Footprints of Utah's Last Dinosaurs: Track Beds in the Upper Cretaceous (Maastrichtian) North Horn Formation of the Wasatch Plateau, Central Utah

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PALAIOS, 2002, V. 17, p. 327–346

Dinosaur track beds occur at several localities in the uppermost Cretaceous (Maastrichtian) North Horn Formation in the Wasatch Plateau, central Utah. The track bed localities, separated by up to 80 km, also contain dinosaur body fossils. At the type locality at North Horn Mountain in Emery County, more than 100 individual exposures and/or stratigraphic levels within a 1.2-km^2 study area exhibit tracks in vertical cross-sectional view. These biogenic structures are similar to others that have been interpreted elsewhere as deep dinosaur tracks. At the type section, track beds vertically span at least 183 m from the base of the formation up to a few meters below the highest dinosaur eggshells, which are interpreted to occur immediately below the Cretaceous-Tertiary (K-T) boundary interval. Track occurrence in the North Horn Formation demonstrates that large dinosaurs were present in central Utah until very shortly before the K-T boundary.

The track structures feature deformation, overprinting, and slip striae that are interpreted to exhibit individual dinosaur behavior. Some striae exhibit repeating patterns that suggest tubercle configuration or scale patterns on dinosaur feet. Track groupings at any individual level suggest that many animals repeatedly congregated in topographic lows of the floodplain or near shifting anastomosing river systems, and track-size distribution largely suggests the presence of different sizes or age groups of herbivores. The conditions produced by anastomosed fluvial environments provided the depositional setting responsible for formation and preservation of most of the North Horn tracks.

INTRODUCTION

Most dinosaur tracks that have been described in the literature are exposed in plan view on bedding planes (e.g., Farlow and Chapman, 1997; Lockley, 1997); among these are specimens that are found in the tunnel roofs in coal mines (Lockley et al., 1983; Lockley, 1991; Lockley and Hunt, 1995a). Although they are recognized much less frequently, many other dinosaur tracks appear in vertical cross-section in outcrop as disturbed beds that superficially resemble load casts or undulating beds bearing sole marks (Loope, 1986; Parker and Balsley, 1989; Lockley, 1990). Nadon (1993) described this type of track occurrence in Late Cretaceous deposits of the St. Mary River Formation of Alberta, Canada, and he reported that these tracks were associated with anastomosing fluvial paleoenvironments. Engelmann and Hasiotis (1999) also reported the same type of deep track beds as sole traces in the Jurassic Morrison Formation at widespread localities in Utah, Colorado, and Wyoming.

Difley and Ekdale (1998) first reported deep dinosaur tracks in vertical cross-section at the type locality of the North Horn Formation at North Horn Mountain, Emery County, Utah. This paper expands that report and details widespread, but previously unrecognized, dinosaur track beds at several other localities in the North Horn Formation of central Utah. Described herein is a succession of track beds in terrestrial deposits that spans nearly the entire Maastrichtian portion of the North Horn Formation type section at North Horn Mountain, and the connection of those track beds with deposits of anastomosing fluvial systems. This report also examines the relationship between sedimentology and paleoenvironments, dinosaur behavior, and how the tracks were made. Some of the dinosaur track beds, such as those close to the Cretaceous-Tertiary (K-T) boundary interval, occur at stratigraphic levels entirely lacking skeletal dinosaur elements, or where rare eggshells are the only previously known evidence for the presence of dinosaurs.

LOCATION AND PREVIOUS WORK

The study area includes several localities of the North Horn Formation in the Wasatch Plateau, central Utah (Fig. 1): (1) North Horn Mountain and Black Dragon Canyon are located on the east-central edge of the Wasatch Plateau west of Castle Dale; (2) Flagstaff Peak is located on the Wasatch Plateau south of North Horn Mountain; (3) Fairview Canyon is located on the west central slope of the Wasatch Plateau east of Fairview; and (4) Price Canyon is located on the northern slope of the Wasatch Plateau, northwest of Price.

Dinosaur fossils first were reported in the K-T North Horn Formation at the type section on North Horn Mountain (Spieker, 1946), at nearby Wasatch Plateau localities in Black Dragon Canyon (Gilmore, 1946), at Flagstaff Peak (Ferron Mountain; Spieker, 1960), and at Trail Mountain, as well as in Price Canyon on the northern edge of the Wasatch Plateau (Difley and Ekdale, 1999). The type locality has yielded the bones and teeth of theropods (*Tyrannosaurus* and others), sauropods (*Alamosaurus*), ceratopsians (*Torosaurus* and others), hadrosaurs (Gilmore, 1946; Lawson, 1976; Loewen et al., 2001), and other dinosaurs (Cifelli et al., 1999), as well as at least a half dozen dinosaur eggshell types (Jensen, 1966; Bray, 1999; Difley and Ekdale, 1999).

The stratigraphy of the North Horn Formation was de-

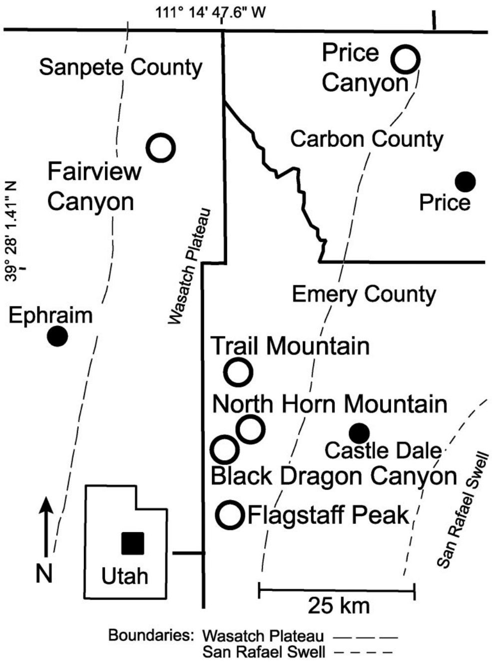

FIGURE 1—Map of central Utah showing dinosaur track bed study sites (open circles) and nearby towns (solid circles).

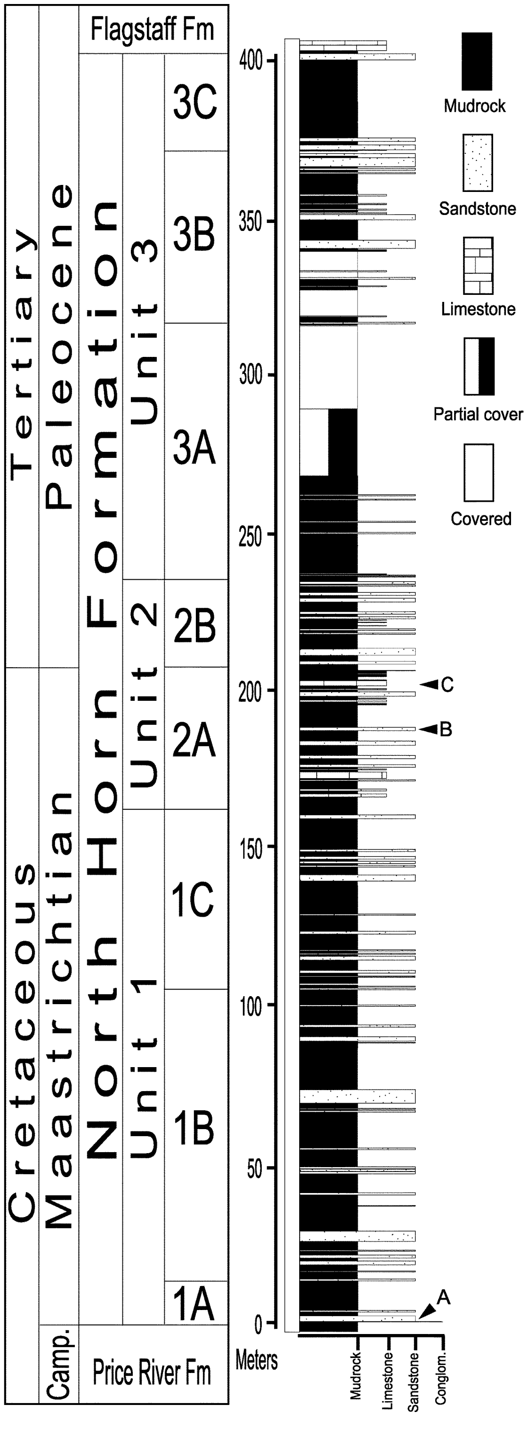

FIGURE 2—Stratigraphic column of the type section of the Cretaceous-Tertiary North Horn Formation at North Horn Mountain. Levels of the lowest (A) and highest (B) unequivocal track beds and highest eggshells (C) are indicated.

scribed at North Horn Mountain by Spieker (1946), Lee (1953), Kucera (1954), Franczyk and Pitman (1991), and Difley and Ekdale (1999), at Fairview Canyon near Fairview by Oberhansley (1980) and Jensen (1988), and in Price Canyon by Fouch et al. (1987) and Olsen (1995).

NORTH HORN FORMATION STRATIGRAPHY

The North Horn type section (39° 11.40′-13.00′ N, 111° 14.21′-15.00′ W) is 403 m thick (Fig. 2), and it provides a reference section for the other localities. The formation is Maastrichtian in its lower portion and Paleocene in the upper. It consists of three lithostratigraphic units, and these can be subdivided further based on lithologic and paleontologic differences.

Unit 1, the lowest unit, consists chiefly of variegated mudstone interbedded with fine-grained, heavily bioturbated sandstone lenses and sheets (80% mudrocks, 20% sandstone and larger grain sizes); sandstones contain some thin horizons of granule-to pea-sized conglomerate (clasts commonly consist of yellow to white calcareous nodules). Fossiliferous limestones (lime wackestones and lime mudstones), sometimes with invertebrate or root traces, are locally common, and uncertainly bedded. Mudstones have a high clay content (very slick when wet), and they commonly display smectitic ("popcorn"-like) weathering. They generally are internally massive, and they fracture into slickensided prisms (up to ~7 cm long) or display a smaller, fine, blocky, ped-like structure. Thin sections of the mudstone reveal micro-cracking patterns. Calcareous (white to gray) and iron-oxide nodules are distributed throughout the mudstone. Commonly the calcareous nodules (notably ~1 cm diameter) are coated generously with iron stain; rusty yellow, red or gray, sometimes vertically-oriented mottling occurs within the mudstone. Ledge-forming and terrace-forming sandstone sheets, lenses, and ribbons may be massively bedded, or they may display abundant physical and biogenic sedimentary structures. The structures include cross-bedding (trough and planar); ripples (current and climbing); and wavy, planar, and laminar bedding that may be parallel, non-parallel, or highly irregular.

Sandstone beds commonly are separated by mudstone as partings or thin beds. Intermittently exposed sandstone lenses and ribbons may be traced laterally up to about 350 m, and may be up to about 5 m thick and 3 to 30 m wide. In a few cases, they contain moderately dipping lateral accretion surfaces (up to ~3 m high by ~7 m long); several beds (2 to 6) may be stacked. Sandstone sheets (~1 m thick) may be traced up to about 300 m.

The lowest subunit (1A) is thin, and its mostly gray mudstones contain abundant organics. The middle subunit (1B) consists of mudstones with gray, or subdued variegated, to red color hues, along with notable calcitic and iron-oxide nodules. Mudstones of the third subunit (1C) generally are more brilliantly colored (e.g., up to as bright as Munsell 10R5/6) than the lower subunits.

Dinosaur remains (bone and eggshell) occur throughout Unit 1. Taxa include *Alamosaurus*, *Tyrannosaurus rex*, *Torosaurus* and other ceratopsians, and hadrosaurs (Gilmore, 1946; Jensen, 1966; Lawson, 1976; Bray, 1999; Cifelli et al., 1999; Difley and Ekdale, 1999; Loewen et al., 2001; Difley, unpublished data). Less common and restricted to scattered levels are other vertebrates, such as mammals, lizards (*Polyglyphanodon*), crocodilians, turtles and fish (Gilmore, 1946; Cifelli et al., 1999; Difley, unpublished data).

Unit 2, the middle unit, is dominated by fossiliferous, commonly dark gray, thinly bedded organic-rich shales and mudstones. It contains highly fossiliferous limestone, and very thin layers of low-grade coal. Sandstone occurs largely as fine-grained lenses, bearing cross-bedding, ripples, and wavy, planar, and irregular beds. The lower part of the unit (2A) contains more limestone, more organics, and fewer sandstone beds than the upper (2B). The mudstones of Unit 2B are lightly variegated over thin intervals at the base and top of the unit, and throughout this unit, dark, organic-rich alternates with largely yellow mudstone.

The K-T boundary interval, defined here as the stratigraphic span between the highest dinosaur remains and the lowest Paleocene pollen, is near the contact between Units 2A and 2B. Difley and Ekdale (1999) determined stratigraphic proximity to the K-T boundary based on disappearance of several Cretaceous taxa (represented by bone and eggshell of dinosaurs and by microfossils) within this interval (~6 to 30 m below the Unit 2A/2B contact).

Freshwater aquatic fauna (including crocodilians, soft-shelled turtles, fish, bivalves, gastropods and ostracods) are common throughout Unit 2, but they are relatively abundant in Unit 2A (Difley and Ekdale, 1999). The only identifiable dinosaur skeletal material in Unit 2A is a small fragment of an ornithiscian jaw that occurs low in the unit. Based upon poorly preserved, partial tooth sockets, it cannot be identified more closely than either ceratopsian or hadrosaurian (Difley, unpublished data).

Unit 3, the uppermost unit, is mostly covered at North Horn Mountain due to recent mass wasting. Low in the unit (3A), variegated mudstone is dominant and is interbedded with minor fine- to medium-grained sandstone displaying cross-bedding or wavy bedding. The mudstone contains some rusty yellow mottling. The middle part of the unit (3B) consists of alternating mudstone, sandstone, and limestone. The upper part of the unit (3C) contains conspicuous red (e.g., up to as bright as Munsell 5R 5/6) and variegated mudstone with some sandstone.

PALEOENVIRONMENTS

Depositional Environments in Unit 1

Fluvial Setting

Depositional settings in Unit 1 of the North Horn type locality (and stratigraphic equivalents at other localities) are interpreted as dominantly fluvial floodbasin environments, based upon lithologic characteristics (e.g., discontinuous nature of sandstone lenses and related sheets within predominant banded, variegated mudstones; Spieker, 1946) and occurrences of fossils that are usually associated with these environments (Gilmore, 1946). At North Horn Mountain, prominent thin, vertical, linear fins or vertical ledges of sandstone sequences (3 to 5 m) cap variegated mudstone (Fig. 3A). Although splay sheets may be incorporated into the fins and ledges, many appear to be remnants of linear stream courses that generally flowed northeastward (Zawiskie, 1983; Franczyk and Pitman, 1991). Straight to slightly sinuous sandstone ribbons and fins that have emerged in eroded relief in badlands represent remnants of exhumed anastomosed streams (Fig. 3B, C), such as are documented also in the Lower Cretaceous Cedar Mountain Formation of Utah (DeCourten, 1998). The sandstone ribbons and fins are composed of single to multi-storied beds, and they display laterally restricted, vertical stacking.

Anastomosed Environments

Lithologic and geometric characteristics that Nadon (1994) attributed to anastomosed fluvial environments in the St. Mary River Formation of Alberta and Montana are common in the sedimentary sequences of the North Horn Formation. In a survey of numerous fluvial formations, Nadon (1993) included the North Horn Formation as a candidate for anastomosing environments based partly upon lithologic characteristics, such as the presence of sandstone lenses and sheets, and the predominance of fine-grained sediments. Other shared characteristics include sandstone ribbons contained within dominant mudstone (shale, claystone, siltstone); narrow, stacked sandstone lenses and/or lateral accretion structures (Fig. 3D); and ripple lamination, cross beds, and planar beds (Fig. 3A).

Other features shared with Unit 1 of the North Horn type locality were attributed to an anastomosed fluvial environment by Smith (1983) who described a modern, low energy, anastomosing river in an intermontane setting. This example has avulsing, aggrading, low gradient, sandy channels with low sinuosity, prominent levees, and adjacent crevasse splays and wetlands. Nadon (1994) additionally characterized anastomosed fluvial environments as suspended-load rivers with interconnected channels in a low gradient, foreland-basin setting having distinct wet-dry cycles (savannah or semi-arid). There may be rapid vertical aggradation of deep, stable channels with levees associated with sandstone crevasse-splay sheets and sandstone ribbons encased in dominant fine-grained sediments.

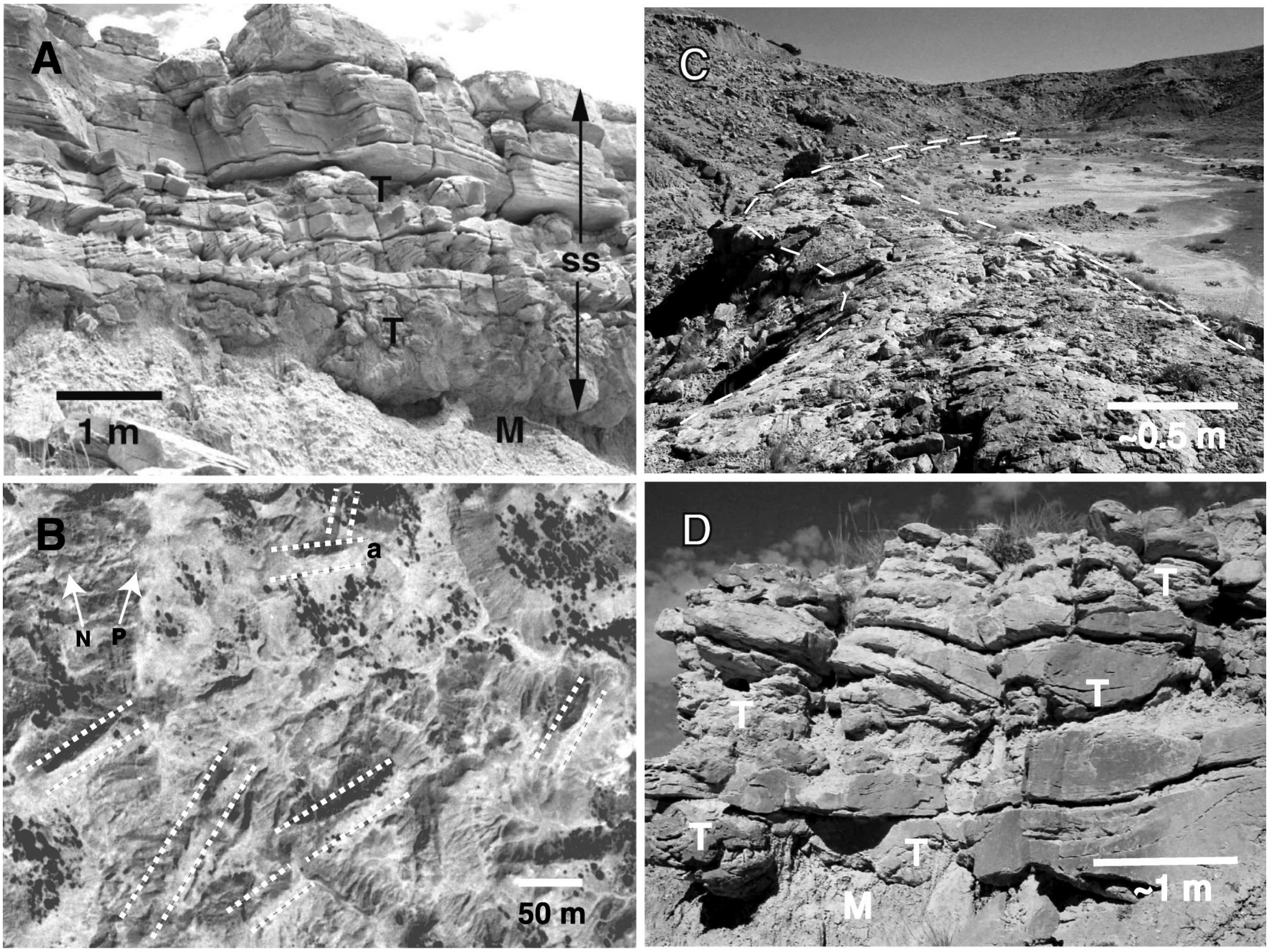

FIGURE 3—North Horn Mountain south face, Unit 1. (A) Track bed in Unit 1B in outcrop showing two track intervals (T) separated by sandstone beds that display trough cross-bedding that indicates apparent current direction from right to left. Sandstone outcrop (sandstone sequence, SS) overlies mudstone (M) and may represent a recurrent splay deposit or crevasse channel. Upper tracks (pillow-shaped) originally were formed in mud interval between channel/splay sheet episodes. Lower tracks represent a chaotic trample zone where many dinosaurs made deep footprints or repeatedly trampled in mud. (B) Aerial view of badlands in Unit 1B (39° 11.71′ N, 111° 14.80′ W) showing erosional remnants of fluvial channel ribbon sandstones from several exhumed anastomosed paleorivers (channel margins indicated by dashed lines), all of which bear dinosaur tracks. Not all of the delineated paleochannels were active at one time. Thus, this figure is not intended to illustrate an entire anastomosing paleosystem. Note that one exhumed channel structure (a) in the upper middle edge of the photo truncates another, which indicates that these two channels flowed successively. Mean paleoflow (arrow, P) is generally northeast (Zawiskie, 1983; Franczyk and Pitman, 1991). North (arrow, N) is to the top of the figure. (C) Slightly sinuous exhumed sandstone paleochannel (outlined by dashed lines) is $\sim$ 3 m wide and elevated about 1.5–2 m above the surrounding terrace. The stacked sandstone beds indicate that the structure may have formed during two or three channel-building episodes. The beds are dinoturbated at the paleochannel margins and show evidence of slight lateral migration. Unit 1C, (39° 12.05′ N, 111° 14.76′ W). Scale is approximately 0.5 meter. (D) Lateral accretion structure (upper part migrating from left to right) with undulating, chaotic sandstone dinosaur track beds (T) between intervals of inclined bedding planes, overlying and interbedded with mudstone (M), Unit 1B, (39° 11.63′ N, 111° 14.87′ W). Scale is approximately 1 m.

Anastomosed systems develop laterally and vertically. Over a period of time (sometimes seasonally) they may change from isolated river channels to expansive sheets of flowing water, and then change to multiple, small channels that split and rejoin. These fluvial systems may go from stages of active flow and avulsion (i.e., an abrupt change of course) to abandonment of channels and sheets (Smith et al., 1989).

Anastomosis (as defined by Nadon, 1993, 1994) is the process of forming a stream environment in which channels branch and rejoin. Proof of the existence of coeval channels with simultaneous flow is unnecessary to accurately identify anastomosing systems (Kirschbaum and McCabe, 1992; Nadon, 1994). Instead, anastomosed settings may be inferred from total lithofacies associations, similarity of vertical profile, and geometric distribution.

In plan view, both anastomosed and braided systems may lie in multiple channels, but anastomosed streams are represented in cross-section by discrete, fine-grained, suspended-load channels that are encased in dominant mudstone (Miall, 1996), while braided facies contain coarse-grained, bed-load or mixed-load deposits. An idealized vertical profile of a braided stream displays a high ratio of coarse grains to mudrocks, in contrast to that of an anastomosed stream, which contains a high percentage of mudrock (Miall, 1996, figs. 8C, J). An idealized vertical profile of a meandering stream displays a high percentage of lateral accretion features and a slightly lower ratio of mudrocks to sandstones than that seen in anastomosed stream profiles (Miall, 1996, figs. 8G-J). A typical vertical profile at the North Horn type locality bears no resemblance to that of Miall's (1996) braided stream. Furthermore, the percent ratio of mudrocks to sandstones (4:1) in Unit 1 at the North Horn type section better matches that indicated by the idealized anastomosed stream profile than the meandering stream profile, although the North Horn has some lateral accretion structures (Fig. 3D).

Lateral accretion elements occur, although rarely, in anastomosed fluvial settings (Kirschbaum and McCabe, 1992; Nadon, 1993). At the North Horn type locality, the fluvial sandstones represent small rivers (Franczyk and Pitman, 1991). These bear smaller-scale lateral accretion structures that are not as laterally or vertically persistent as those that are more typical of meandering settings (Miall, 1996, figs. 8G-I), and they could represent proximal crevasse channels in anastomosed systems (Nadon, 1994). Lateral accretion structures in the North Horn Formation might be interpreted as point bars of meandering rivers, but such structures also may be found where slight meandering occurs within straight reaches of anastomosed rivers (Smith, 1983).

Low paleoslope may aid the development of anastomosis (Kirschbaum and McCabe, 1992; Nadon, 1994), because such low gradient is subject to rapid stream avulsion and the formation of broad splay sheets. Low paleogradient for the North Horn Formation type locality is indicated by the predominance of fine-grained rocks, and this is consistent with its inferred central geographic placement in the eastern North Horn depositional basin (Stanley and Collinson, 1979; Difley and Ekdale, 1999). A very low paleogradient or paleoslope is consistent with anastomosis, and a low paleoslope also is compatible with the suggestion of Franczyk and Pitman (1991) that the North Horn type area represents a fine-grained, downstream facies of coarser North Horn deposits, which they located miles to the south. Aggradation of sand sheets, channels, and muddy layers over a low depositional gradient may continue over long periods under constant subsidence, such as might be produced in foreland basins (Miall, 1996; Nadon, 1994) like the depositional setting of the North Horn deposits (Lawton et al., 1990).

Flood Basin Succession

A typical North Horn flood basin succession in Unit 1 consists of successive, closely spaced sandstone beds 3–5 m thick (sandstone succession; Fig. 3A) and an underlying mudstone flood sequence (commonly about 5–25 m, but may be up to 35 m thick with occasional thin sandstone interbeds). Beds within the sandstone succession commonly are thinly bedded, planar or ripple laminated, or tabular to trough cross bedded. One or more succeeding disturbed horizons may be interbedded with additional planar and/or cross-bedded structures.

Individual beds in the sandstone succession are about 0.3–1 m thick, and they are separated by thin to very thin mudstones (0.3 m thick and less). This successional pattern repeats throughout Unit 1, where it coarsens upward from mudstone to sandstone. At the top of the succession, the sandstone commonly fines upward and displays intense bioturbation by invertebrates. Similar gross upward-coarsening lithologic successions of anastomosed deposits were described by Rust and Legun (1983, p. 389) as "progradation of depositional lobes" into "local depressions on the floodplain." Perez-Arlucea and Smith (1999) and Morozova and Smith (2000) described the same pattern as progradation of fluvial deposits into low-lying wetlands. The upward-fining, intensely bioturbated sandstone bed at the top of the North Horn successions may represent fluvial abandonment similar to that described by Rust and Legun (1983) and Perez-Arlucea and Smith (1999).

Splay Sheets

Sandstone sheets of relatively uniform thickness (usually about 0.3 to 1 m) cap extensive geomorphic terraces, which may be traced laterally for up to about 300 m at North Horn Mountain. Intensely bioturbated, fine-grained, sandstone beds, each about 1 m thick, may be distributed sporadically within the flood-sequence mudstone. They are commonly finer-grained and more thoroughly bioturbated at the top. These probably represent overbank-splay deposits, where the finer-grained, heavily bioturbated tops represent abandonment (Rust and Legun, 1983; Miall, 1996). These sandstones, interpreted as crevasse splays, commonly are bioturbated throughout by invertebrates and are sometimes laterally continuous with, and thin away from, neighboring channel lenses. The splays probably represent crevassing of channel levees, which spread across the adjacent lowest-lying floodplain (where there may have been ephemeral wetlands), became a part of the overbank, or reoccupied and became incorporated within other channel sequences (Perez-Arlucea and Smith, 1999).

Channels

Sandstone lenses in Unit 1 commonly are laterally restricted. Some are concave up, curved sandstone beds that turn up at the edges and/or sandstone beds that pinch out at channel edges commonly showing current direction perpendicular to the channel trend; beds such as these may represent stream levees (Nadon, 1994).

Anastomosed channels often are stacked vertically due to lateral stability of channel deposits resulting from confining levee deposits (Nadon, 1994). One example at the North Horn type locality is an exhumed, two- or three-story channel, having a slightly sinuous course (Fig. 3C; Smith et al., 1989). The channel is a narrow ribbon sandstone (3 m wide, ~1.5 m thick), having little lateral offset, as described elsewhere by Eberth and Miall (1991). Another exhumed channel (Fig. 3B, a) is about 4 m thick, up to 30 m wide, and it has five or six stories separated by thin mudstone. Although its lateral margins are eroded, they appear to have little offset. Eberth and Miall (1991, p. 237) interpreted similar structures elsewhere as "vertically aggrading anastomosed streams."

One small (2 m wide), straight-coursed, single-story sandstone lens within a sandstone splay sheet likely represents a feeder channel that may have drained the sheet

(Miall, 1996). This type probably represents a stage of the anastomosing system where avulsion of larger, confined channels occurred, spreading into crevasse-splay sheets, and finally channelizing and draining through small, multiple feeder channels (Smith et al., 1989).

Paleosols

The flood sequence mudstones underlying a sandstone succession are interpreted as floodplain paleosols. With the exception of part of Unit 1A, these mudstones typically lack thin, horizontal layers that suggest lacustrine settings (Nadon, 1993). Internal structure of the mudstone may be blocky or angular, but it is frequently prismatic and/or slickensided. These are common characteristics of paleosols (Retallack, 1997) that were alternately wet and dry during soil formation (Kirschbaum and McCabe, 1992). Further evidence that the mudstones are paleosols is provided from thin section examination of inclusions in gray calcareous mudstone within the sole of the lowest bed of a sandstone succession (Fig. 3A), which reveals microcracking reminiscent of that associated with weathered or desiccated paleosol products (Blodgett, 1988; unpublished data). Based upon high clay content with swelling, and frequency of prismatic or slickensided internal structure, most of the mudstones may represent vertisols which form in sub-humid to semi-arid settings (Retallack, 2001).

Mudstone-color variation possibly records moisture, sedimentation cycles in the floodplain, length of subaerial exposure, or intensity of soil formation (Nadon, 1994). Mudstones are variegated to gray, and commonly contain gray to yellow ferruginous mottling. Gray mudstone, with or without mottles, may have formed in low-lying, local wetlands on the floodplain. Gray, clayey to silty organic floodplain muds with roots and/or iron-oxide mottling may represent seasonal wetland environments (Perez-Arlucea and Smith, 1999; Morozova and Smith, 2000).

Commonly, sandstone immediately overlies gray mudstone. This stratigraphic order may represent avulsion of fluvial sands onto the lowest-lying proximal floodplain, where there were seasonal wetlands with a water table close to the surface (Smith et al., 1989; Nadon, 1993). A thin band of red mudstone (commonly ~6 cm thick) is often interbedded with the gray mudstone, and may indicate a pause in sedimentation and/or sediment oxidation under longer subaerial exposure (Retallack, 1985).

That some of the mudstones originated during seasonal floods and/or intervals of high water table is indicated by abundant yellow, vertically-oriented iron-oxide mottling that probably represents rooted horizons in seasonally water-logged soils (Retallack, 1997). Based upon vertical lengths of oriented iron-oxide traces within the variegated mudstone, herbaceous plants of varying size, but usually having shallow root systems (up to 15–20 cm depth) are interpreted to have grown on the floodplain. Larger vegetation, possibly trees, is inferred from traces of much deeper (1 m) roots with larger diameter (2.5 cm).

Calcareous and iron oxide nodules (and ferruginous mottling) that occur in mudstones throughout Unit 1, along with a vertisol interpretation (above), suggest that the mudstones are paleosols that formed in a semi-arid fluvial flood basin. Seasonal precipitation (Hubert, 1978) or alternation between wet (or waterlogged) and dry conditions are suggested to Retallack (1997, 2001) by the occurrence of both calcareous and iron oxide nodules. Calcareous nodules precipitate and accrete during intermittent wet-dry, while the ferruginous nodules may result from chemical alteration of iron in soils under periodic waterlogged conditions. Aridity is suggested for the occurrence of calcareous nodules, because chemical weathering in a humid climate would dissolve the nodules (Reeves, 1976; Miall, 1996). Additionally, semi-arid conditions are consistent with the occurrence of certain North Horn Formation fauna. The occurrence of calcareous nodules with *Alamosaurus* in Unit 1 at the North Horn type locality (Gilmore, 1946) suggests to Bakker (1986) that *Alamosaurus* lived in a dry, well-drained habitat. Lehman (1987) likewise places *Alamosaurus* in a "savannah" (semi-arid) setting.

Local Ponds

Fossiliferous limestones are locally common and sometimes associated with the sandstones. They often preserve mollusks, ostracods, and charophytes, and probably represent ephemeral floodbasin ponds or small lakes. The limestones sometimes contain invertebrate or root traces, which may be interpreted as a paleosol overprint (Platt and Wright, 1992). Association with channel deposits, roots, and freshwater fauna indicate the limestone occurred in a floodplain setting (Kirschbaum and McCabe, 1992).

In summary, a typical North Horn floodbasin succession begins with thick (5–25 m), variegated and/or gray mudstone. The mudstone may be interbedded sporadically with thin sandstone sheets or small, thin, isolated, laterally narrow sandstone lenses (~0.3–1 m thick) encased in mudstone. The floodbasin succession coarsens upward into a succession (~3–5 m) of sandstone beds interbedded with thin mudstone (Fig. 3A); this latter succession ordinarily overlies a gray mudstone possibly representing wetlands. The mudstones largely are interpreted as paleosols that occur on a semi-arid fluvial floodplain with occasional splays or overbank deposits and isolated fluvial channels. The sandstone succession is interpreted as a sequence of crevasse-splay and channel deposits that resulted from massive or repeated avulsion into a topographic low, perhaps an ephemeral wetland. Therefore, based upon total facies distribution, (i.e., including predominance of fine-grained rock types, bedding, sedimentary structures, and geometry), the fluvial facies of the North Horn type locality is interpreted to represent anastomosed fluvial environments.

Depositional Environments in Unit 2A

The thinly bedded, fossiliferous, fine-grained carbonaceous rocks and limestones in Unit 2A represent wetlands that varied from shallow lakes to marshes or swamps. A wetland fluvial element is represented in Unit 2A by fine-grained sandstone lenses that are interbedded with the mudrocks. There are no variegated mudstone beds that might suggest an extensive floodplain or the same type of intensive paleosol development as indicated in the underlying unit. Limestones and gray or dark-colored, thinly bedded or laminated mudstones or shales containing abundant aquatic fauna, such as fish and mollusks, but no roots, are interpreted as lacustrine (Kirschbaum and McCabe, 1992; Nadon, 1994). In contrast, unstructured, fossiliferous (molluscan), dark gray mudrocks with abundant carbonaceous debris (remains of vegetation), and/or with iron-oxide mottling may represent marshes (Nadon, 1994; Perez-Arlucea and Smith, 1999).

The fluvial units of Unit 2A have a few characteristics of anastomosing environments, such as predominance of fine-grained rocks, indicators of low-gradient streams, and vertical profiles that match those of progradation of anastomosed sand bodies into lacustrine and marsh environments (Perez-Arlucea and Smith, 1999). However, conspicuous characteristics of anastomosis (e.g., extensive terrace-forming splay sheets) are not developed clearly as in Unit 1.

DISTRIBUTION OF TRACK BEDS

Dinosaur track beds in the North Horn Formation are distributed vertically from the base of Unit 1A to the upper part of Unit 2A (Fig. 2), which is approximately the same stratigraphic distribution as for dinosaur body fossils that are found in the type section at North Horn Mountain (Fig. 4). Track beds first appear near the base of the formation at approximately the same stratigraphic level where the lowest dinosaur body fossils have been found. They reach their greatest concentrations in Unit 1B, where the sandstone sheets and channels are best developed. The last unequivocal track beds appear about 15 m below the highest dinosaur eggshells (level of C in Fig. 2).

Geographically, most of the beds that were studied for this project are located in an area of the south face of the type section (Fig. 4). Track beds also were observed about 6 km east, 3 km north of the main southwest toe of North Horn Mountain, and 5 km southwest of North Horn Mountain in Black Dragon Canyon.

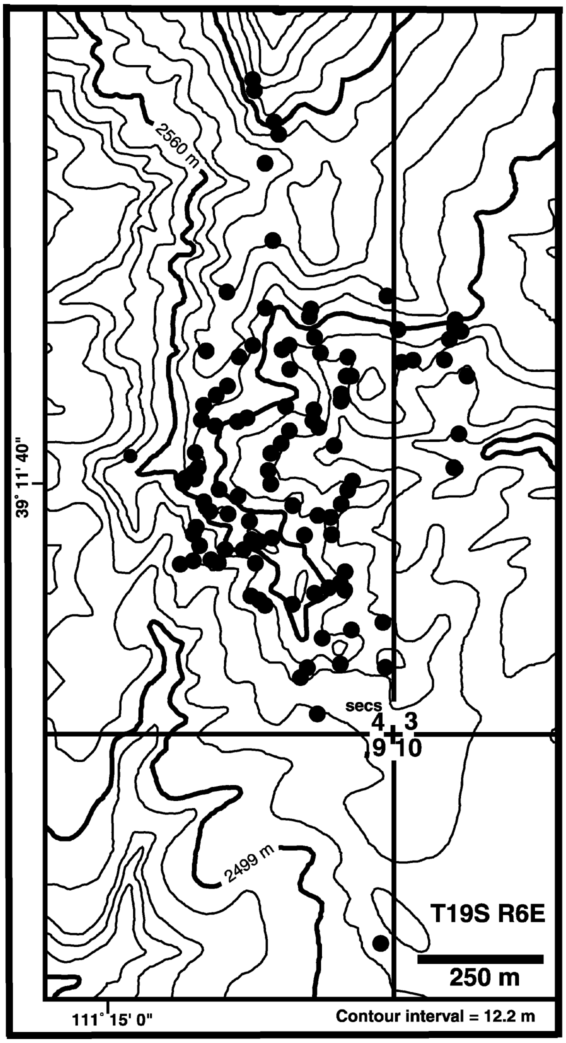

FIGURE 4—Map of dinosaur track-bed study sites covering an area of 1.2 km² in Unit 1 of the North Horn Formation, south face of North Horn Mountain (39° 11.41′ N, 111° 14.60′ W at section corner). Levels of greatest concentration of track distribution broadly coincide with levels where well-known dinosaur body fossils have been recovered (Gilmore, 1946). A large portion of the track levels shown provide *in situ* evidence of dinosaur occurrence at stratigraphic levels where no bone has been found, thus bridging many gaps in dinosaur biostratigraphy at the type locality. Locations of tracks in Unit 2 are not shown. Altogether, the track beds in Units 1 and 2 span a vertical section of at least 183 m, tracing dinosaur occurrence almost continuously from the base of the formation to just below the K-T boundary interval (redrawn from Maptech version, USGS 7.5’ quadrangle topo map The Cap Quadrangle).

DESCRIPTION OF TRACK BEDS AT NORTH HORN MOUNTAIN

Typical Track-Bed Succession

The North Horn Formation dinosaur track beds occur in cross-sectional outcrop view in single or successive sandstone beds. In these beds, the tracks may be stacked vertically and are viewed in cross-section, so they are not true trackways, in which a series of repeated tracks are seen in plan view to indicate directional locomotion. Dinosaur tracks often are found at: the base of sandstone ledges, ribbons, and fins; between beds; and beneath the levee edges (Fig. 3A, B). Track beds in outcrop may occur as either a chaotic mix of mudstone and small, irregular, discrete sandstone bodies, fine conglomeratic sandstone, a single sandstone having an irregular or undulating sole, or as a thin succession of contorted or undulating sandstone beds. Such beds that result from dinosaur trampling are described as “dinoturbated” by Lockley (1991). Typically, a track bed appears at the base of a horizontal sandstone bed (Fig. 3A). The tracks also appear as irregularities within sandstone beds that form shallowly-dipping lateral accretion structures (Fig. 3D). Track beds at the type section may contain from one to several tracks, or have up to about 60 m of continuous lateral exposure. Track beds may be traced intermittently up to nearly 250 m, although continuity often is interrupted by gullies and hollows. At localities where tracks are visible on at least three sides of an outcrop, some continuous track beds extend for a minimum area of 8000 m².

Typically, track beds immediately overlie a variegated mudstone sequence, although the tracks themselves usually occur in gray mudstone. This may reflect a flooding sequence succeeded by seasonal wetlands. Often, the track

FIGURE 5—Detail of outcrop adjacent to that in Figure 3A. Track interval in mudstone in Unit 1B at North Horn Mountain showing multiple trample horizons below cross-bedded and planar-bedded fluvial sandstone beds. Deformed tracks include dish-shaped structures that resulted from repeated trampling when the sand fill of previous and/or partially filled footprint depressions was wet.

beds immediately underlie a cross-bedded, laterally accreted (Fig. 3D) and/or laminated channel sequence.

A track bed may occur at any level within a sandstone succession, but it most often appears at the base of the lowest sandstone under a narrow overhanging ledge (Fig. 3A). The lowest sandstone bed in the succession may have on its sole cylindrical to pendulous structures, separated into irregular ball-and-pillow sandstone structures (Fig. 5). The basal sandstone bed commonly is underlain by chaotic, disconnected, or isolated, sometimes trough-lunate sandstone bodies suspended within a mudstone interval that is often 1–2 m thick. The density of irregular, detached, sand-filled tracks within this mudstone varies from single, isolated bodies to groupings of closely packed structures. The disturbed horizons could be a single bed, or successively or alternately disrupted sandstone beds separated by thin mudstone.

Dinosaur body fossils (bones, teeth), eggshells, and plant fragments frequently are associated with track beds, usually immediately under the lowest bed of the sandstone succession. Track beds and overlying sandstone beds also are bioturbated commonly by various invertebrate burrowers that include social insects (Fig. 6A, B).

Individual Track Description

Individual tracks vary in definition, and only rarely do they display the outline of structures that could be interpreted as toes. The North Horn tracks in mudstone are similar in morphological cross-section to certain Cenozoic tracks in cohesive sand reported by Loope (1986). Tracks occur as isolated or superimposed sandstone casts of footprint impressions that were made in mud, now eroded away to reveal the casts. In cross-section, pillar-like or barrel-like morphologies are more easily recognizable, but commonly the casts are irregularly cylindrical to "U"-shaped (with a smaller basal diameter than at the top), and in some the base is expanded with respect to top. Individual undeformed tracks are usually roughly circular in plan view (although some smaller casts are "D"-shaped or subangular in plan). Track casts are commonly no more than about 40 cm across and about 40 cm deep, but individual tracks with pillar-like, cylindrical morphologies may measure from about 25 to about 53 cm in apparent diameter to about 47 cm deep.

Some tracks preserve morphology that suggests transverse cross-sectional shape of the dinosaur foot. One partial cast with vertical striae had an approximately subangular, "D"-shaped transverse cross-section 29 x 22 cm, suggesting that the foot was at least 29 cm wide and at least 22 cm thick (front to back). Another partial track cast also is subangular in transverse cross-section. It represents an apparent forward-facing portion of a foot impression measuring 26 cm wide and at least 16 cm thick. It has wide striae on the front and striae overprinted at different angles on the sides, suggesting a pivoting (Figs. 6C, 7A).

Superimposed tracks represent multiple footprints, and these form structures that are sometimes up to about 1 m across. Some track casts bear evidence of incremental vertical slippage of a dinosaur foot, and sometimes small-scale sedimentary faulting of the mud. One such cast (40 cm diameter x 25 cm deep) displays apparent records of track deformation episodes. The track preserves a clear vertical cross-section that shows two episodes of graded, fining-up sand to pea-size pebble fill. It displays at least 11 regularly-spaced, flat, vertical striae on its exterior. The striations are typically 12–13 mm wide, alternating with 5-mm wide vertical depressions. Its base is about 20 cm across, smaller than its top, and it has a lateral pressure ridge from apparent incrementally vertical foot slippage.

Other tracks exhibit on their margins (outside surfaces) multiple parallel striae that are oriented vertical to subvertical, and may reach to the base of the track. Striae, which could represent spacing of tubercles or scales, may be sinuous, chevron-like, uniformly repeating, or superimposed at different angles (Fig. 7A). Track-cast striae vary in width and arrangement. Some striae are finely-spaced, usually only about 1 mm across (Fig. 6D). Some wider, arched to slightly flattened striae typically range from 20 to 35 mm across (Fig. 6C), while others have repetitious, alternating width measurements (e.g., 20 mm and 13 mm, or 16 mm and 5 mm, and similar intervals). One example is a cylindrical cast that is 38 cm diameter and 19 cm deep, and has very closely spaced vertical striae, each approximately 11 mm wide, spread across its entire exposure.

The sediment that fills the track is a massive to horizon-

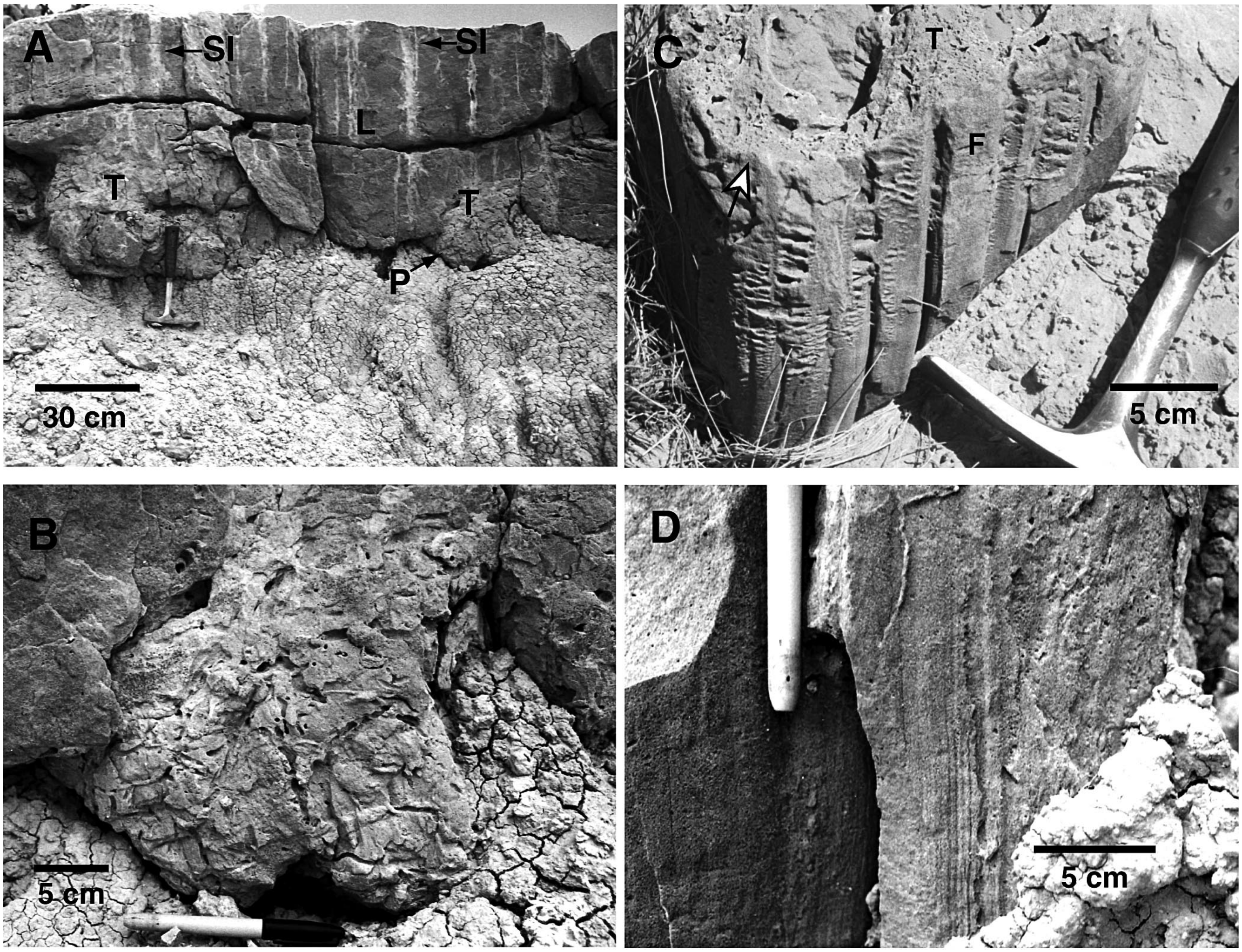

FIGURE 6—Track bed structures, North Horn Mountain south face. (A) Dinosaur track bed in Unit 1C showing secondary bioturbation by invertebrates. Vertical social insect (possibly termite) galleries (SI) dissect lensoid stream-bed deposit (L) and dinosaur tracks (T). Track (T) in lower right track bed is permeated with *Planolites* (P). (B) Detail of (P) above in lower right corner in (A) showing invertebrate burrows (*Planolites*, P) in the sandstone infill of a dinosaur track where wet sand, or sand in quiet water became a habitat for invertebrates, such as burrowing insects. (C) Dinosaur track cast with wide parallel striae that may have been produced by button-like tubercles on a foot, Unit 1B. Subangular transverse cross section of the forward-facing (F) portion (arrow at rounded corner). The presence of chatter marks suggests that the footprint was made in stiff mud. Cobble-size mud-chip impressions in top (T) possibly represent desiccation after the depression infilled. (D) Dinosaur track cast with fine parallel striae that may have been produced by small tubercles on a foot, Unit 1B.

tally or obliquely layered sandstone, muddy sandstone, or granule-size lag that was trapped by the depression. Scattered on the exteriors of the track casts, or disseminated throughout the cast fill, are granule-sized calcite nodules, kaolinite, rock fragments, and organics. Commonly, the track cast is capped by additional coarse lag consisting of caliche nodules, pebbles or flat, poorly lithified mud chips (or their impressions).

Bases of the track casts are frequently flattened or rounded (convex down), with coarsely-crinkled and irregular surfaces, and they sometimes contain embedded pebbles (or their impressions). Structures within the track casts that could be interpreted as toe impressions are very rare, but the preserved few are important because they may provide clues to identification of the track makers. In Unit 1, the bases of the track casts that are most likely to preserve toe impressions are often flattened to rounded. Irregular bulges and rounded surfaces on the basal portions of tracks are possibly amorphous impressions of short toes of herbivores that punched through upper, drier mud, into lower, wetter, more deformable mud substrate. Sometimes a small to moderate bulge occurs low on one side of a cast, and that could be interpreted as obscure remnants of toe impressions. Nadon (1993, fig. 4) figured this type of track and interpreted it to be made by an ornithopod.

Other structures on the sides of casts that might be made by toes are one to three vertical to subvertical, bifurcated (inverted “Y”), linear bulges that stand out in bold relief. These often bear striae, are very closely spaced, and are oriented nearly parallel with respect to one another. The bulges range from 8 to 16 cm across and retain a uniform dimension over their entire length (up to about 45 cm). The linear bulges may be truncated nearly flat at the

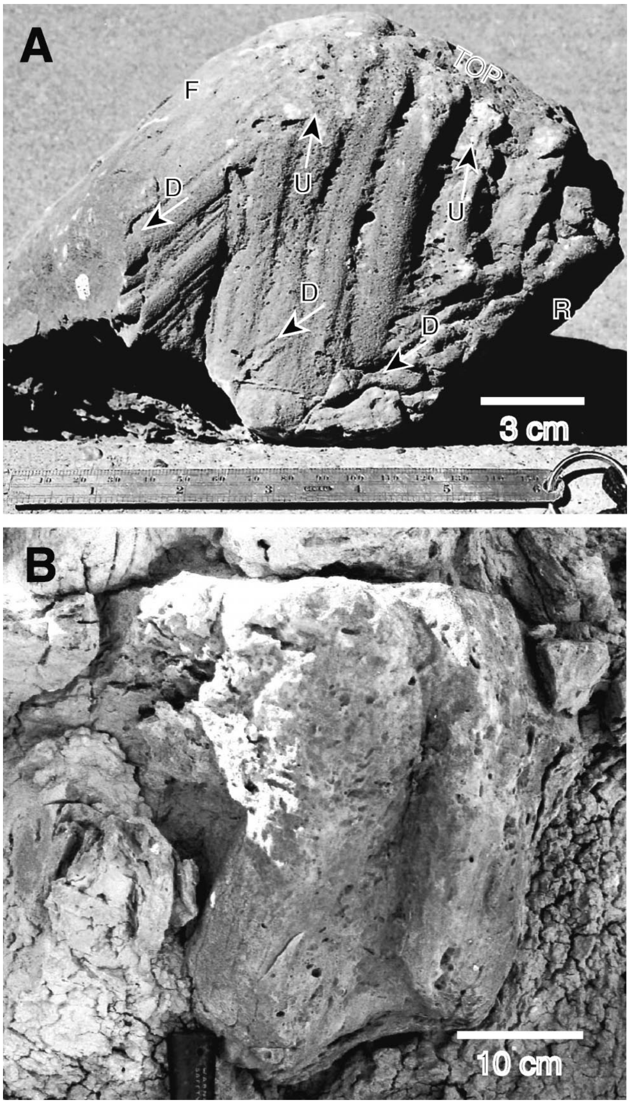

FIGURE 7—Track-cast structures in Unit 1B at North Horn Mountain south face. (A) Sandstone track cast (different view of Fig. 6C) displaying striae at divergent angles. Striae (D) were created during a downward step when the foot was pushed into the mud. The foot was pivoted forward about 30° to take a step, and pulled out, creating the striae at U and overprinting D. F, R are the inferred front and rear faces, respectively, of cast. (B) Sandstone track cast exhibiting two apparent toe impressions with long, shallowly striated, broad, closely spaced impressions, and rounded (lobed) terminations. The parallel arrangement is interpreted to result from a dinosaur pulling its foot from mud.

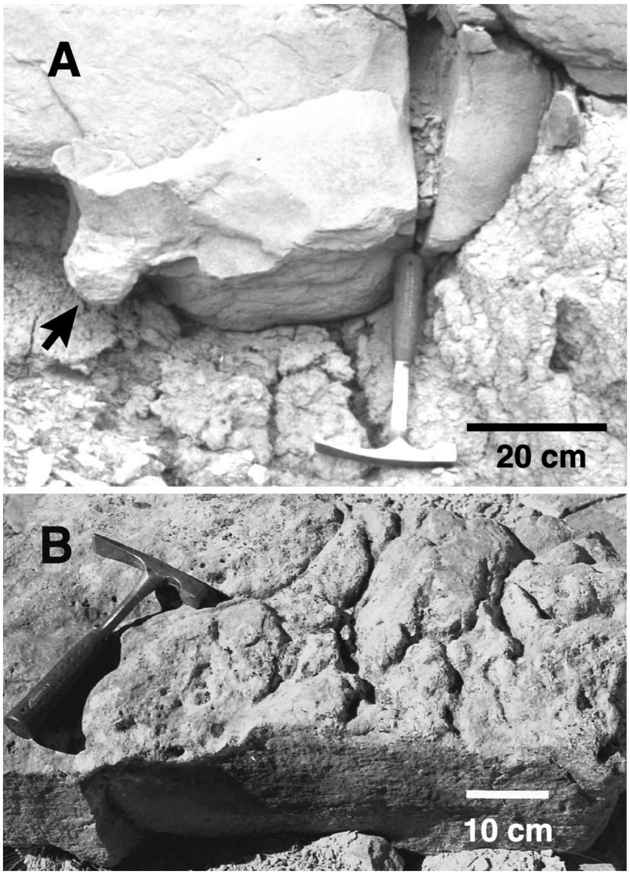

FIGURE 8—Biogenic and sedimentary structures, North Horn Mountain south face. (A) An individual dinosaur track that shows a possible toe impression (arrow), Unit 2A, from level of B in Figure 2. (B) Load casts lying base up, Unit 1B. Sandstone structures interpreted as load casts in the North Horn Formation have smaller, more uniform or aligned undulations, less relief, or lack other highly irregular forms associated with dinosaur tracks.

base of the cast, or they may bear smoothly rounded or lobed terminations. One cast, about 37 cm across (Fig. 7B), has two visible toe impressions that are 10–16 cm across and 35–40 cm in height. Both toe impressions have vertical, shallow striae and are each rounded at the base of the track. In only one case are there claw-like grooves or gouges parallel with the vertical bulges observed in Unit 1. In this instance, the grooves (4 cm across) occur on the outside and in a fold of a superimposed (multiple track) cast (60 x 36 cm), and they are nearly parallel with an inverted "Y"-shaped linear bulge (45 cm long and up to 10 cm across). The inverted "Y" may be impressions of toes that were pulled from mud. Two other casts with similar grooves occur in proximity along the same bedding plane.

In Unit 2, one cast (~60 cm across) has a rounded base and appears to bear a toe cast represented by a smaller projection (11 cm across and 10 cm long with a smoothly rounded termination oriented at an angle oblique to the cast (Fig. 8A). Striae are preserved the length of the projection but are not visible in the photo.

Deformed track casts grade into undulating, globular, or highly irregular sandstone forms that are individually unrecognizable as tracks. Some are detached, deformed ball structures, that may graduate into dish-like, lunate, or trough structures with laminated fill (Fig. 5). The undulating forms sometimes are associated with concentrations of granule-sized caliche, kaolinite, or rock fragments.

Undulating forms that grade into genuine load casts sometimes may be recognized as tracks when they occur along the same bedding plane adjacent to recognizable tracks, and they have relief and dimensions similar to those of associated distinct tracks (Loope, 1986). Size distribution of irregular track forms also supports an interpretation of tracks belonging to dinosaurs that are represented by skeletal material such as described by Gilmore (1946). Deeply convoluted concentric laminae are not usually visible within a track cast. Dinoturbated sediments often display shallow undulations or are crinkled (Lockley and Hunt, 1995a), where each thin undulation is non-concentric (irregularly or randomly arranged). True load casts often are distinguished from biogenic disturbances by smaller, more uniform sizes, generalized alignment of structures, and less apparent vertical relief visible on the exteriors of the structures (Fig. 8B). Several salient differences exist between biogenically disturbed sediments and gravity-driven soft-sediment structures. Many non-biogenic structures (e.g., periglacial ball-and-pillow deposits) contain interior layering (i.e., convolute lamination) that concentrically conforms to the exterior morphology of the structure (Pettijohn and Potter, 1964). The concentrically layered fill of ball-and-pillow structure contrasts sharply with the infill of a track cast, that is often horizontally or obliquely layered. Convolute bedding, probably caused by lateral disturbance by dinosaurs, occurs within a few track beds.

True tracks are further distinguished from non-biogenic structures by vertical to subvertical striae that often appear on the margins (outside surfaces) of some track structures; the bases of track casts often bear polygonal pressure imprints. Sometimes the non-biogenic structures indicate flow directions that are not obvious in track structures. Ambiguous biogenic structures often are traceable laterally (in the same bed) to less debatable track structures that bear earmarks of biogenic activity (such as slip marks), uniformly repeating configurations (such as could result from scale or tubercle impressions), or smaller secondary bulbous configurations that could be attributed to toe impressions (Fig. 8A).

The better preserved tracks display features that may make identification of the vertebrate taxa easier or that show unequivocal dinosaur behavior. These morphologies include pillar-like casts of single tracks that clearly display striae and toe impressions (Fig. 7B), or casts that preserve transverse foot outlines from which measurements may be obtained (Figs. 6C, 7A), or bear deformation features that clearly show multiple or successive trampling. Problems, such as restricted areas of ledge overhang (Fig. 3A), lack of track clarity, and the rarity of toe impressions, prevent taxonomic identification of the dinosaurs represented by footprints in the North Horn track beds. As paleoenvironmental and paleoecological indicators, they are especially useful when compared to modern track settings.

Comparison with Modern Cattle Tracks

Fossil track morphologies compare favorably to those of modern ungulate tracks in mud. While various track morphologies may have been influenced by different soil classes, the different morphologies and clarity of preservation in fossil tracks result from the diverse sediment moisture conditions in which they originated (Fig. 6C) and their proximity to the water table (Lockley and Hunt, 1995a). Shapes of different fossil tracks can be compared to tracks created by modern cattle in standing water (Fig. 9A, B), wet mud (Fig. 9C, D), or stiff, slightly moist mud (Fig. 9E, F). Resemblances between the finely striated impressions shaped by the hoofed feet of cattle and the feet of non-hoofed dinosaurs originate from comparable movements made in a similar sandy-grit mud substrate. The finest striae that appear in the traces made by both dinosaurs and cattle (Fig. 9C, D) were not generated by features on the animals' feet as were the larger striae, which apparently were created by tubercles of two sizes in Figure 6C, D.

TRACK BEDS AT OTHER LOCALITIES

Dinosaur track beds occur also at other Wasatch Plateau localities (Fig. 1): in Black Dragon Canyon and at Flagstaff Peak (Emery County), in Fairview Canyon (Sanpete County), and in Price Canyon (Carbon County).

Black Dragon Canyon

Track beds identical to those at North Horn Mountain occur 5 km southwest at the Lizard Locality in Black Dragon Canyon, the type locality of the Cretaceous lizard *Polyglyphanodon* (Gilmore, 1942; 39° 09.95′ N, 111° 16.36′ W). A nest site containing *in situ* dinosauroid eggshells (*Spheruprismatoolithus condensus*) occurs in variegated mudstone at the base of, and exposed adjacent to, a track bed. Because of the faulted strata of the Lizard Locality, this apparent association of the nest site with a track bed is equivocal.

Price Canyon

The Maastrichtian portion of the North Horn Formation is about 50 m thick (Fouch et al., 1987; Olsen, 1995). Dinosaur tracks have been found high in the Maastrichtian unit (39° 46.57′ N, 110° 54.89′ W) and consist of two types. The first is represented by several small, closely-spaced triangular sole marks under an overhanging ledge at the base of a sandstone bed (Fig. 10A). They bear similarity to track types figured by Loope (1986, fig. 13). Although the tracks display no obvious claw impressions, they might be attributed to small bipedal dinosaurs. The second type of track has a larger diameter and occurs as poorly preserved, shallow, and sparsely spaced sandstone sole traces that occur at the same stratigraphic level as the smaller tracks.

Flagstaff Peak

A dinosaur tracksite occurs at the Flagstaff Peak locality that was described by Spieker (1960; 39° 02.94′ N, 111° 16.39′ W). These tracks are found at the same stratigraphic levels and near sites of three eggshell types and abundant fragmentary bone, which may be attributed to *Alamosaurus* (Spieker, 1960).

Four single tracks and one superimposed track are exposed in both plan view and vertical cross-section (Fig. 10B). Four tracks occur within a 4.5-m lateral exposure, and the next laterally adjacent portion (5.5 m) of the outcrop is missing before the fifth track occurs. Each track is 51 to 56 cm across, and 28 to 30 cm deep. They are composed of fine-grained sandstone that is bioturbated heavily, preserving invertebrate burrows (*Planolites* and *Taenidium*).

Fairview Canyon

The North Horn Formation in Fairview Canyon (39° 39.17′ N, 111° 21.26′ W) is divided into three units (Ober-

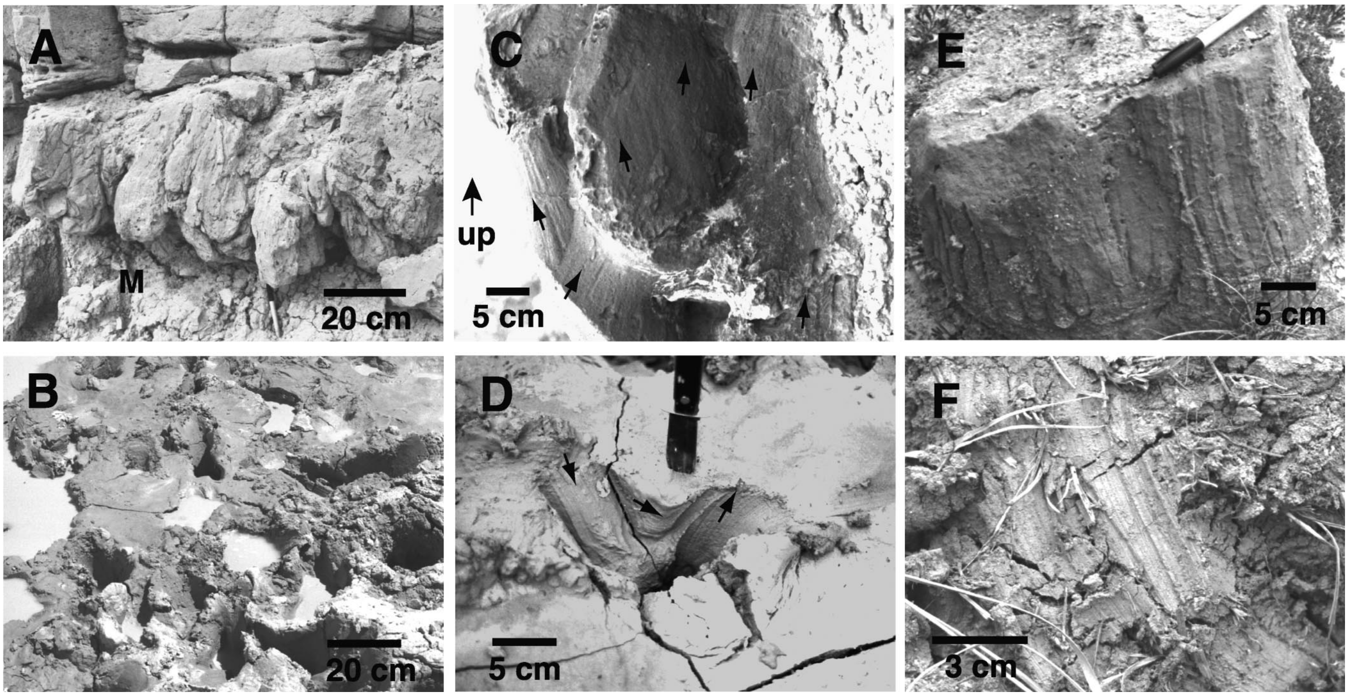

FIGURE 9—Dinosaur tracks in Unit 1B at North Horn Mountain, and cattle tracks in modern mud. (A, B) Dinoturbated bed and a modern analog in standing water. (A) Cross-sectional view of a sandstone-trample bed that reflects trampling in mud (M) by multiple dinosaur feet. (B) Oblique view of multiple tracks of modern cattle in mud along the edge of a pond. The irregularity of the modern footprint-depression morphology and arrangement in the mud could produce casts similar to the fossil trample bed in A. (C, D) Deformed, striated, superimposed fossil track casts and their modern track mold analog in soft mud. (C) Lateral view of sandstone track cast created by multiple dinosaur feet that repeatedly or sequentially trampled the same spot and deformed a soft mud substrate. Note striae with multiple orientations (arrows parallel to striae). (D) Oblique view of a deformed modern cow track created when the animal stepped in the soft mud, pivoted, and then pulled its foot out of the mud. Striae with multiple orientations (arrows) in mud are similar to those of the fossil cast in C. Resemblances here between the finely striated impressions shaped by hoofed cattle and non-hoofed dinosaurs originate from comparable movements made in a similar sandy-grit mud substrate; fine striations shown here were not generated by features on the animals' feet as were those in Figure 6C, D. (E, F) Fossil tracks and a modern analog in stiff mud. (E) Superimposed sandstone track cast showing vertical slip striae produced by at least two side-by-side steps. The repeating pattern suggests origination by scale patterns or bimodally-sized tubercules on dinosaur feet. (F) Irregularities on the hoof of a modern cow produced slip traces in moist mud similar to those left in the fossil cast in E.

hansley,1980), which appear to be equivalent to those at North Horn Mountain. The lower, middle, and upper units, respectively, are 63 m, at least 130 m, and at least 158 m in thickness. The latter two units are truncated by faulting. Farther east, in the nearby Fairview Lakes quadrangle (39° 37.50′-45.00′ N, 111° 15.00′-22.50′ W), the total North Horn Formation thickness is 410 m (Oberhansley, 1980), which is nearly identical to that of the type section at North Horn Mountain 53 km away.

The Fairview Canyon track beds occur at several intervals in the lowest unit about 3 to 7 m and about 17 m above the base of the North Horn Formation (basal placement interpreted from Oberhansley, 1980). No other dinosaur fossils have been reported previously in the North Horn Formation from this area in Sanpete County, but during this study some dinosaur bone was found in the lowest track beds. The bone material is ascribed a dinosaurian origin based upon size (up to 10 cm wide and 38 cm long).

The lower unit of the North Horn Formation at the track-bed level consists of fine- to medium-grained sandstone in beds of medium thickness that may be cross-bedded or channel-form and interbedded with silty variegated (gray, purple to reddish brown) mudstone. Tracks occur on the soles of the sandstone beds as irregular sandstone pillow structures. These beds directly overlie dark gray silty mudstone that commonly contains iron-oxide nodules. The track casts occur as both single casts and superimposed structures. Individual *in situ* tracks are up to about 40 cm diameter and about 40 cm deep (Fig. 10C).

A few tracks display vertical striae, having some striae sets that overprint other striae at divergent angles. One individual track cast with fine-grained sandstone fill appears to show the shape of toes. This footprint is up to 37 cm in diameter and 20 cm deep.

Comparison of Track Bed Sites

The North Horn track beds in Unit 1, and age-equivalents, have been documented from Price Canyon in the north to Flagstaff Peak in the south, a distance of 80 km (Fig. 1). Although the track beds cannot be traced continuously throughout this area, tracks between the former two areas and west to Fairview Canyon potentially cover at least 1300 km^2 in the Wasatch Plateau.

North Horn Mountain track sites generally occur in finer-grained rocks than in Fairview Canyon, which may indicate that the North Horn Mountain sites represent a gentler paleoslope occupying a more central position in the basin. Lateral accretion structures at North Horn Mountain and laterally successive channel structures in

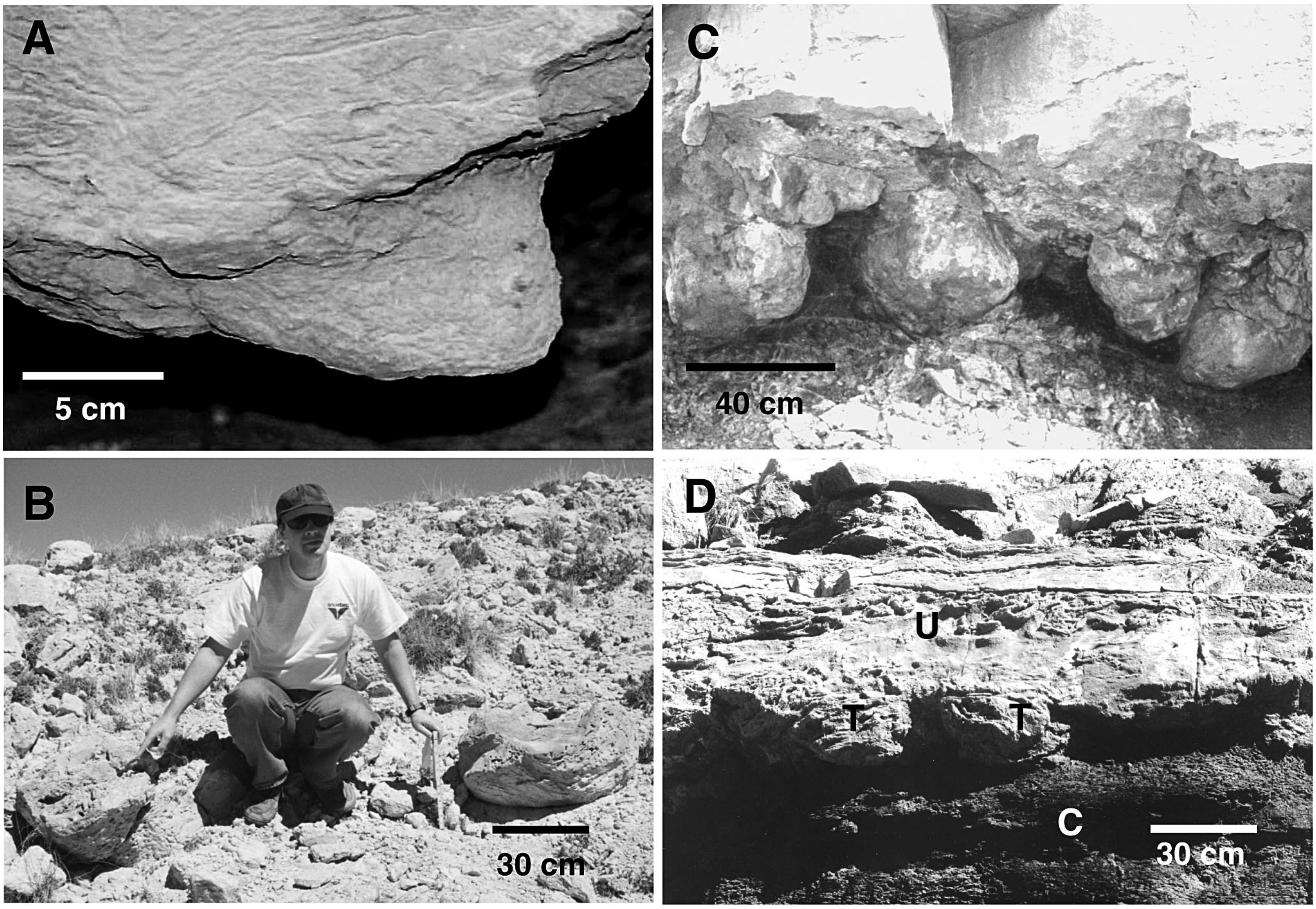

FIGURE 10—Dinosaur track beds at other Wasatch Plateau localities. (A) Track, possibly made by a small bipedal dinosaur, in the basal part (Maastrichtian) of the North Horn Formation in Price Canyon, Carbon County (39° 46.57′ N, 110° 54.89′ W). (B) Two *in situ* tracks that are exposed in both plan and side view. The sediment filling the tracks is heavily burrowed and preserves abundant *Planolites*. Flagstaff Peak, Emery County (39° 02.94′ N, 111° 16.39′ W). (C) Dinosaur tracks exposed in convex hyporelief in dark gray mudstone in fluvial sandstones at a level where dinosaur bone has been found. Fairview Canyon, Sanpete County (39° 39.17′ N, 111° 21.26′ W). (D) Disturbed sandstone bed overlying coal beds (C) exhibits undulating (U), crinkled soft-sediment deformation that probably resulted from dinoturbation. Sandstone also contains discrete dinosaur tracks (T). Uppermost Blackhawk Fm., Upper Cretaceous (Campanian), Joes Valley Reservoir, Emery County, Utah (39° 17.32′ N, 111° 15.91′ N).

Fairview Canyon may indicate that both had similar anastomosing fluvial environments. Dinosaur tracks at both localities occur on the soles of channel sandstones in successive horizons. Similar types of streams occurred at both North Horn Mountain and Fairview Canyon, possibly representing a temporary cessation of flow, and allowed dinosaurs to trample abandoned stream beds between successive fluvial episodes. Similar evidence of dinosaur behavior and stream type are shared by these two localities, which are separated by at least 53 km.

Size and shape of dinosaur tracks at North Horn Mountain and Fairview Canyon are similar. Herbivorous dinosaurs are inferred to have been present from the tracks at both localities because the tracks are not three-toed with evidence of prominent claws.

Portions of the North Horn Formation tracks and their modes of occurrences are comparable to slightly older track beds in the Campanian uppermost Blackhawk Formation near Joes Valley Reservoir, Emery County, Utah (39° 17.32′ N, 111° 15.91′ W; Utah Geological Survey site Em316T). Tracks in both the North Horn and Blackhawk Formations occur on the soles of successive sandstone beds in fluvial environments. Like some beds in Unit 2A at North Horn Mountain, the sandstone track beds near Joes Valley are heavily disrupted, crinkled, undulating or "dinoturbated," as defined by Lockley (1991), when seen in cross-sectional view. Indeed, many such track beds are not individually recognizable as dinoturbated (Lockley and Hunt, 1995a), but they may be identified by their association with recognizable tracks. The Joes Valley tracks often are observed in a soft, dark gray to black, organic-rich mudstone (Fig. 10D). One track on the sole of a sandstone bed in the Joes Valley area was attributed to a theropod by DeCourten (1998) on the basis of sharp ridges interpreted as claw impressions. Two or three narrow, pointed toes are visible in some of the Joes Valley tracks. At least one track is superimposed upon another of a slightly smaller size, and the toes generally are oriented southward. Although there are some similarities between the tracks in the North Horn and Blackhawk Formations, the North Horn substrates, except in rare instances, apparently were too moist to preserve detail of the type of toe impressions that yield reliable orientations.

PALEOECOLOGY

Dinosaur tracks in the Maastrichtian part of the North Horn Formation form an ichnofacies (Figs. 3A, 5) whose existence is likely owed to conditions provided by anastomosed fluvial environments. Chaotic trampled beds record the progressive encroachment of rivers or the overflow of levees into ephemeral wetlands on the floodplain. Many of the dinosaur footprint depressions were preserved by rapid burial when they were filled with sand, as fluvial action periodically transported sand into the area, or were covered by sands of crevasse splays.

North Horn Mountain track beds are more numerous in Unit 1B than in Unit 1C (Fig. 4). This distribution corresponds to the range of the greatest concentration of dinosaur bones and eggshells based on field observations (Difley, unpublished data). Mudstones of Unit 1C are largely redder than those that occur lower in Unit 1, and fewer track beds occur there. Unit 1C also represents an anastomosed system, but it is possible that part of this unit may represent drier, or lower water-table conditions, or more subaerial exposure than was ideal for track preservation. Environmental conditions during deposition of Unit 1B generally provided the best conditions for track preservation. Although it is probable that footprint depressions were made in dry substrates, eolian and other natural erosional processes may have destroyed them before they could be infilled.

Dinosaurs trampled proximal floodplain and stream deposits during cycles of low water volume and fluvial abandonment. This is indicated where tracks are visible beneath and between the lateral edges of sandstone sheets and ledges (Figs. 3D, 6A). Tracks produced in the floodplain mud were infilled by sand. A typical sandstone succession was deposited over sand-filled dinosaur tracks. Primary structures such as ripple laminae, cross-beds, and planar beds reflect fluctuating current (Fig. 3A). During each temporary abandonment, dinosaurs again walked on exposed fluvial, sand and mud deposits, creating additional track levels within the same sandstone succession. Little evidence exists for tracks preserved at the tops of the sandstone successions that marked final abandonment of channels.

Dinosaurs left depressions that trapped soil products, such as caliche granules, pebbles, and organic debris. Both the interiors and exterior margins of casts display this material mixed with sand and mud. Small pebbles, soil nodules, and plant debris appear to have been pushed by the foot from the disrupted substrate surface down the walls of the track and into the depression, which was then infilled with sand, mud, pebbles, and plants by stream overflow events.

Irregularly-shaped track casts or successive, thin, crinkled, sandstone layers probably were formed by trampling of previously infilled depressions before the sand fill could stiffen by dewatering. This flattening is represented by numerous examples where an undeformed cylindrical to oblate track with a flattened base, and often with vertical striae, overlies an irregular tabular sandstone body that has pressure crinkles on its base. Previously infilled tracks were pushed aside and deformed by trampling, and this was followed by a supply of additional mud that settled out or was pushed over the lower track forms. Filled tracks that escaped trampling before dewatering were left undeformed, or at least much less deformed (Fig. 11A).

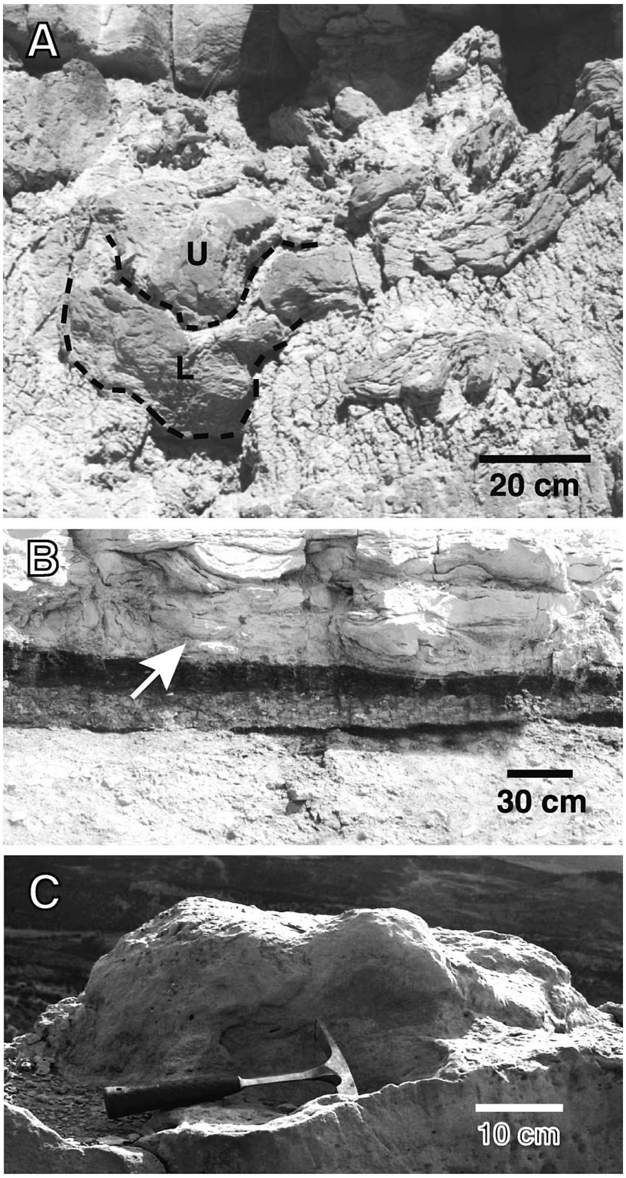

FIGURE 11—Dinosaur track beds, North Horn Mountain south face. (A) Superimposed dinosaur tracks in Unit 1B. Both the upper (U) and the lower (L) track casts are underscored by dashed lines. The upper undeformed track represents a step made by a dinosaur that deformed a soft, underlying footprint depression that had been infilled by sand. (B) Dinosaur track bed (arrow) showing several trample episodes, overlying a black shale bed (with dull coal) containing bivalve fossils in Unit 2A (at level of B in Fig. 2). (C) Track-like structures on base of upturned fallen sandstone block. The sandstone deformational features were made in black, organic-rich mudstone about 4 m below the highest eggshell bed in Unit 2A (at level of C in Fig. 2). Undulating forms and track-like structures are not found at North Horn Mountain above the bed shown here. Scale bar is 10 cm.

Striae, slippage marks, and mini-faulting on track casts suggest that the animals' feet slipped horizontally, vertically, or incrementally into mud of different moisture content. Some overprinted striae on the track casts record the emplacement and removal of the foot from mud (Fig. 7A). Deformed casts with smaller tops than bases (due to the top of the track wall collapsing inward) represent tracks made in substrates with higher water content, and could have formed closer to water than many non-deformed depressions. Deep vertical-walled depressions might have filled with water and dissolved into shallower depressions, thus destroying details of toe and sole impressions. Alternately, lower portions of the deep footprint depressions might have penetrated water-logged, less cohesive muds that could not hold an impression. Preservation of striae on some of the tracks suggests that at least the upper part of the walls of many of the deep footprint depressions probably dried completely before sand filled them. North Horn sediments, as a rule, probably retained moisture without rapid dewatering since few depressions preserve striae (Lockley, 1986). Dewatered tracks often preserve the best detail (Nadon, 1993)

An anastomosing stream system appeared to have supplied the right soil conditions, moisture content, and depositional succession for preserving different types of tracks that are displayed in the North Horn Formation. One example is where variably preserved tracks, including one deep track with a toe-like protrusion, were left in the lateral sides of an exhumed ribbon sandstone channel having two to three stories (Fig. 3C). Another example is poorly preserved, flattened tracks between as many as six successive stories (altogether ~5 m thick) of sandstones (a in Fig. 3B). This is interpreted as a stacked channel sequence that resulted from periodic fluvial abandonment and channel reoccupation where dinosaurs left depressions in the muddy sediment left during abandonments. Those depressions were filled and flattened under the weight of each succeeding sand influx, suggesting rapid deposition.

Dinosaurs probably left deep footprints in the wet, or soft mud of seasonal wetlands in floodplain depressions or near rivers where the water table was close to, or slightly above, the surface. Lockley (1986) suggests that deeper tracks are sometimes made in water as deep as about 0.5 m. This is consistent with tracks positioned immediately beneath beds deposited by rivers that avulsed into topographic lows that probably held seasonal water. Depressions made in mud in shallow standing water, where the water table was high, may explain the lack of clarity that characterizes the bulk of the North Horn tracks. Different track depths and morphologies could have originated also in sediments with moisture that varied with distance from water. No tracks were preserved far from sandstone channel/crevasse splay structures, possibly because there was no sand to cast the depressions, or because the moisture content of the sediment was inadequate for track preservation (Lockley, 1991).

The distribution of pebble lags and mud chips across the tops of track casts suggests periods of dessication or pauses between fluvial depositional episodes (Fig. 6C). Dinosaurs walked on sand-splay or channel deposits when they were abandoned during low-energy intervals when muds or silts were deposited. This is evidenced from the abundance of tracks in fine-grained beds between successive sandstone beds (Fig. 3A, D).

Soil horizons formed in the proximal wetlands, ponds, and floodbasin-levee overflows. These horizons contained plant humus, fine pebbles, and calcareous soil granules. Also commonly associated with the footprint horizons are occurrences of indeterminate bone, jaw fragments, and eggshells, such as might be expected to accumulate in soil horizons in a floodbasin (Freytet and Plaziat, 1982).

That dinosaurs occupied floodbasin wetlands and floodplains adjacent to rivers is evidenced by dark gray and variegated mudstones containing a succession of dinoturbated sandstone bodies that underlie and are adjacent to fluvial sandstones. In one instance (at 39° 11.73′ N, 111° 14.52′ W), at least 2.5 m of dark gray mudstone is partially overlain by and partially adjacent to a lensoid sandstone with levee structures that show current directions toward the wetland and perpendicular to the trend of the channel. This represents a river with a levee that periodically overflowed into the proximal wetland, thus filling successive levels of track depressions with sand during aggradation of the wetlands deposits. Successively trampled strata may have been a natural build-up during aggradation in low-lying areas of the floodplain. Thus, dinosaurs may have occupied wetlands near rivers, at least seasonally, when the mud was soft enough to record track depressions and when the tracks could be preserved by sand fill.

Dinosaurs probably trampled through plants that grew near streams and, thus, churned the vegetation and clasts into their footprint depressions. That dinosaurs were walking on top soil is evidenced by portions of the track cast fill, and the commonly gray mudstone (whose color probably resulted partly from soil humus from decayed vegetation) in which the footprint depressions were made. Thin section examination of fill from North Horn track casts reveals a microscopic cracking pattern that is typical of soils (Freytet and Plaziat, 1982; Difley, unpublished data). In addition, some of the horizons immediately underlying the disturbed sandstone horizons contain short fragments of carbonaceous and ferruginous roots and rootlets that are interpreted to represent scattered plant litter on the soil surface. Yellow, vertically oriented mottling in variegated mudstone consists of iron-oxide nodules and ferruginous haloes. These are interpreted as trace fossils of *in situ* plant roots in water-logged soil conditions during seasonal flooding.

Toe impressions are observed only as casts of scrapes in the sidewalls of depressions made when the foot was pulled from the mud. Dinosaur tracks with clear sole and toe impressions may not be preserved often in the North Horn Formation, because the same moisture conditions that allowed formation of deep depressions also permitted partial collapse of the mud walls before the undeformed impression could be infilled by sand. The basal part of the impression may have deformed or filled with water, and due to lack of soil cohesion, the impression was not sustained.

Because the tracks are preserved in cross-sectional view (except for a few tracks in plan view at Flagstaff Peak), it is difficult to identify taxa. Trails made by single individuals cannot be distinguished, so the general layout (e.g., distance between tracks, gait, size and pattern differences that would separate manus from pes, as described by Lockley and Hunt, 1995a) is nearly impossible to obtain. Only rarely can the transverse cross-section of the foot be determined (Figs. 6C, 7A). Near absence of toe imprints, rare transverse foot cross-section, and inability to map individual trails creates difficulty in determining dinosaur group behavior or travel direction. Consequently, it is not easy to assess social groupings, or determine if track size differences represent adults and juveniles or manus and pes. However, the dense concentration of tracks near paleostream edges or in ephemeral wetlands suggests that the dinosaurs might have mingled in small groups, or possibly in larger herds. The stratigraphically successive, repetitious track beds of the North Horn indicate habitual return of dinosaurs to a local area (Lockley and Hunt, 1995a). Either herding behavior or multiple returns to the water could achieve the trampled effect on the sediment that is displayed. The overprinting of different track sizes suggests that different types of dinosaurs or different age groups, or both, could have been present when trackbeds were produced.

Tracks and the K-T Boundary

The K-T boundary interval has been inferred to occur within Unit 2 of North Horn Mountain on the basis of the disappearance of Cretaceous fossils and the appearance of Paleocene fossils (Difley and Ekdale, 1999). The extensive, semi-arid floodplain conditions that produced an excellent track record during the deposition of Unit 1 no longer existed during deposition of Unit 2. Rocks that represent the wetlands/lacustrine environment of Unit 2A do not contain the abundance or clarity of those tracks that were made in the semi-arid environment. These contrasts are quite possibly due to a substrate difference, but deformed sandstone beds that were typical of trampling in Unit 1 occur high in Unit 2A (Figs. 8A, 11B).

Although the North Horn tracks have not been documented as close to the K-T boundary as has been reported in other Western Interior areas (Lockley, 1991; Lockley and Hunt, 1995a), track occurrence in Unit 2A demonstrates that large dinosaurs were present in central Utah and evidently abundant until very shortly before the K-T boundary. The tracks occur at stratigraphic levels where eggshells were the only previous evidence of dinosaurs. Less ambiguous tracks that are approximately 60 cm in diameter, Fig. 8A) occur about 15 m below the level of the highest eggshells in Unit 2A. Undulating sandstone bedforms that are found only about 4 m below the highest eggshells are similar to those associated with tracks in Joes Valley (Fig. 10D), and such are recognized elsewhere as tracks (Loope, 1986; Lockley and Hunt, 1995a). The highest undulating forms in Unit 2A at North Horn Mountain also occur in the same bed with the more usual track-like deformational structures (Fig. 11C). They exhibit an apparent 45-cm diameter and morphology reminiscent of a small bilobed track illustrated by Loope (1986, fig. 19). Other disturbed structures in this bed are similar to track types that occur in Units 1B and 1C, and in the same horizon with a lower track bed in Unit 2A (Figs. 8A, 11B). Convolute deformational features occur adjacent to track-like structures and undulating layers. Individual tracks with striae or toes have not been recognized within this highest bed.

Evidence that the sandstone deformation features in Unit 2A are mostly dinoturbation structures include the following: the different types of deformation structures show relatively uniform size and morphology; they exhibit approximately the same size distribution as the tracks in Unit 1; they are much too large to be attributed to any animal smaller than a dinosaur; some have a projection, suggesting a toe cast, or striae, reflecting tubercles or scales on a dinosaur foot; and they do not occur above the K-T boundary interval where eggshells that are attributable to dinosaurs also terminate. No track beds occur in wetland/fluvial sandstones of Unit 2B, nor do track beds reappear in the sandstones when there was a return to full fluvial flood-basin conditions in Unit 3A (Spieker, 1946). The base of Unit 3A is stratigraphically equivalent to strata some 5 km away (39° 10.80′ N, 111° 17.49′ W) where Puercan (Pu3; ~64.11 Ma, Woodburne and Swisher, 1995) mammals occur (Tomida and Butler, 1980; Cifelli et al., 1999). This stratigraphic level was deposited nearly a million years after the K-T boundary (65 Ma, Woodburne and Swisher, 1995). Thus, if the last eggshells occur near the K-T boundary, then large dinosaurs (represented by large tracks) also survived until near the K-T boundary.

Association of Nest Sites and Tracks

Nadon (1993) noted an association of dinosaur nest sites and tracks in deposits that represent anastomosed stream deposits. The same association is common in the type section of the North Horn Formation. Eggshells have been recovered from several track sites, and additional eggshells occur at the same stratigraphic levels adjacent to track beds (unpublished data). Thousands of Jensen's (1966) class C eggshells (dinosauroid-spherulitic basic type having a ?prolatospherulitic morphotype of Bray, 1999) originate from a single horizon in Unit 1B. The eggshell horizon is at least 15 m wide, and is situated a mere 5 m distant from a track bed that occurs at the same stratigraphic horizon. The eggshell horizon, which occurs in a dark gray band within variegated mudstone, may represent a flood-basin wetland nesting area that was occupied almost entirely by a single dinosaur taxon, as indicated by only very rare occurrence of any other eggshell type. The fact that a sandstone bed that immediately overlies the part of the eggshell site situated nearest the associated track bed suggests that the nesting site could have been abandoned when a river avulsed or encroached upon it. The coincidence of the eggshell stratum adjacent to tracks suggests a setting where dinosaurs (possibly herbivores) nested in wetlands that may also have been close to a river. Nadon (1993) suggests seasonal wetlands associated with anastomosed fluvial systems may have provided nesting herbivores (e.g., ornithopods with wide, closely spaced, webbed toes adapted for walking in soft muds) some protection for their young from predators (e.g., theropods with long, thin toes). McCrea (2000) also notes that theropods may have found difficulty moving efficiently in water-logged areas.

Other Fossil Biota Associated with Tracks

Invertebrates temporarily inhabited some of the moist track fills during the times of reduced current energy or pauses in stream flow (Fig. 6B). The relationships of dinosaur tracks to invertebrate burrows (including galleries of social insects) suggest a relative sequence of events (Fig.

6A) in which aquatic invertebrates or insects, represented mostly by *Planolites*-producing organisms, burrowed the wet or soft dinosaur track fill. Long afterwards, termites and/or other social insects that occupied the floodbasin burrowed into the drier, abandoned stream beds that included the structures created by dinosaur trampling. Cooccurrence of termite galleries with deep dinosaur tracks has been reported previously from the Jurassic Morrison Formation of Utah (Engelmann and Hasiotis, 1999).

Other fossil organisms represented in the North Horn Formation, some of which are associated with track beds, include a variety of sizes and kinds of herbivorous (*Alamosaurus*, *Torosaurus*, hadrosaurs; Gilmore, 1946; Lawson, 1976) and carnivorous dinosaurs (*Tyrannosaurus rex*; Loewen et al., 2001), mammals, reptiles (*Polyglyphanodon*, crocodiles, turtles), invertebrates (mollusks, insects), microfauna (ostracods), and plants (gymnosperm and angiosperm trees, herbaceous foliage, ferns, aquatics, charophytes). This assemblage represents a diverse inland ecosystem (Cifelli et al., 1999; Difley and Ekdale,1999).

Track Maker Candidates

Although the North Horn tracks are not defined clearly in plan view, their cross-sectional size, morphology (pillar, barrel-shaped and a few broad toe impressions; Figs. 7B, 9E), and geometry suggests that they were made by herbivorous dinosaurs. There is little unequivocable evidence that the tracks reported here were made by carnivorous dinosaurs, although the type section at North Horn Mountain has yielded theropod bones (Gilmore, 1946; Loewen et al., 2001). Deep, cross-sectional theropod tracks (DeCourten,1998, fig. 8–11) bear three nearly vertical, sharp ridges that correspond to claws with spacing that conforms to theropod toes. Only a single North Horn track with an inverted “Y”-shaped morphology in Unit 1 has been observed that could represent theropod toes and claw traces. Although the specimen appears to represent long, thin toes, it cannot be confirmed that the track represents a theropod. Striae on most of the North Horn tracks are flatter, more numerous, and more closely spaced (Figs. 6C, D, 7A, B, 9E) than those on DeCourten’s (1998) theropod claw ridges, and so they probably do not represent claws. North Horn tracks are largely similar in size and shape to deep tracks that have been attributed to ornithopods in the Cretaceous by Nadon (1993) and to sauropods in the Jurassic by Engelmann and Hasiotis (1999).

Although they found no clear tracks, Engelmann and Hasiotis (1999) interpreted Morrison Formation tracks to be made by sauropods based upon their conformity with the morphology of the typical sauropod manus and pes. Sauropods are possible candidates as track makers in the North Horn, based upon foot measurements (a width of about 44 cm), calculated from Gilmore (1946, fig. 7A) for the single forefoot specimen of the North Horn Mountain sauropod *Alamosaurus* (USNM 15560). This suggests that the size of its manus falls within the size ranges of the North Horn tracks. Implicit is an even larger pes size for *Alamosaurus*. However, data are insufficient to identify a sauropod manus and pes. The sauropod *Alamosaurus* is known with certainty only from Unit 1 (Gilmore, 1946; Cifelli et al., 1999), although large tracks in Unit 1 at North Horn Mountain continue up into Unit 2 where the sauropod is less likely to occur due to a change from largely dry to a predominantly wet environment (Difley, unpublished data). *Alamosaurus* has been associated only with semiarid environments (Bakker, 1986; Lehman, 1987, 2001).

Other possible North Horn track makers are ceratopsians and ankylosaurs. *Torosaurus* and other ceratopsians are represented by body fossils at North Horn Mountain (Gilmore, 1946; Lawson, 1976). Feet of the Milwaukee Public Museum *Torosaurus* specimen (VP6841) were reconstructed from *Triceratops*. Forefoot measurements calculated for *Torosaurus* based on this specimen (Johnson and Ostrom,1995, figs. 12.2, 12.3) are about 45 cm across, which also falls within the range of the North Horn tracks. The ceratopsian manus is about two-thirds the size of the pes (Lockley and Hunt, 1995b). Based upon *Torosaurus* manus reconstructions, its pes is estimated at about 69 cm across, which is somewhat larger than the ranges of the North Horn tracks. Maastrichtian ceratopsian track sizes from the Denver area, Colorado, vary from 30 to 80 cm across (manus and pes undifferentiated, Lockley and Hunt, 1995b). These tracks range from sizes coincident with the North Horn tracks to those far larger.

Although ankylosaurs have foot dimensions that likewise fall within the general size range of the North Horn tracks (McCrea et al., 2001), only one questionable ankylosaurid tooth specimen has been found in the North Horn Formation in Black Dragon Canyon 5 km from the North Horn type locality (Cifelli et al., 1999). North Horn tracks in Unit 1 do not show toe impressions or characteristic plan view geometry that would allow ceratopsian or ankylosaur tracks to be distinguished one from another. Impressions of ceratopsian and ankylosaur tracks are difficult to distinguish in plan-view, and until recently both were poorly known (Lockley and Hunt, 1995b; McCrea et al., 2001). Ceratopsians usually have a blunt 4-toed pes and 5-digit manus. Late Cretaceous ankylosaurs are known with a 3-toed pes and 5-digit manus, and thinner toes than ceratopsians (Lockley and Hunt, 1995b). A Cenomanian track (manus) having 1 to 2-mm tubercles on the sole, displays slide marks about 3–5 mm wide in plan view (McCrea et al., 2001, fig. 24b). These are surprisingly similar to vertical striae (approximately 10 mm across) on some North Horn track casts. Albian ankylosaur tracks are known to range from 38 to 52 cm. Earlier Cretaceous ankylosaur tracks exhibit variable morphology, ranging from oval (54–60 cm manus and pes combined) in wet substrates to forms with four widely separated toes (manus 24–31 cm, pes 30–34 cm across) in firm substrates (McCrea, 2000). The toes are spread more widely than toes displayed in the North Horn tracks. However, one cross-sectional track in Unit 2 (Fig. 8A) has a single protruding toe-like morphology that is reminiscent to that of the Lower Cretaceous ankylosaurid tracks in plan view made in wet environments (McCrea, 2000, fig. 6).

Nadon (1993) ascribed tracks in the St. Mary River Formation to “ornithopods,” and he described them as bearing wide toes or having a circular morphology without toe definition. North Horn tracks in Unit 1 with toe impressions closely match this description (Fig. 7B). One track with three closely spaced, wide, lobe-like toes is interpreted to have resulted from the animal pulling its foot from mud. This interpretation also is consistent with the rounded hadrosaur tracks illustrated by Nadon (2001, fig. 27.3B).

Nadon's (1993, fig. 4) track cast is similar in size and morphology (flattened base and rounded basal margins) to some North Horn tracks that are similarly preserved. Other track similarities include striae and type of sediment fill, as well as bedding occurrence and environmental setting (ephemeral wetland within anastomosed fluvial system).

Nadon (1993) noted the association of Cretaceous and Jurassic tracks and nests (or eggshells) with anastomosing fluvial environments. He surveyed the literature that described numerous formations representing fluvial settings and, based upon a combination of lithologic and paleontologic characteristics, he included the North Horn among candidate formations that might represent anastomosing fluvial environments. This present study confirms the presence of tracks in the North Horn Formation, such as those described by Nadon (1993, fig. 4) as "ornithopod" tracks. Additionally, Lockley (1991) attributes similar footprint evidence (broader footprints with shorter steps than theropods) to the work of ornithopod dinosaurs.

Ornithopods are likely candidates for some of the North Horn track makers. Both large and small hadrosaur skeletal elements have been recovered from North Horn Mountain (Gilmore, 1946). Their skeletal remains occur near the levels of the track sites, and jaw elements were found in the trampled zones of two of the track-bed sites. The possible nest site that occurs near a track level at North Horn Mountain (described above) has eggshells of the dinosauroid-spherulitic type, which have been associated with hadrosaurs in Montana by Bray (1999). The North Horn tracks generally are within the lower size range of hadrosaur tracks reported by Nadon (1993). However, many of the North Horn tracks are half the size of those reported for Campanian hadrosaurs elsewhere (Lockley et al.,1983).

Striae in tracks in the St. Mary River Formation in Montana and Alberta were interpreted as traces produced by tubercles on dinosaur feet (Nadon, 1993). This also may be true for the striae in the North Horn tracks that may have been made by flat and button-like (Figs. 6C, 7A) and fine tubercles or scales. This observation is consistent with the pattern size of hadrosaur tubercle imprints reported by Currie et al. (1991; Fig. 6D).

Hadrosaur integument reported by Anderson et al. (1999) from the Upper Cretaceous Neslen Formation of east-central Utah contained tubercles consistent in size and arrangement with the larger striae on the North Horn track casts (Figs. 6C, 9E). The difference is that none of the Neslen dinosaur integument is from the foot, and it is not known whether the tubercles on the Neslen specimen represent a type of dinosaur that also had tubercles on its feet. The size and shape of the striae on the North Horn track-cast specimens are consistent with striae that could have been made by tubercles similar to the bimodally-sized, polygonal, and button-like tubercles in the Neslen specimens. Moreover, tubercles like those on the Neslen specimens could have yielded strongly striated slip marks that were both patterned and unpatterned, depending upon the orientation of the foot as it pushed into the mud.

Since the North Horn tracks do not occur in plan view (with one exception noted), the criteria for recognition of dinosaur taxa from tracks (Lockley and Hunt, 1995a) are difficult to apply especially to those tracks that occur beneath very narrow overhanging sandstone ledges. Therefore, there is no direct plan-view evidence to distinguish the tracks of the herbivores that occur in the North Horn. However, the track beds are fairly consistent in style throughout Unit 1. Many of the tracks in Unit 2 are similar to those in Unit 1, and small differences may be attributed to environmental setting or substrate. The possibility that the tracks that continue up from Unit 1 into Unit 2 could be ornithiscian is supported by the occurrence low in Unit 2 of a poorly preserved ornithiscian jaw fragment, which cannot be identified more closely than ceratopsian or hadrosaurian.

The North Horn track beds almost certainly represent herbivore behavior. Based upon ranges of exterior track dimensions and skeletal occurrence in the North Horn, the herbivores may have been sauropods (*Alamosaurus*), hadrosaurs, or ceratopsians (Gilmore, 1946), or possibly ankylosaurs (Cifelli et al., 1999). Further evidence that these are mostly herbivore tracks is that they contain striae and/or wide, lobe-like toe impressions, and lack toe impressions that could be interpreted with certainty as belonging to theropods. Generally, the sizes of the North Horn tracks range at the small end of the scale for the most likely candidates. Most individual tracks appear to be circular like tracks of ornithopods. The few toe impressions observed in Unit 1 of the North Horn were broad with rounded terminations, and closely spaced like those of hadrosaurs (Fig. 7B), not widely spaced like those of ankylosaurs or ceratopsians or thin like ankylosaurs or theropods. The toe impressions appear longer than the blunt, enclosed toes shown on ceratopsian tracks (Lockley and Hunt, 1995b). In Unit 2, the only track with a toe-like structure more closely matches the morphology of ankylosaur feet, but it is difficult to draw firm conclusions from a single specimen.

CONCLUSIONS

Maastrichtian dinosaur track horizons are distributed widely in the North Horn basin in the Wasatch Plateau of central Utah. Particular moisture and sedimentation conditions were responsible for the preservation of footprints in mud, and the tracks were preserved in rapid, vertical succession. An anastomosed fluvial environment created a habitat for abundant dinosaurs, and this setting likewise created conditions that recorded the dinosaurs' footprints.

Tracks are displayed within the badlands terraces and labyrinthine gully system of the south face of North Horn Mountain, which exposes sandstone splay sheets and channel lenses of an exhumed anastomosed stream system within the North Horn Formation. The semi-arid, fluvial environment was best developed during the deposition of Unit 1, and especially in Unit 1B of the North Horn type area (and in stratigraphic equivalents in other localities).

The North Horn tracks near the K-T boundary interval add nothing substantial to the debate about the cause(s) of the disappearance of dinosaurs. The North Horn tracks, however, do document the presence of large dinosaurs in Utah at the end of the era, and these dinosaurs probably represent some of the same taxa that left their skeletal remains and tracks in the early part of the formation.

Although this study is limited by lack of tracks in plan view, or rarity of tracks with clear toes, the dinosaur track record in the North Horn Formation is, nevertheless, important in augmenting the existing dinosaur skeletal record. The North Horn tracks attest to dinosaur activities and faunal associations, and the track beds close gaps in the skeletal record at stratigraphic levels where no bones or eggshells have been found to date. Indeed, the evidence of dinosaurs provided by tracks far outnumbers that left by the skeletal record. The tracks reveal that dinosaurs were far more common in the latest Maastrichtian North Horn Formation in central Utah than the relatively impoverished skeletal record might suggest. Dinosaurs were sufficiently abundant to leave a widespread track record, not only at North Horn Mountain, but also at many other localities throughout central Utah.

Tracks were made by large numbers of big dinosaurs that repeatedly utilized the same low areas near anastomosed rivers. Because of the apparent mingling behavior, the paucity of tracks with thin, elongate toes, and the size of the footprints, it is believed that these track beds were produced principally by herbivorous dinosaurs rather than carnivores (theropods). Traces of dinosaurs and invertebrates, together with body fossils of dinosaurs and others, help to create a better, more complete picture of dinosaur distribution in central Utah during the latest Cretaceous.

ACKNOWLEDGEMENTS

We thank Ken Carpenter, Margie Chan, Walter Coombs, John A. Difley, Seth Difley, Thea Difley, Steve Hasiotis, Martha Hayden, Jim Kirkland, Bob Lamond, Mark Loewen, Greg Nadon, Bob Peyton, Phil Policelli, Jeff Quick, Quintin Sahratian, Scott Sampson, and Craig Sanders for their interest and assistance in accomplishing this work. We also thank Martin Lockley and an anonymous reviewer for their helpful criticisms of an earlier version of the manuscript.

REFERENCES

Anderson, B.G., Barrick, R.E., Droser, M.L., and Stadtman, K.L., 1999, Hadrosaur skin impressions from the Upper Cretaceous Neslen Formation, Book Cliffs, Utah: Morphology and paleoenvironmental context: *in* Gillette, D.D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Special Publication No. 99–1, Salt Lake City, p. 295–301.

Bakker, R.T., 1986, The Dinosaur Heresies, New Theories Unlocking the Mystery of the Dinosaurs and Their Extinction: Zebra Books, Kensington Publishing Corp., New York, 482 p.

Blodgett, R.H., 1988, Calcareous paleosols in the Triassic Dolores Formation, southwestern Colorado: *in* Reinhardt, J., and Sigleo, W.R., eds., Paleosols and Weathering Through Geologic Time: Principles and Applications: Geological Society of America Special Paper 216, Boulder, p. 103–121.

Bray, E.S., 1999, Eggs and eggshell from the Upper Cretaceous North Horn Formation, central Utah: *in* Gillette, D.D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Special Publication No. 99–1, Salt Lake City, p. 361–375.

Cifelli, R.L., Nydam, R.L., Eaton, J.G., Gardner, J.D., and Kirkland, J.I., 1999, Vertebrate faunas of the North Horn Formation (Upper Cretaceous-Lower Paleocene), Emery and Sanpete Counties: *in* Gillette, D.D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Special Publication No. 99–1, Salt Lake City, p. 377–388.

Currie, P.J., Nadon, G.C., and Lockley, M.G., 1991, Dinosaur footprints with skin impressions from the Cretaceous of Alberta and Colorado: Canadian Journal of Earth Science, v. 28, p. 102–115.

DeCourten, F., 1998, Dinosaurs of Utah: University of Utah Press, Salt Lake City, 300 p.

Difley, R.L., and Ekdale, A.A., 1998, Dinosaur track beds in the uppermost Cretaceous North Horn Formation: Journal of Vertebrate Paleontology, v. 18,(supplement) No. 3, p. 38A.

Difley, R.L., and Ekdale, A.A., 1999, Biostratigraphic aspects of the Cretaceous-Tertiary (KT) boundary interval at North Horn Mountain, Emery County, Utah: *in* Gillette, D.D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Special Publication No. 99–1, Salt Lake City, p. 389–398.

Eberth, D.A., and Miall, A.D., 1991, Stratigraphy, sedimentology and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico: Sedimentary Geology, v. 72, p. 225–252.

Engelmann, G.F., and Hasiotis, S.T., 1999, Deep dinosaur tracks in the Morrison Formation: Sole marks that are really sole marks: *in* Gillette, D.D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Special Publication No. 99–1, Salt Lake City, p. 179–183.

Farlow, J.O., and Chapman, R.E., 1997, The scientific study of dinosaur footprints: *in* Farlow, J.O., and Bret-Surman, M.K., eds., The Complete Dinosaur: Indiana University Press, Bloomington, p. 518–553.

Fouch, T.D., Hanley, J.H., Forester, R.M., Pitman, J.K., and Nichols, D.J., 1987, Chart showing lithology, mineralogy and paleontology of the nonmarine North Horn Formation and Flagstaff Member of the Green River Formation, Price Canyon, central Utah: United States Geological Survey Map I-1797-A.

Franczyk, K.J., and Pitman, J.K., 1991, Latest Cretaceous nonmarine depositional systems in the Wasatch Plateau area—Reflections of foreland to intermontane basin transition: *in* Chidsey, T.C., Jr., ed., Geology of East-central Utah: Utah Geological Association Publication No.19, Salt Lake City, p. 77–93.

Freytet, P., and Plaziat, J.-C., 1982, Continental Carbonate Sedimentation and Pedogenesis—Late Cretaceous and Early Tertiary of Southern France: Contributions to Sedimentology, v.12: E. Schweizerbart'sche Verlagsbuchandlung (Nagele u. Obermiller), Stuttgart, 213 p.

Gilmore, C.W., 1942, Osteology of *Polyglyphanodon*, an Upper Cretaceous lizard from Utah: Proceedings United States National Museum, Washington, D.C., v. 92, v. No. 3148, p. 229–265.

Gilmore, C.W., 1946, Reptilian fauna of the North Horn Formation of Central Utah: United States Geological Survey Professional Paper 210-C, p. 29–53.

Hubert, J.F., 1978, Paleosol caliche in the New Haven Arkose, Newark Group, Connecticut: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 24, p. 151–168.

Jensen, J.A., 1966, Dinosaur eggs from the Upper Cretaceous North Horn Formation: Brigham Young University Geology Studies, v. 13, p. 55–68.

Jensen, N.R., 1988, Geology of the Fairview 7½' Quadrangle, Sanpete County, Utah: Brigham Young University Geology Studies, v. 35, p. 101–121.

Johnson, R.E., and Ostrom, J.H., 1995, The forelimb of *Torosaurus* and an analysis of the posture and gait of ceratopsian dinosaurs: *in* Thomason, J., ed., Functional Morphology in Vertebrate Paleontology: Cambridge University Press, p. 205–218.

Kirschbaum, M.A., and McCabe, P.J., 1992, Controls on the accumulation of coal and on the development of anastomosed fluvial systems in the Cretaceous Dakota Formation of southern Utah: Sedimentology, v. 39, p. 581–598.

Kucera, R.E., 1954, Geology of the Joes Valley and North Dragon area, central Utah: Unpublished M.S. Thesis, Ohio State University, Columbus, 210 p.

Lawson, D.A., 1976, *Tyrannosaurus* and *Torosaurus*, Maestrichtian dinosaurs from Trans-Pecos, Texas: Journal of Paleontology, v. 50, p. 158–164.

Lawton, T.F., Franczyk, K.J., and Pitman, J.K., 1990, Latest Cretaceous-Paleogene basin development and resultant sedimentation patterns in the thrust belt and broken foreland of central

Utah: American Association of Petroleum Geologists Bulletin, v. 74, p. 701.

Lee, K.Y., 1953, A petrographic study of the latest Cretaceous and earliest Tertiary formation of central Utah: Unpublished Ph.D. Thesis, Ohio State University, Columbus, 205 p.

Lehman, T.M., 1987, Late Maastrichtian paleoenvironments and dinosaur biogeography in the Western Interior of North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 60, p. 189–217.

Lehman, T.M., 2001, Late Cretaceous dinosaur provinciality: *in* Tanke, D.H., and Carpenter, K., eds., Mesozoic Vertebrate Life, New Research Inspired by the Paleontology of Philip J. Currie: Indiana University Press, Bloomington, p. 310–328.

Lockley, M.G., 1986, The paleobiological and paleoenvironmental importance of dinosaur footprints: PALAIOS, v. 1, p. 37–47.

Lockley, M.G., 1990, La dinoturbacion y el fenomeno de la alteracion del sedimento por pisadas de vertebrados en ambientes anitguos (Dinoturbation and the phenomenon of vertebrate trampling in ancient environments): Il Curso De Paleontologia En Cuenca, v. 10, p. 270–296.

Lockley, M.G., 1991, Tracking Dinosaurs, A New Look At An Ancient World: Cambridge University Press, New York, 238 p.

Lockley, M.G., 1997, The paleoecological and paleoenvironmental utility of dinosaur tracks: *in* Farlow, J.O., and Bret-Surman, M.K., eds., The Complete Dinosaur: Indiana University Press, Bloomington, p. 554–578.

Lockley, M.G., and Hunt, A.P., 1995a, Dinosaur Tracks and Other Fossil Footprints of the Western United States: Columbia University Press, New York, 338 p.

Lockley, M.G., and Hunt, A.P., 1995b, Ceratopsid tracks and associated ichnofauna from the Laramie Formation (Upper Cretaceous: Maastrichtian) of Colorado: Journal of Vertebrate Paleontology, v. 15, p. 592–614.

Lockley, M.G., Young, B.H., and Carpenter, K., 1983, Hadrosaur locomotion and herding behavior: Evidence from footprints in the Mesaverde Formation, Grand Mesa coal field, Colorado: Mountain Geologist, v. 20, p. 5–13.

Loewen, M.A, Sampson, S.D., Getty, M.A, and Difley, R.L., 2001, The upland dinosaur fauna of the Late Cretaceous (Maastrichtian) North Horn Formation: Journal of Vertebrate Paleontology, v. 21,(supplement) No. 3, p. 74.

Loope, D.B., 1986, Recognizing and utilizing vertebrate tracks in cross section: Cenozoic hoofprints from Nebraska: PALAIOS, v. 1, p. 141–151.

McCrea, R.T., 2000, Dinosaur footprints in the Lower Cretaceous (Albian) Gates Formation of Alberta, Canada: Their use in Palaeobiology and Palaeornvironmental interpretation: Paleontological Society of Korea Special Publication No. 4, p. 169–178.

McCrea, R.T., Lockley, M.G., and Meyer, C.A., 2001, Global distribution of purported Ankylosaur track occurrences: *in* Carpenter, K., ed., The Armoured Dinosaurs (Life of the Past): Indiana University Press, p. 413–454.

Miall, A.D., 1996, The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis, and Petroleum Geology: Springer-Verlag, Berlin, 582 p.

Morozova, G.S., and Smith, N.D., 2000, Holocene avulsion styles and sedimentation patterns of the Saskatchewan River, Cumberland Marshes, Canada: Sedimentary Geology, v. 130, p. 81–105.

Nadon, G.C., 1993, The association of anastomosed fluvial deposits and dinosaur tracks, eggs, and nests: Implications for the interpretation of floodplain environments and a possible survival strategy for ornithopods: PALAIOS, v. 8, p. 31–44.

Nadon, G.C., 1994, The genesis and recognition of anastomosed fluvial deposits: Data from the St. Mary River Formation, southwestern Alberta, Canada: Journal of Sedimentary Research, v. B64, p. 451–463.

Nadon, G.C., 2001, The impact of sedimentology on vertebrate track studies: *in* Tanke, D.H., and Carpenter, K., eds., Mesozoic Vertebrate Life, New Research Inspired by the Paleontology of Philip J. Currie: Indiana University Press, Bloomington, p. 395–407.

Oberhansley, G.G., 1980, Geology of the Fairview Lakes Quadrangle: Sanpete County, Utah: Brigham Young University Geology Studies, v. 27,Part 3, p. 73–95.

Olsen, T., 1995, Fluvial and fluvio-lacustrine facies and depositional environments of the Maastrichtian to Paleocene North Horn Formation, Price Canyon, Utah: Mountain Geologist, v. 32, p. 27–44.

Parker, L.R., and Balsley, J.K., 1989, Coal mines as localities for studying dinosaur trace fossils: *in* Gillette, D.D., and Lockley, M.G., eds., Dinosaur Tracks and Traces: Cambridge University Press, Cambridge, p. 353–359.

Perez-Arlucea, M., and Smith, N.D., 1999, Depositional patterns following the 1870s avulsion of the Saskatchewan River (Cumberland Marshes, Saskatchewan, Canada): Journal of Sedimentary Research, v. 69,No. 1, p. 62–73.

Pettijohn, F.J., and Potter, P.E., 1964, Atlas and Glossary of Primary Sedimentary Structures: Springer-Verlag, New York, 370 p.

Platt, N.H., and Wright, V.P., 1992, Palustrine carbonates and the Florida Everglades: Towards and exposure index for the fresh-water environment?: Journal of Sedimentary Petrology, v. 62, p. 1058–1071.

Reeves, C.C., Jr., 1976, Caliche, Origin, Classification, Morphology and Uses: Estacade Books, Inc., Lubbock, 233 p.

Retallack, G.J., 1985, Fossil soils as grounds for interpreting long-term controls on ancient rivers: Journal of Sedimentary Petrology, v. 56, p. 1–18.

Retallack, G.J., 1997, A Colour Guide to Paleosols: John Wiley and Sons, Chichester, 175 p.

Retallack, G.J., 2001, Soils of the Past, An Introduction to Paleopedology: Blackwell Science Ltd., Oxford, 404 p.

Rust, B.R., and Legun, A.S., 1983, Modern anastomosing-fluvial deposits in arid Central Australia, and a Carboniferous analogue in New Brunswick, Canada: *in* Collinson, J.D., and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists Special Publication No. 6, Oxford, p. 385–392.

Smith, D.G., 1983, Anastomosed fluvial deposits: modern examples from Western Canada: *in* Collinson, J.D., and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists Special Publication No. 6, Oxford, p. 155–168.

Smith, N.D., Cross, T.A., Dufficy, J.P., and Clough, S.R., 1989, Anatomy of an avulsion: Sedimentology, v. 36, p. 1–23.

Spieker, E.M., 1946, Late Mesozoic and Early Cenozoic history of central Utah: United States Geological Survey Professional Paper 205-D, p. 117–161.

Spieker, E.M., 1960, The Cretaceous-Tertiary boundary in Utah: International Geological Conference Report of 21st Session, Norden, p. 14–24.

Stanley, K.O., and Collinson, J.W., 1979, Depositional history of Paleocene-Lower Eocene Flagstaff Limestone and coeval rocks, central Utah: American Association of Petroleum Geologists Bulletin, v. 63, p. 311–323.

Tomida, Y. and Butler, R.F., 1980, Dragonian mammals and Paleocene magnetic polarity stratigraphy North Horn Formation, central Utah: American Journal of Science v. 280, p. 787–811.

Woodburne, M.O., and Swisher, C.C., III, 1995, Land mammal high-resolutions geochronology, intercontinental, overland dispersals, sea level, climate, and vicariance: *in* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J., eds., Geochronology, Time Scales and Global Stratigraphic Correlation: Society for Sedimentary Geology, Tulsa, p. 335–364.

Zawiskie, J.M., 1983, Sedimentology and trace fossils of the dinosaur beds of the North Horn Formation, central Utah: Geological Society of America Abstracts with Programs v. 15,No. 6, p. 726.

ACCEPTED MARCH 5, 2002