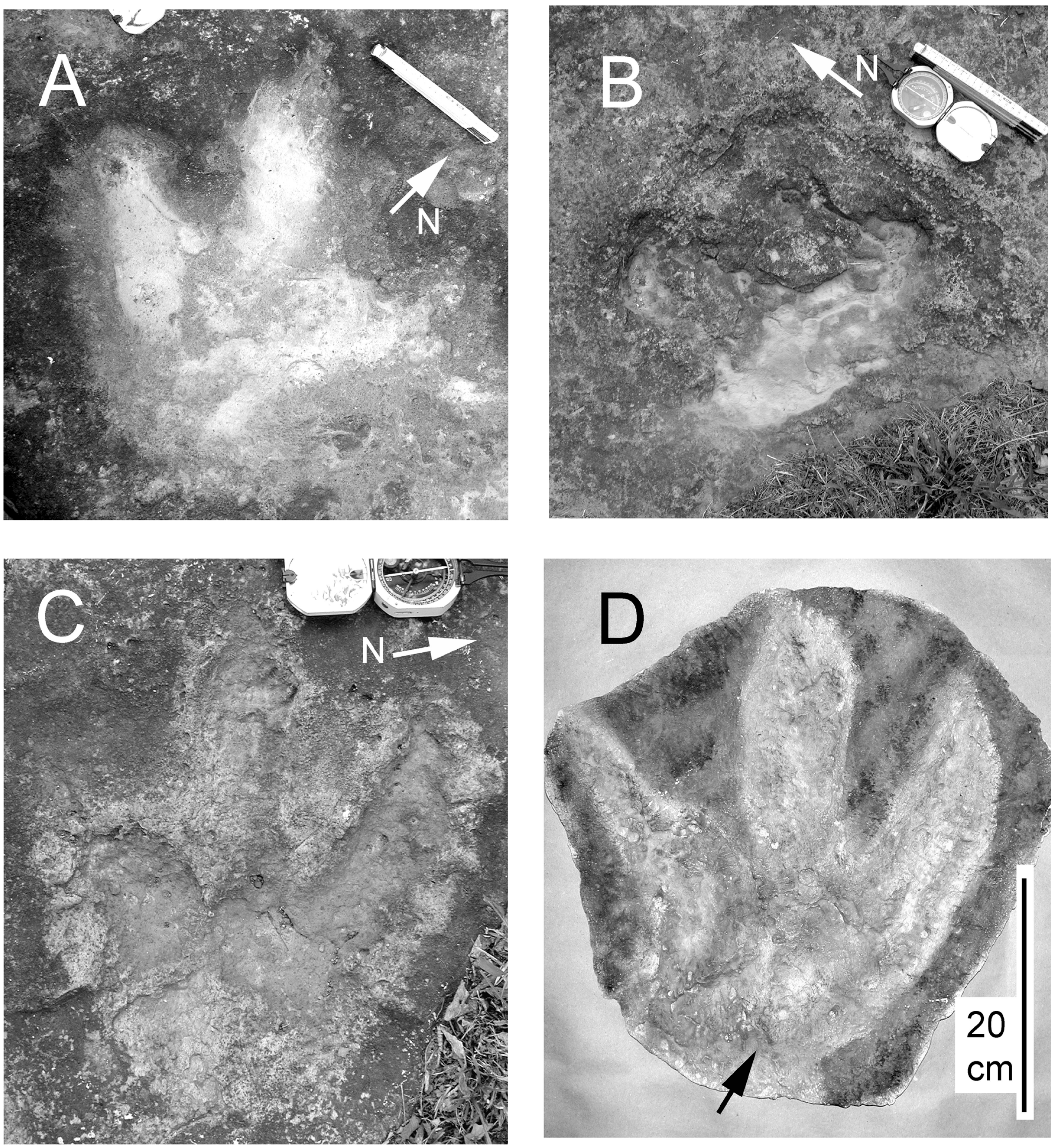

FIG. 4. A, Track number 7 (see Fig. 6), one of most well-preserved tracks at site, showing well-developed tridactyl footprint. Scale in A and B is 20 cm long. **B,** Moderately-preserved track number 1 (see Fig. 6), which may be undertrack or transmitted print (*sensu* Thulborn, 1990). **C,** Track number 17 (see Fig. 6), the best-preserved track at site. **D,** Painted plaster cast of track number 17, produced from silicone rubber mold. Track shows three, relatively broad digits and slightly bilobed posterior margin (black arrow). Scale is same in C and D.

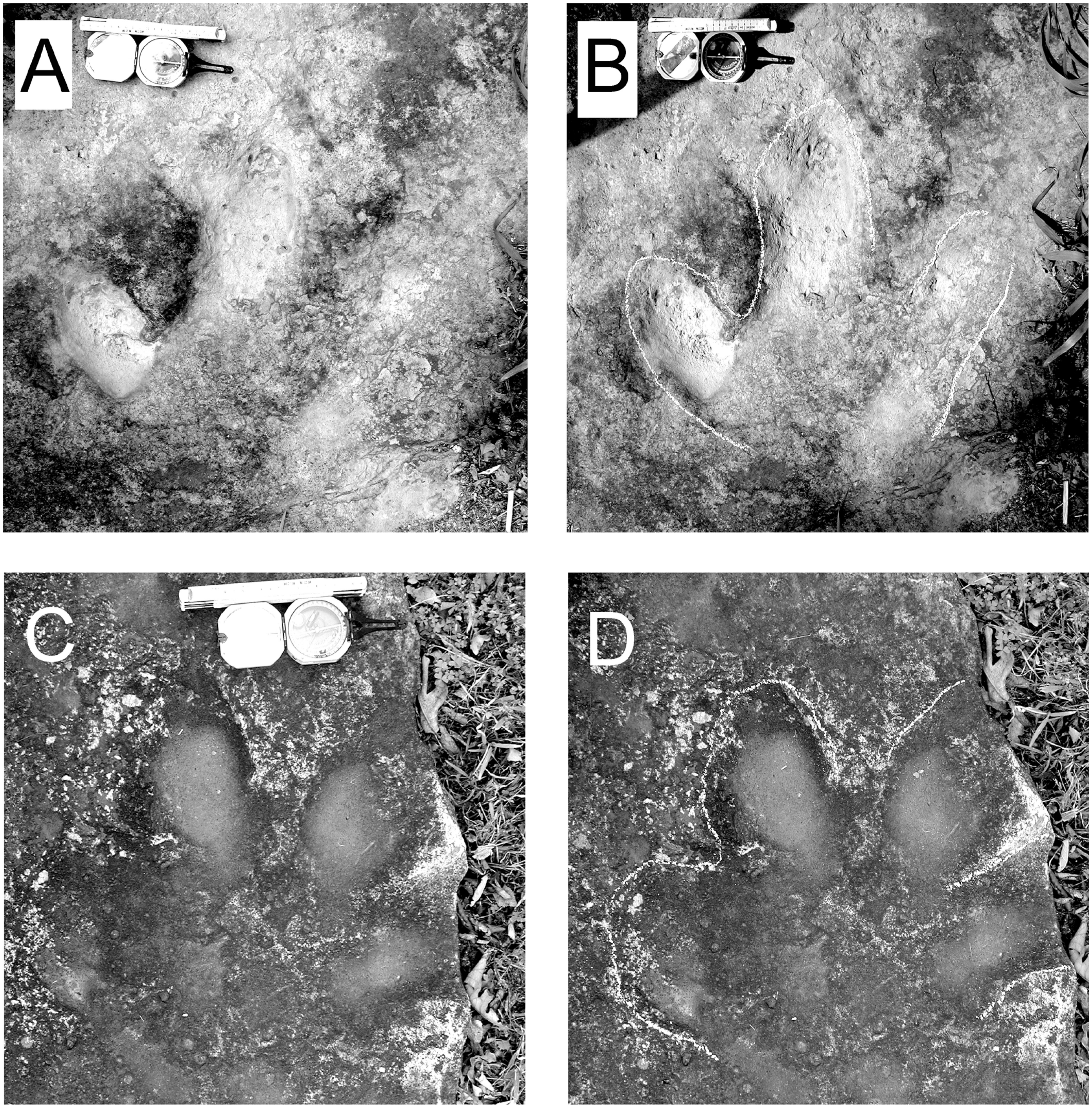

FIG. 5. **A,** Track number 20 (see Fig. 6), largest track at site, with three deep digit impressions that seem to show pad impressions. Scale in A, B, and C is 20 cm long. **B,** Same track with chalked outline. **C,** Similar large track (number 8) with deep digit impressions. **D,** Same track with chalked outline. Four digit impressions are shown, but the fourth, to the lower left, is very shallow and indistinct compared to the other three, which appear to be part of the same print. This track is probably two superimposed tracks, the fourth, shallow digit impression being older.

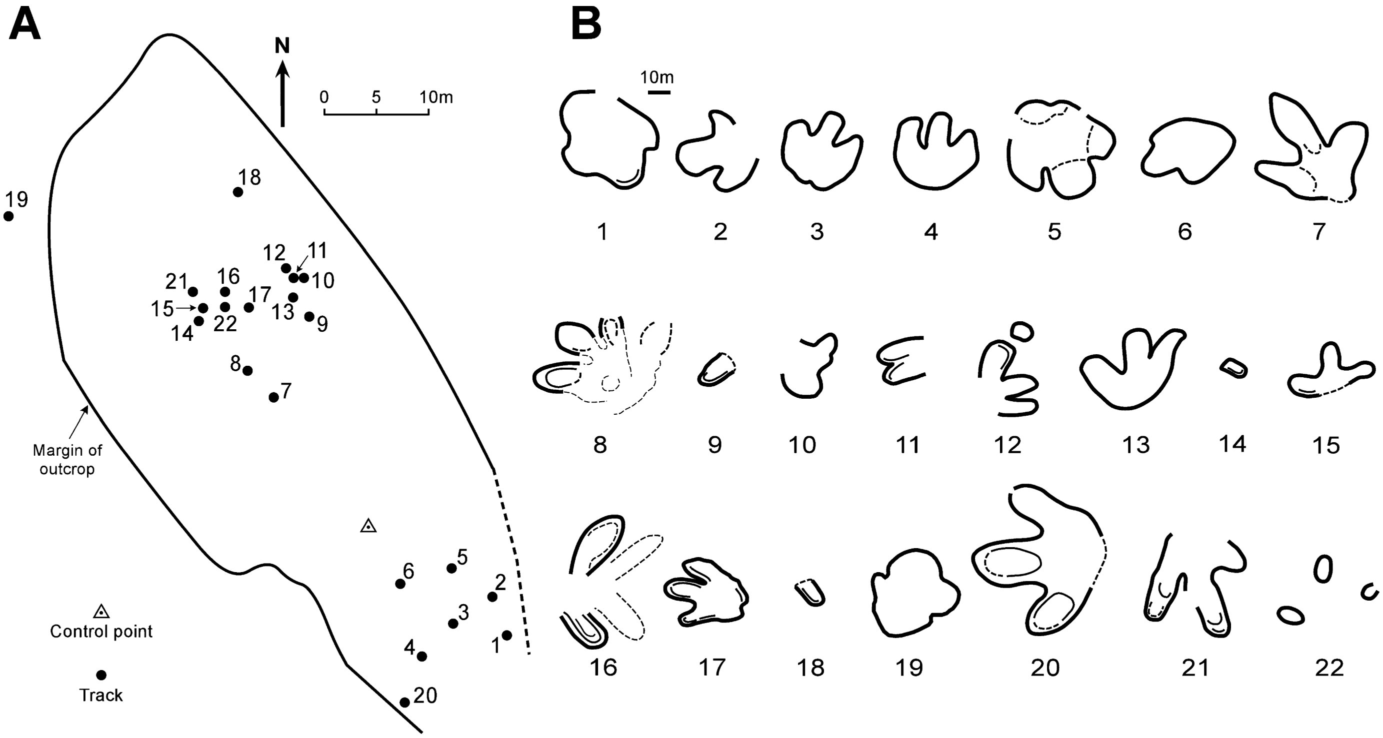

FIG. 6. **A,** Map of tracksite, which is flat-topped sandstone bench, showing distribution of tracks. **B,** Outline drawings of individual tracks.

indistinct depressions that possibly represent wholesale bioturbation by the migration of large vertebrates (Fig. 3B).

The tracks are tridactyl and have broad, blunt digits lacking claw impressions (Figs. 4, 5, 6B). In some tracks there appear to be impressions of broad terminal digital pads (Figs. 5A–B, 6B, numbers 5, 8, 20). Impressions of a broad posterior margin of the foot are present in some tracks, and in at least three cases, the posterior margin seems slightly bilobed (Figs. 4C–D, 6B, numbers 3,5,17). The maximum depth of track impressions varies between 0.5 and 3 cm. Most of the tracks are only moderately distinct, but a few tracks (Figs. 6B, numbers 7, 17, 20) are particularly distinct. Some tracks also have a notably asymmetrical appearance (Fig. 6B, numbers 12, 13; see discussion below).

Most of the tracks are also as wide or wider than they are long (length: width ratios range 0.88–1.63, but all ratios except one are ≤ 1.00). In those tracks that can be measured with confidence, the interdigital angles (II–II, III–IV) vary between 23° and 62°, but generally fall in the range of 23° to 47°. Total divarication from digit II to digit IV in these tracks ranges from 51° to 99°. Individual tracks vary in both morphology and mode of expression. Two end-members in the spectrum of tridactyl imprint morphology are: (1) a track characterized by the hooflike outline of a large, broad, central digit (Fig. 6B, nos. 1, 2, 19) and (2) tracks with more slender and pointed digits (Fig. 6B, number 7). The expression of tracks varies from full footprints, to impressions of two or three digits only, to single-digit impressions. One track preserves only the terminal impressions of three digits (Fig. 6B, number 22). Two tracks show impressions of four digits, but in one case (Fig. 5C–D, 6B, number 8) the fourth digit impression is indistinct and shallow compared to the other three. In the other case (Fig. 6B, number 16), the shape of the print includes two shallow and indistinct digit impressions. In both cases, these tracks are very likely to be superimposed footprints made at different times, rather than single tracks. Individual digit impressions in these tracks are morphologically similar to those in other tracks from the site.

DISCUSSION

Interpretation of Tracks

In overall shape and in the broadness of their digits, the Jefferson County tracks generally resemble Lower Cretaceous ornithopod pes prints described by Currie and Sarjeant (1979), Pittman (1989), Lockley et al. (1992, 1994), and Matsukawa et al. (1999) from western and Gulf Coast North America. Thulborn (1990, Figs. 6.32, 6.33) and Lockley and Meyer (1999) illustrated similar iguanodontid-attributed tracks from North America, South America, and western Europe. The Jefferson County tracks also fall into the same size range as these prints; therefore, they are interpreted as ornithopod footprints. Ornithopod tracks, as a very general rule, can be distinguished from theropod tracks by virtue of length:width ratios of 1.00 or less, relatively broad digits without claw impressions, absence

TABLE 1
Measurements of tracks.

Number	L (cm)	W (cm)	L:W	AZ	Comments
1	37	42	0.88	232°	
2	46	47	—	254°	Bilobed posterior margin
3	42	43	0.98	32°	Aligned with #4
4	46	46	1.00	15°	Aligned with #3
5	42	45	0.93	170°	Possible bilobed posterior margin
6	53	37	1.43	242°	
7	57	58	0.98	335°	Well-preserved
8	50	50	1.00	293°	Probable superimposed footprints
9	19	18	—	238°	Single digit
10	42	>22	—	155°	Very irregular shape
11	18	20	—	245°	Two digit impressions only
12	18	23	—	268°	Skewed
13	45	42	—	10°	Skewed
14	13	6	—	122°	Single digit impression
15	34	46	—	2°	Three digit impressions
16	58	43	0.99	55°	Probable superimposed footprints
17	44	27	1.63	289°	Well-preserved; probable bilobed posterior margin
18	15	8	—	150°	Single digit impression
19	47	48	0.98	~20°	Irregular shape; found on collapsed block
20	55	62	0.89	290°	Largest; found on collapsed block
21	50	47	1.04	175°	
22	—	43	—	350°	

Measured length of track may be incomplete because posterior margin is indistinct or absent. Where possible, length (L) was measured from heel to tip of digit III; if impression of posterior margin of footprint was present, then length: width ratio (L:W) is provided. Maximum width (W) was measured across digits II–IV whenever all three digits were preserved. Azimuth (AZ) of tracks also provided.

of a hallux impression, relatively greater total divarication of digits, and a broad curve at the posterior margin of the print (Thulborn, 1990). Iguanodontid ornithopod tracks, which would be expected in Lower Cretaceous strata, characteristically have: (1) impressions of three digits, (2) total divarication ranging from 30° to 70°, and (3) length: width ratios near 1.00 (Thulborn, 1990; Lockley and Meyer, 1999).

The existence of one- or two-digit impressions at the Jefferson County tracksite is by no means exceptional. A digit or digits may fail to leave impressions in a track because relatively little weight is borne on it/them, in comparison to the principal weight-bearing digit III (Thulborn, 1990). Variation in the morphology of individual tracks has been noted at many dinosaur tracksites and can result from several different factors, including slumping of the track immediately after its production, the existence of a mixture of tracks and undertracks or transmitted prints, and post-exposure erosion (Thulborn, 1990). The indistinct outlines and shallow depths of several tracks at the Jefferson County site are suggestive of undertracks or transmitted prints.

Ornithopod tracks are common in Eurasian and North American Cretaceous mid- to high-latitude, siliciclastic, coastal plain sediments (Lockley et al., 1994). Two common Lower Cretaceous ornithopod ichnogenera of North America are: (1) *Amblydactylus* (Sternberg, 1932; Currie and Sarjeant, 1979), a broad pes print from a bipedal dinosaur, according to Thulborn (1990) attributed to probable hadrosaurs; and (2) *Caririchnium*, a narrower pes print with a distinctive bilobed posterior margin, which is frequently accompanied by manus prints, and which was made by a quadrupedal ornithopod, possibly an iguanodontid (Thulborn, 1990; Lockley et al., 1992, 1994; Matsukawa et al., 1999). Manus prints only rarely co-occur with *Amblydactylus* pes prints (Lockley et al., 1992). Some of the Jefferson County tracks have only a superficial resemblance to *Amblydactylus* in the relative width of the footprint, but one track (Fig. 3, number 17; Fig. 4) is distinctively narrower, like *Caririchnium*, and has a slightly bilobed posterior margin. At least one of the Jefferson County tracks (Fig. 3, number 2) resembles a published illustration of an older Cretaceous iguanodontid print from eastern Jilin Province, China illustrated by Matsukawa et al. (1995, Fig. 6B) in its possession of a large, broad, almost hoof-like digit III and smaller, more pointed digits II and IV. None of the Nebraska tracks are small enough or have the correct morphology to be manus prints (see Matsukawa et al., 1999). The two Jefferson County tracks with four digit impressions are almost certainly superimposed tridactyl footprints, especially because they bear no resemblance to the four-toed Cretaceous ichnospecies *Tetrapodosaurus borealis*, which was made by an ankylosaur (Stenberg, 1932; Currie, 1989).

The poor preservation of the Jefferson County tracks and their limited number precludes the assignment of ichnogenera, much less the identification of two or more track-making species. Under these conditions, it cannot be ruled out that the spectrum of imprint morphologies at the Jefferson County site was made entirely by a single species, and that variations in present appearance among the tracks are due to differences in original substrate consistency, mode of formation (e.g., track vs. undertrack), and differential weathering. The strongly asymmetrical appearance of certain tracks may be the result of the original angle of entry of the pes into the substrate, that is, "sliding" (cf. Currie, 1989, Fig. 31.5).

Significance of Tracks

Hundreds of dinosaur tracks have been found over a large area of Dakota Formation exposure 1000 km from eastern Nebraska in the Colorado-New Mexico Rocky Mountain front-High Plains (Lockley et al., 1992; Matsukawa et al., 1999). Multiple tracksites in this area lie within strata that are roughly time-equivalent to those exposed in Jefferson County, Nebraska. Perhaps the best known of the western Dakota Formation tracksites is the Dinosaur Ridge/Alameda Parkway tracksite, where dozens of tracks occur on a bedding plane in well-sorted sandstone, together with oscillation ripples, burrows, and other features suggesting tidal influence (McKenzie, 1968, 1972; Lockley et al., 1992).

The concentration of western Dakota Formation dinosaur tracks in a narrow stratigraphic interval has been considered particularly significant. Lockley et al. (1992) and Matsukawa et al. (1999) placed them at or near a depositional sequence boundary, but Lucas et al. (2000) strongly refuted these conclusions.

The Jefferson County, Nebraska site bears a general similarity to many of the western Dakota Formation tracksites in the characteristics of tracks and in their geologic context. The regional stratigraphy established by Brenner et al. (2000) suggests that the Nebraska tracks may be near a parasequence boundary or, at the very least, an exposure surface between two well-defined sequence boundaries. In contrast to the many western Dakota Formation tracksites, however, the Jefferson County tracksite is for now a unique occurrence in its surrounding area.

The comparative rarity of vertebrate fossils, whether trace or body, from the eastern-margin Dakota Formation may be purely circumstantial. There are only a few extensive outcrops comparable in size to those found in the Rocky Mountain region, and there has been little scientific interest in the Dakota Formation in the Midcontinent. The preservation of tracks at the Jefferson County site seems exceptional largely because it is the first regional discovery. In retrospect, few, comparable bedding-plane exposures of Dakota Formation sandstones in Nebraska have been examined closely, and therefore a reliable assessment of the commonness of vertebrate traces cannot yet be made. The track bed is conspicuous, however, as an early-cemented horizon. This characteristic is the chief reason for the current exposure of the tracks and is likely to have been the major contributor to their preservation. No macro- or microscopic evidence was found for the penecontemporaneous stabilization of the track bed's surface by microbial mats (e.g., Kvale et al., 2001), but such a process might also have been at work.

The widespread presence of early diagenetic cements in the Dakota Formation (Brenner et al., 2000) and the identification of analogous sandstone facies at multiple sites in eastern Nebraska and Iowa suggest that additional tracksites along the cratonic margin of the Western Interior Seaway may await discovery.

CONCLUSIONS

The Jefferson County, Nebraska tracks document the existence of continental environments suitable for large terrestrial vertebrates well into Dakota Formation times. Moreover, because of the rarity of Cretaceous tracksites and the extreme rarity of body fossils in the midcontinental United States, the Jefferson County tracks constitute an important biogeographic and biostratigraphic data point. Ongoing fieldwork may eventually locate additional tracksites, and existing palynostratigraphic and chemical stratigraphic data will facilitate their placement relative to a sequence stratigraphic framework. Such work could provide new information to test the much-debated hypothesis of Lockley et al. (1992) that dinosaur tracks can have a close relationship with genetic depositional surfaces.

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