Recognizing and Utilizing Vertebrate Tracks in Cross Section: Cenozoic Hoofprints from Nebraska

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Because vertebrate tracks exposed in vertical outcrops are frequently overlooked or misinterpreted as physically induced deformation structures, important paleoecologic and sedimentologic information remains untapped. Laminations within eolian dune sands of the Nebraska Sand Hills (Holocene) and ephemeral-stream deposits of the lower Arikaree Group (late Oligocene) are commonly broken or sharply downwarped to form isolated or paired, concave-up structures that vary from 4 to 22 cm in diameter. A central ridge divides the lower portion of some structures into two distinct lobes. Although bedding-plane exposures are rare in both deposits, extensive search revealed some structures in linear alignment, confirming a biogenic origin for the deformation. The Holocene tracks, probably made by bison, were repeatedly produced during the migration of the large eolian bedforms, suggesting that food and water were available in interdune areas. Smectite grain coatings made surface sands cohesive, thereby strongly influencing track morphology and enhancing preservation potential. Oligocene tracks were produced in very fine sand by several species of hoofed vertebrates. Close vertical spacing of track-bearing beds reveals that most sediment accumulated in relatively thin packages. The general absence of heavily trampled horizons (as would be expected along diastems) may be the result of rapid consolidation of sands by evaporite cementation. Tracks may have been produced during brief intervals of time immediately following deposition and preceding cementation.

INTRODUCTION

Vertebrate trackways are a well-known source of paleontologic and sedimentologic information (Sarjeant, 1975). Perhaps because vertebrate tracks are so easy to recognize on bedding-plane exposures, until recently little attention has been given to their appearance in vertical section. Photographs and drawings published by Van der Lingen and Andrews (1969), McKee and Bigarella (1972), Lewis and Titheridge (1978), Laury (1980), and Hunter et al. (1984) have, however, documented the deformation that takes place when large animals move across soft, laminated sediment. On the basis of their observations of Quaternary deposits in East Africa, Laporte and Behrensmeyer (1980) have recently argued that large vertebrates have the potential to rework terrestrial sediments to the same extent that benthic invertebrates rework marine strata. Preservation of tracks requires compactible substrates that are accessible to vertebrates; rates of trampling and burial control whether sediments record individual tracks or are totally bioturbated (Laporte and Behrensmeyer, 1980, fig. 4a).

The Holocene tracks described here are from exposures of dune and interdune deposits within the Nebraska Sand Hills and were probably produced by bison. Oligocene hoofprints are well exposed in outcrops of fluvial sheet-flood deposits within the Gering Formation (Arikaree Group) at Scotts Bluff National Monument in westernmost Nebraska; these tracks were made by several different species of cloven-hoofed mammals. The morphology of both Holocene and Oligocene hoofprints indicates that they were produced in cohesive sand. Much of surface sand in the Sand Hills is cohesive even when dry, due to clay coatings on grains; such coatings greatly enhanced the preservation potential of the buried tracks. Individual tracks or pairs of tracks in the Holocene and Oligocene sediments are typically widely spaced laterally, but closely spaced vertically. The vertical spacing of track-bearing laminae allows division of strata into discrete depositional packages. Close vertical spacing suggests that sand-driving winds deposited relatively thin sediment packages in the Nebraska Sand Hills and that tracks were produced by resident, rather than migratory populations. Much of the Gering Formation is composed of similarly thin packages that accumulated within an ephemeral stream system dominated by sheet-flood events. The lack of heavily trampled zones (which might be expected to mark diastems) suggests that the Holocene sediment accumulated steadily; in contrast, the same pattern in the Oligocene rocks could be the result of rapid cementation of newly deposited sand by evaporites. The abundance of vertebrate tracks in these strata shows that, under certain conditions, eolian dune fields and ephemeral-stream floodplains can be very favorable sites for preservation of vertebrate tracks.

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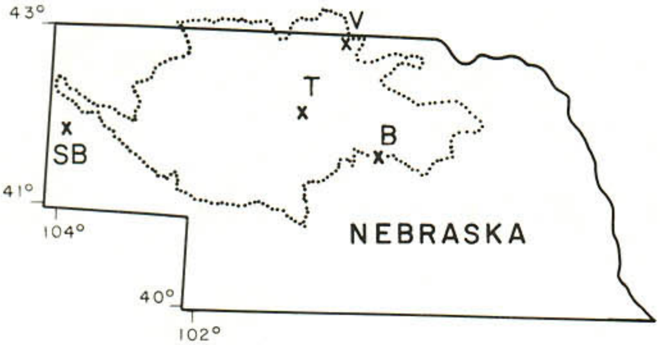

FIGURE 1—Map showing outline of the Nebraska Sand Hills and location of Burwell (B), Thedford (T), Valentine (V), and Scotts Bluff National Monument (SB).

The main purposes of this paper are: 1) to document sedimentary structures produced by the hooves of large mammals in nonmarine sands and sandstones of central and western Nebraska; 2) to provide criteria by which these features can be differentiated from nonbiogenic deformation structures; and 3) to further demonstrate the utility of vertebrate tracks for sedimentological and paleoecological interpretations.

HOLOCENE OF THE NEBRASKA SAND HILLS

Location and Geologic Setting

Occupying an area of 57,000 square kilometers, the Nebraska Sand Hills (Fig. 1) are the largest dune field in the Western Hemisphere (Smith, 1965). This dune field, now stabilized by prairie vegetation, is composed of simple and compound, transverse to oblique bedforms that reach heights up to 100 m (Ahlbrandt and Fryberger, 1980). Carbon-14 dates reported by Ahlbrandt et al. (1983) from sediments directly beneath the dunes suggest that the dune field is primarily Holocene in age. The sedimentary structures within the dunes are visible in a large number of exposures throughout the Sand Hills (Ahlbrandt and Fryberger, 1980). Most of the observations for this paper were made near the eastern margin of the Sand Hills at excavations for the Calamus River dam near Burwell, Nebraska, and at blowouts and stream cuts near Thedford in the central Sand Hills (Fig. 1). Structures interpreted here as vertebrate tracks are present throughout the Sand Hills; many are recognizable in published photographs from the northern and central Sand Hills (Ahlbrandt and Fryberger, 1980, figs. 9, 10, 11, and 13). At all vertically extensive exposures, it is clear that the tracks are not restricted to the upper portions of the dunes, but are distributed throughout the thickness of the eolian deposit (Fig. 2).

All deformation structures interpreted as hoofprints are developed in thin, inversely graded laminae dipping between 0 and 24 degrees. These laminae were clearly deposited by migrating wind ripples and, in the terminology of Hunter (1977), can be classified as subcritically climbing translatent strata. Laminae with very low dips accumulated in interdune areas or as sand sheets (Fryberger et al., 1979); more steeply dipping strata were deposited on leeward slopes of bedforms, where side winds swept ripples across surfaces with dips well below the angle of repose.

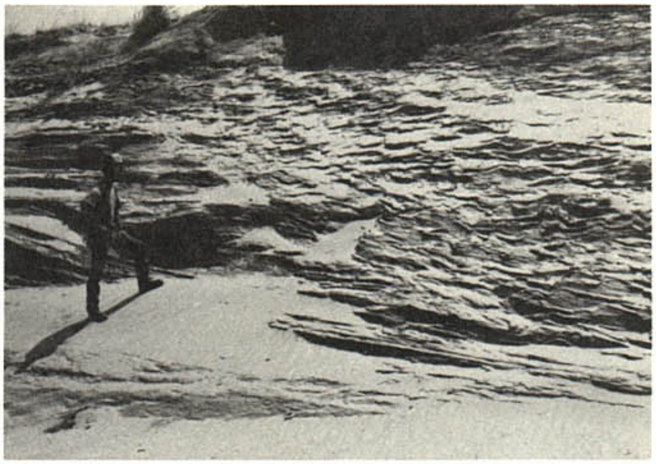

FIGURE 2—Concave-up deformation structures in large-scale cross-stratified Holocene dune deposits at Calamus River dam site near Burwell, Nebraska. Note that deformation occurs throughout vertical extent of exposure.

Description of Tracks

The features interpreted here as vertebrate tracks are concave-up deformation structures that are circular to oval in plan and range from 7 to 16 cm in diameter (Figs. 3, 4, 5). Near the tops of structures, laminae are abruptly truncated or sharply folded (Figs. 3, 4a). As in the structures reported by Van der Lingen and Andrews (1969), concavity dies out gradually downward. Although deformation extends vertically as much as 25 cm, individual laminae are displaced no more than 15 cm. Within some individual structures, a central ridge divides the lower portion into two distinct lobes, which are visible in both cross-sectional and plan views (Fig. 4). The interiors of many struc-

FIGURE 3—Tracks in horizontal wind-ripple laminae. Interdune or sand-sheet deposit near Burwell. Pen is 13 cm in length.

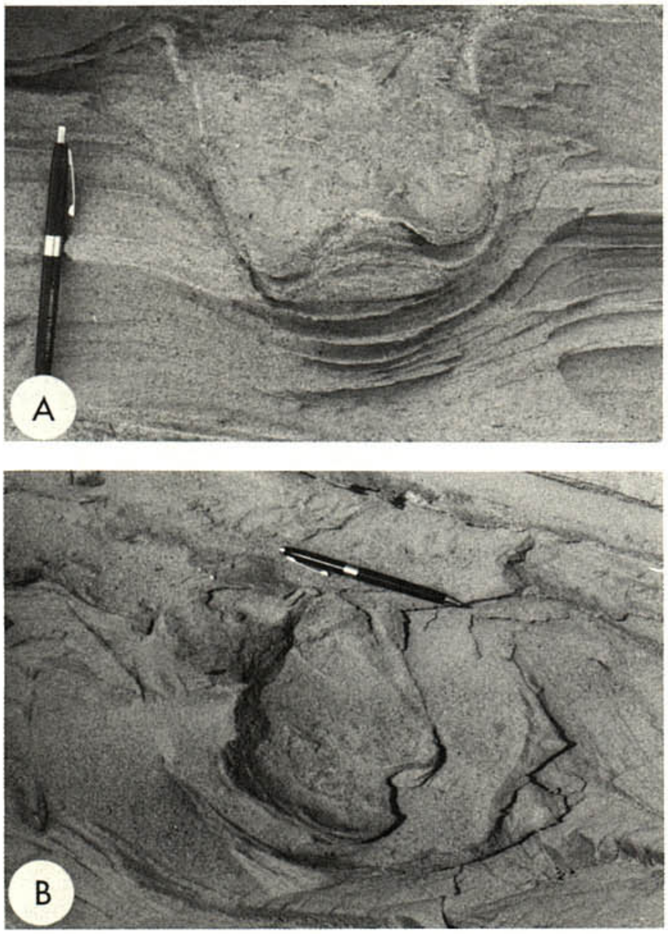

FIGURE 4—A) Track with vertical walls and bilobed lower portion. Surface concavity was infilled by coarse-grained lag deposit. Note raised "rim" at upper margins. Subhorizontal lines crossing structures are post-depositional accumulations of silt and clay (soil lamellae or "dissipation structures" of Ahlbrandt and Fryberger, 1980). B) Plan view of bilobed track near the middle of a three-meter-thick crossbed set.

tures are composed of material that is texturally distinct from the underlying and surrounding deformed sediment. Commonly, this central portion contains very coarse sand and granules (Fig. 4a); in rare cases, a thin (about 5 mm) layer of silt is preserved on the floor of the concave-up structure.

Along individual stratigraphic levels, concave-up structures are laterally isolated or in pairs. The structures are commonly closely spaced vertically (Fig. 3) and may dominate the aspect of outcrops exposing several meters of strata (Fig. 2); laterally adjacent beds may lack such deformation.

Interpretation

In contrast to the easily recognized vertebrate trackways appearing on bedding planes (Sarjeant, 1975), most tracks appearing in cross section have probably been either ignored or misinterpreted (Lewis and Titheridge, 1978). Tracks in vertical outcrops can closely resemble other types of deformation. In the Sand Hills, fortuitous exposures and small excavations provided glimpses of short trackways (Fig. 6) that along with the bilobed morphology of some structures, confirmed the biogenic hypothesis. After the structures are recognized as tracks, the distribution of individual deformation structures and other aspects of their morphology provide important sedimentological and paleoecological insights.

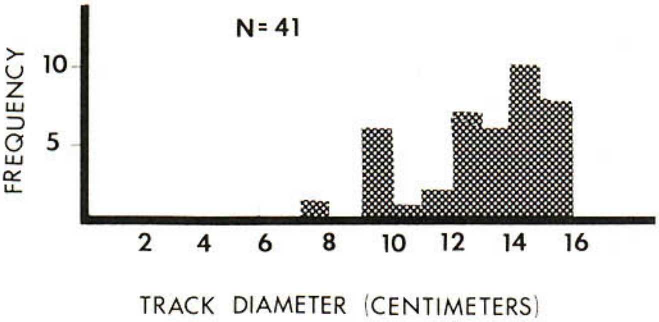

FIGURE 5—Size-frequency data for Holocene tracks measured from vertical exposures, Nebraska Sand Hills. Some variation in diameter is result of oval plan of structures (Fig. 4b).

Contrast with Nonbiogenic Structures

The size-frequency distribution of the deformation structures (Fig. 5) strongly supports the biogenic interpretation: none of the structures are too large or too small to be tracks. When closely spaced, however, the Sand Hills structures superficially resemble convolute bedding, a structure that Allen (1982) defines as a "laterally extensive series of more or less regular folds developed throughout or confined to the upper part of a single sedimentation unit." Convolute bedding, however, is typically developed in strata that, due to rapid sedimentation, were originally very loosely packed (Allen, 1982, p. 343). Accordingly, this structure has been used as evidence for rapid deposition (Collinson and Thompson, 1982, p. 145). Studies of

FIGURE 6—Part of short trackway in large-scale cross-stratified sand, Calamus dam site, Burwell, NE. Note lack of root traces in laminae below tracks. Machete handle is 15 cm long.

modern wind-ripple deposits indicate that the strata containing the Sand Hills deformation structures had low initial porosities and were deposited relatively slowly. Because of strong differences in grain packing and porosity, the different eolian stratification types vary in their susceptibility to deformation (Bagnold, 1941; Hunter, 1981). Avalanche or grainflow strata are loosely packed; the large-scale deformation commonly found in ancient eolian sandstones is commonly concentrated in deposits of this type, because their high porosity allows liquefaction. In contrast, strata dominated by climbing-ripple deposits—apparently due to their low initial porosities—are rarely involved in this kind of deformation (Doe and Dott, 1980). In light of the evidence from modern and ancient eolian sands, the abundance of relatively large-scale deformation structures in the wind-ripple deposits of the Sand Hills initially seemed incongruous. It was this paradox that led to the hypothesis that the deformation structures within the typically stable strata are biogenic.

Ahlbrandt and Fryberger (1980) explained some deformation structures within eolian strata of the Sand Hills (which are identical to the ones interpreted here as tracks) as the result of compression at the base of slipface deposits. Several workers have reported observations of this type of deformation. From the Coorong region of southern Australia, Brown (1969) described arcuate folds up to 200 m long and 0.5 m in amplitude that developed within lagoonal muds that were overridden by dunes 15–30 m high. McKee et al. (1971) experimentally produced small-scale warps, folds, and overthrusts in avalanching sand, but noted that "no contorted structures caused by tensional or compressional stresses normally occur in saltated deposits. . . . " There are, furthermore, fundamental differences in form between the products of lateral compression and the Sand Hills deformation structures. The circular to oval plan, lack of directional asymmetry, and steep margins of the Sand Hills structures give them a "punched-in" appearance, clearly indicating that they were formed by vertically, rather than laterally directed stress.

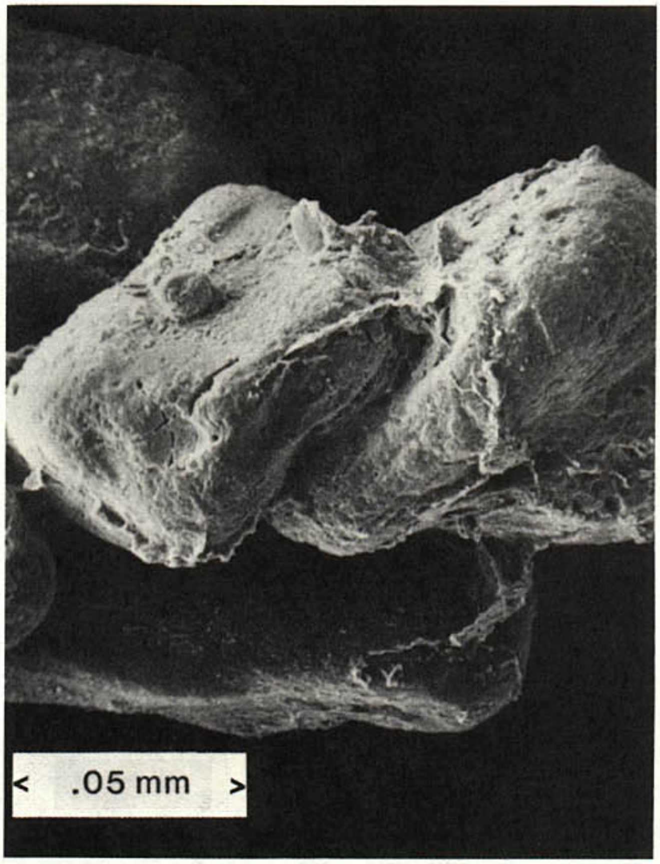

FIGURE 7—SEM image of sand grains with detrital clay coatings and bridges. Sample is a "crumb" of recently deposited, but cohesive surface sand collected from the side of a vertical-sided cow track in the central Sand Hills.

The Substrate

Track morphology indicates that tracks were made in cohesive sand. Coarse-grained sediments overlying truncated laminae (Fig. 4a) are lag deposits that filled vertically walled depressions. Silts preserved in similar positions represent dust that was trapped and protected by concavities. Tracks made in moist, well-sorted sand (wetted sand of McKee et al., 1971) have steep walls, which can be maintained as long as the sand remains moist (Lewis and Titheridge, 1978, fig. 1d). Were the Sand Hills tracks formed in moist sand and buried before drying? Observations of modern cattle tracks in the Sand Hills suggest an alternative hypothesis. Unlike beach sand, dune sand from the Sand Hills contains as much as 4% silt and clay (Ahlbrandt and Fryberger, 1980, p. 21). The clay fraction is smectite, occurring as thin, detrital coatings on sand grains (Fig. 7; Ahlbrandt and Fryberger, 1982, fig. 21d). Such grain coatings are deposited by water moving through the vadose zone; they can survive considerable eolian transport (Walker et al., 1978; Walker, 1979).

In the Sand Hills during August, 1985, vertical-sided cattle tracks were abundant in wind-rippled, cohesive surface sands with a moisture content less than 1%. "Crumbs" of this cohesive sand collected in the field were found to retain their structure even after 24 hours of oven drying at 40°C. Using samples of loose sand from the Sand Hills and distilled water, cohesive sand "crumbs" identical to those collected in the field can be produced in the laboratory with a single wetting/drying cycle (Fig. 8).

In the field, cohesive surface sands are relatively resistant to wind erosion. Tracks made within such sands have a much higher preservation potential than tracks produced in mobile, cohesionless sands that have not been moistened (Figs. 9, 10). This observation may explain the prevalence of tracks with vertical sides in Holocene strata of the Sand Hills and suggests that clay-coated dune sand is an especially suitable medium for the preservation of tracks. In their study of the Permian Lyons Sandstone, Walker and Harms (1972) hypothesized that thin layers of clay deposited during calm periods between sand-driving winds may have allowed the preservation of small tracks and raindrop imprints made in dry sand. Walker (1979) later showed the importance of grain coatings composed of detrital clays to the reddening of eolian dune sands. With further

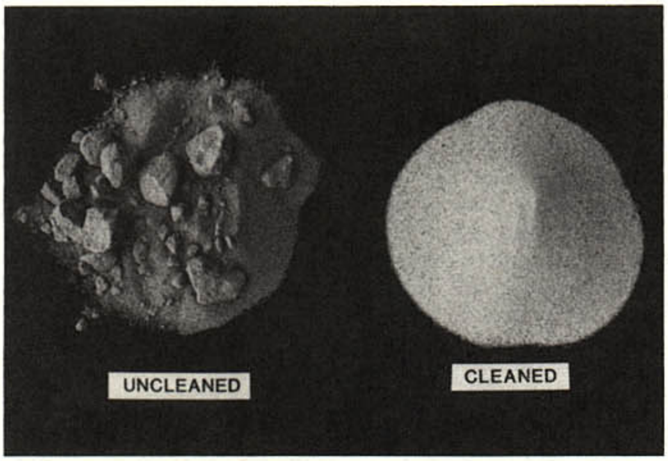

FIGURE 8—Crumbs of cohesive sand (left) produced in the laboratory when loose surficial sand from the Sand Hills was placed in a paper cup, saturated with distilled water, and dried in an oven at 40°C. Cohesionless sample on right was ultrasonically cleaned and wet sieved to remove clays prior to identical treatment. Original sample is a moderately sorted, nearly symmetrical fine sand ($Mz = 2.21$; $\sigma_1 = 0.662$; $Sk1 = .088$) containing 1.3% clay, 10 YR 7/3 (Munsell Color Chart).

petrographic work and laboratory experiments, it may be possible to assess the role (if any) of detrital clay coatings in the preservation of the delicate surface traces found in Paleozoic eolian sandstones.

Track-Makers and Paleoenvironments

The size and morphology of the tracks, the probable age of the Sand Hills, the known mammalian fossil record, and paleoecological arguments strongly suggest that bison are responsible for the tracks. The tracks of modern bison (Fig. 10) are nearly identical in size and form to those preserved within the Sand Hills.

Until recently, students of the Sand Hills had placed major dune formation in either the early or late Wisconsin (Pleistocene). Fluvial deposits from the east-central Sand Hills, which are now known to underlie as much as 40 m of dune sand, have, however, yielded 10 radiocarbon dates ranging from 8410 to 3000 yrs. B.P., indicating that the dune field is primarily of Holocene age (Ahlbrandt et al., 1983). This view has been challenged by Wright et al. (1985), on the basis of radiocarbon dates and pollen from five interdune lake deposits in the northern and western Sand Hills. At the Calamus dam site, all tracks lie above a peat deposit that has been radiocarbon-dated at 7260 ±90 yrs. B.P. (J. Swinehart, unpublished data; Beta-11621); most tracks are above an organic-rich interdune deposit dated at 3450 ± 110 yrs. B.P. (ibid, Beta-11622). A diverse assemblage of large herbivores, including camels, mammoths, horses, and sloths roamed the Great Plains during the Pleistocene; of these, only camels produce tracks that are at all similar in size and shape to those described here. The youngest radiocarbon date for a North American fossil site containing camel bones is 8240 ± 960 yrs. B.P. (Mead and Meltzer, 1984). All track observations are consistent with a Holocene age for the deposits; the largest cloven-hoofed mammals of the Holocene—bison—are capable of producing all the tracks so far observed.

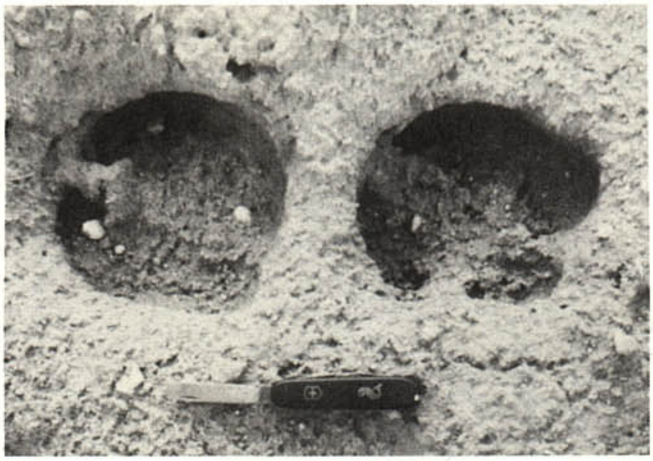

FIGURE 9—Bison tracks in clay-coated eolian sand containing less than 1% water (by weight), Fort Niobrara National Wildlife Refuge, near Valentine. Knife is 15 cm long.

Paleoecological considerations also suggest that these tracks were made by bison. Archaeologic as well as paleontologic evidence from several Great Plains and Middle Rocky Mountain sites links bison to semiarid grassland environments in which sandy sediments have been subjected to episodes of eolian transport. Not only have bison bones been recovered from the Sand Hills (Ahlbrandt and Fryberger, 1980) and from dune sands at many other localities, but at the 10,000-year-old Casper site in east-central Wyoming, paleo-Indians used para-

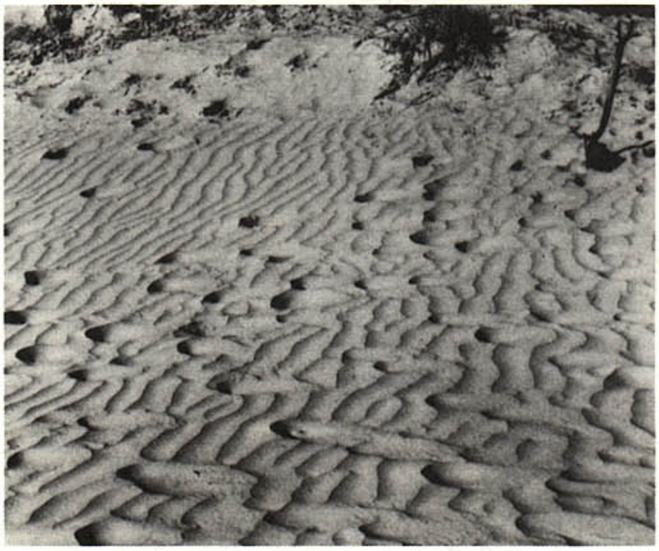

FIGURE 10—Loose sand covering a deposit of cohesive sand, which contains numerous vertical-sided cattle tracks. Central Sand Hills near Thedford. Shovel in background for scale.

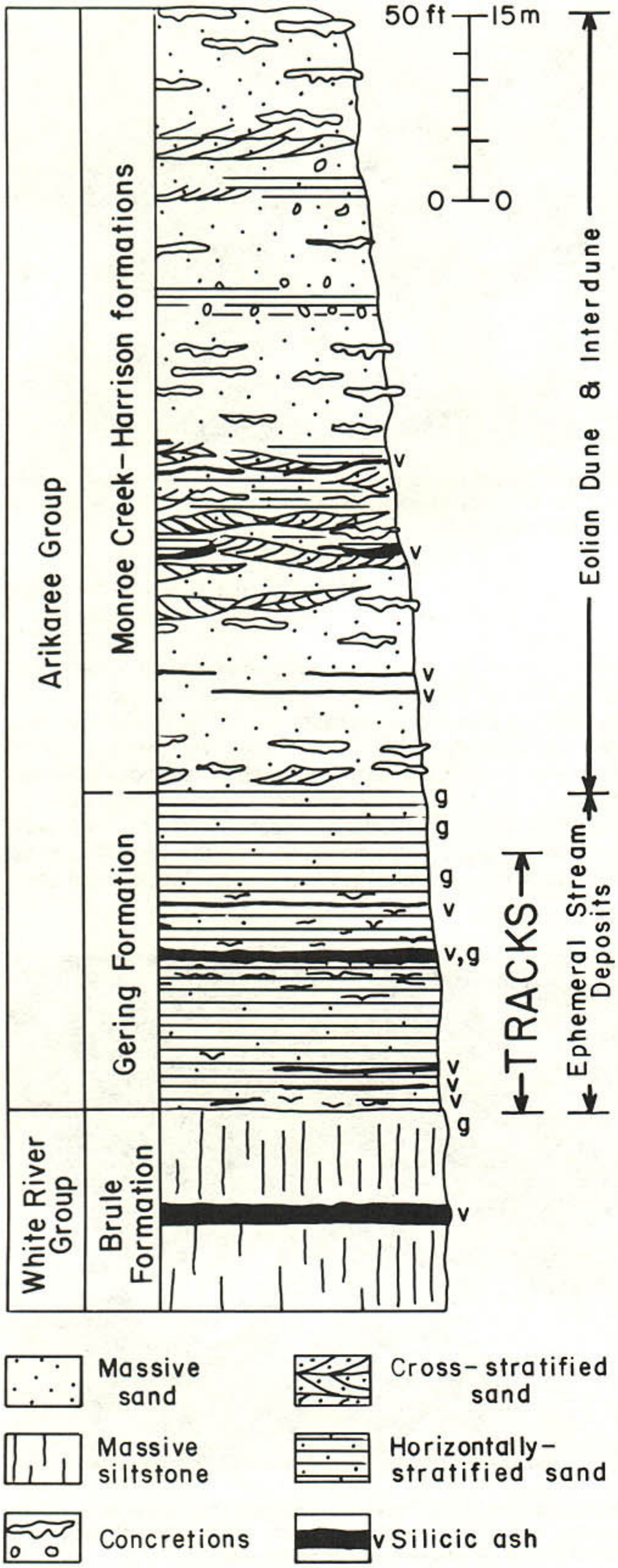

FIGURE 11—Stratigraphic section and interpretation of depositional processes; Scotts Bluff National Monument (from Swinehart and Loope, in press). g = evidence of gypsum crystallization.

bolic eolian dunes as natural traps for bison procurement (Frison, 1974).

The abundance of tracks in these sediments seems difficult to reconcile with the lack of root traces below track-bearing laminae. Were the tracks produced during transient movements of nonresident herds? The wide spacing of tracks along bedding planes and the close vertical spacing of track-bearing laminae argue against infrequent mass-migration events. McKee and Bigarella (1972) observed that small roots penetrating dune sand follow lamination, thereby leaving few traces. Track abundance and distribution suggest that semipermanent water—perhaps located in interdune areas—and vegetation were available to resident individuals or herds while the dunes were actively migrating.

OLIGOCENE OF SCOTTS BLUFF NATIONAL MONUMENT

Stratigraphic and Sedimentologic Setting

Nonmarine rocks of mid-Tertiary age are well exposed and easily accessible at Scotts Bluff National Monument in westernmost Nebraska (Fig. 1). These rocks contain abundant volcaniclastic material, which, together with epiclastic debris shed eastward from the Rocky Mountains, blanketed the surface of the Great Plains (Stanley, 1976; Swinehart et al., 1985). At Scotts Bluff, siltstones of the Brule Formation (White River Group) are unconformably overlain by 27 m of very-fine-grained, horizontally stratified sandstones of the Gering Formation (Arikaree Group) (Fig. 11). Structures interpreted here as vertebrate tracks are restricted to the lower two-thirds of the Gering Formation. The Gering is overlain by about 65 m of large-scale crossbedded to massive sandstones of similar texture (Monroe Creek–Harrison unit, Fig. 11). A volcanic ash bed near the base of the Gering at Scotts Bluff has yielded a radiometric date of 25.6 m.y. (Evernden et al., 1964), placing these basal Arikaree rocks within the Oligocene Series (Harland et al., 1982). Figure 12 shows the location of features described and illustrated in this paper.

At Scotts Bluff, the Gering is horizontally bedded; the only channels observed during this study are a few tens of centimeters deep. Small-scale, steeply dipping cross-lamination (Fig. 13), and planar lamination exhibiting parting lineation, are widespread throughout this stratigraphic interval and are clear evidence of fluvial deposition (Stanley and Fagerstrom, 1974).

Early diagenetic features in fluvial sediments commonly provide important clues to depositional processes and paleoclimate (Collinson, 1978). Rosettes of calcite-cemented sand composed of discoids up to 8 cm in diameter are present at four separate stratigraphic intervals within the Gering (Figs. 11, 14). The morphology of the discoids and rosettes is identical to that of modern gypsum sand crystals described by Cody (1979). After burial, as the gypsum was dissolved by less saline groundwater, replacement of gypsum by calcite was probably facilitated by the commonness of the calcium ion. The thick volcanic ash bed near the middle of the Gering (Fig. 11) and the

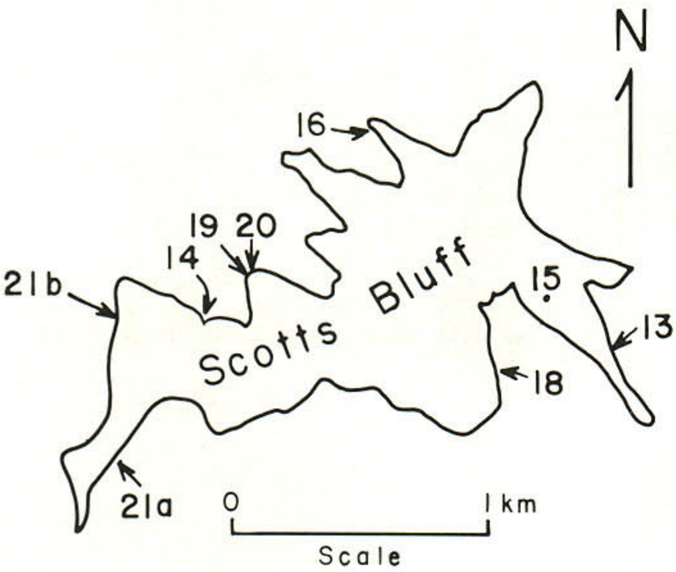

FIGURE 12—Approximate map pattern of contact between Brule Formation (White River Group) and Gering Formation (Arikaree Group); from Scottsbluff South Quadrangle, 4400-foot contour. Numbers show locations of text figures.

uppermost one meter of the Brule Formation contain abundant discoids, 0.4 to 8 cm in diameter, that are composed of calcite spar. Within this finer-grained material, gypsum crystal growth pushed the matrix aside to form relatively pure crystals; after dissolution of gypsum, voids were filled by calcite. Gypsum crystals of similar size and morphology to those recorded in the strata of the study area are today confined to inland and coastal sabkhas, where the groundwater table approaches the land surface and undergoes evaporation (Watson, 1983). According to Watson, such materials are restricted to environments where annual rainfall is less than 200 mm/yr and where there is a monthly excess of evaporation over precipitation throughout the year. Evidence of growth of evaporites within the relatively permeable fluvial sands of the study area strongly suggests that the strata were deposited by ephemeral streams.

FIGURE 13—Subaqueous climbing-ripple deposits and concave-up deformation structures, near middle of Gering Formation. Head of hammer is 18.5 cm long.

FIGURE 14—Calcite-cemented sand, pseudomorphous after gypsum "desert roses," middle part of Gering Formation. Knife handle is 9 cm long.

Several lines of evidence indicate that a portion of the Arikaree Group in eastern Wyoming and western Nebraska accumulated within an eolian dune field (Bart, 1977; Stanley, 1980; Hunt, 1985; Swinehart and Loope, in press). Within the Monroe Creek–Harrison interval at Scotts Bluff, starting at about 10 m above the highest occurrence of tracks, inverse grading and wind-ripple foresets (Hunter, 1977) occur in horizontally bedded sands and within wedge planar crossbed sets up to 1.7 m thick. Where the crossbed sets are overlain by horizontal wind-ripple deposits, the intervening bounding surfaces commonly have an irregular, "corrugated" appearance with local relief up to 10 cm (Fig. 15). Analogous surfaces are common in modern interdune areas where wind erosion has etched moist, wet, or evaporite-cemented, crossbedded dune sands into strong relief (McKee, 1966, pl. VII, c and d; Fryberger et al. 1983, p. 298). Trenches dug in modern interdunes reveal crossbeds with wavy or "corrugated" upper bounding surfaces, overlain by flat-bedded interdune deposits (Fryberger et al., 1983, fig. 23a; Simpson and Loope, 1985). Stanley (1980) has noted that physical and biogenic structures of the mid-Tertiary eolian strata of the Great Plains bear many similarities to those within the Holocene sands in the Nebraska Sand Hills. Traces of invertebrates and plant roots are especially closely analogous, suggesting to Stanley that habitats and climatic conditions were very similar. The absence, however, of vertebrate tracks in the eolian strata of the Arikaree Group—both at Scotts Bluff and at the Bear Creek locality described by Bart (1977)—indicates that, unlike the Holocene

FIGURE 15—Eolian interdune deposits overlying irregular contact with cross-stratified dune sands, Monroe Creek–Harrison interval, summit to museum trail. Differential wind erosion of lightly cemented or damp cross-strata took place in interdune area adjacent to stoss side of dune. No tracks were observed in these eolian strata.

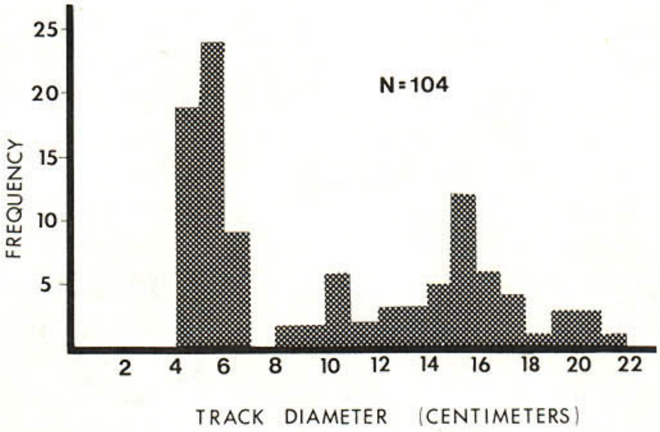

FIGURE 17—Size-frequency data for deformation structures interpreted as tracks in Gering Formation, Scotts Bluff. Note that largest tracks are larger than those of Holocene bison (Fig. 5).

Sand Hills, the mid-Tertiary dune fields either did not harbor a population of large vertebrates, or lacked conditons favorable for the preservation of their tracks.

Description and Interpretation of Tracks

Concave-up deformation structures that closely resemble the Sand Hills (Holocene) bison tracks are common in the Gering Formation (Figs. 13, 16, 19). Deformations in the Gering vary in apparent diameter from 4 to 22 cm (Fig. 17). Because these rocks are poorly indurated, bedding-plane exposures are small. On the undersides of overhanging ledges, however, the circular to oval plan of the deformation structures is easily observed. An extensive search of such exposures revealed several distinct trackways composed of three to five aligned tracks (Fig. 18). In vertical outcrops, isolated, paired, and closely spaced deformation structures are visible. Some of these structures have vertically walled infillings and bilobed lower portions (Fig. 19). As in the Sand Hills, tracks were produced in relatively firm but compactible sand. None of the tracks so far observed suggest that the substrate was "quick" at the time of deformation. According to Simons et al. (1961), horizontally laminated sands deposited during upper-flow-regime conditions are firm relative to sediments deposited by avalanching on the lee side of ripples or dunes. For most tracks, due to uniformity of grain size and to disruption caused by burrowing and evaporite diagenesis, it is difficult to discern whether the parent sediment was originally parallel or cross-laminated. Therefore, no attempt has been made to compare track depth in the two types of strata.

In contrast to the Holocene hoofprints, the Oligocene tracks appear in sediments that also show some evidence of physically induced deformation: convolute lamination appears in some exposures (Fig. 20). In nearly all cases, however, biogenic and

FIGURE 16—Large, closely spaced tracks at the tops of numerous, thin sediment packages, near base of Gering Formation.

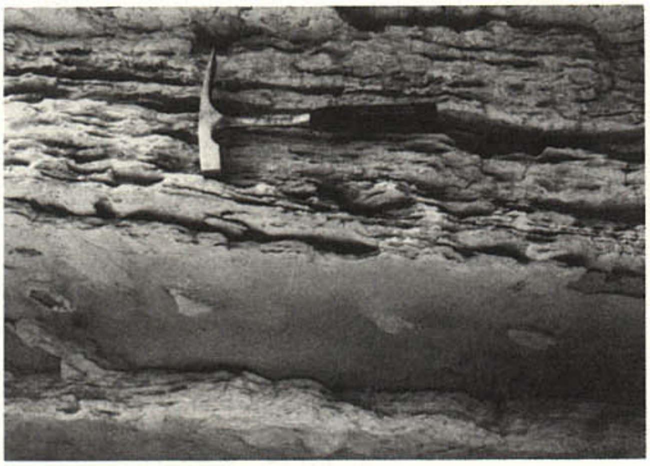

FIGURE 18—Overhanging ledge revealing four aligned, bilobed tracks, middle part of Gering Formation.

FIGURE 19—Cross-sectional view of small, bilobed track made in cohesive sand by small entelodont or camel; middle part of Gering Formation. Coin is 1.9 cm in diameter.

physically induced structures can be confidently differentiated on the basis of scale, continuity, or three-dimensional geometry.

A diverse assemblage of large mammals is known from late Oligocene rocks of the Great Plains. The distinct polymodal nature of the size-frequency distribution (Fig. 17) suggests that the tracks of several species are preserved in the Gering sands. The modern ungulate orders, Perissodactyla and Artiodactyla, first appeared in the Eocene (Romer, 1966). By the late Oligocene, diversification of artiodactyl subgroups was well under way. Representative taxa of six artiodactyl and four perissodactyl families are known in Gering sediments of Wildcat Ridge, southeast of Scotts Bluff (Swisher, 1982). A single fortuitous bedding-plane exposure (Fig. 21a) indicates that at least some of the largest tracks were produced by a two-toed animal. Morphologically similar tracks from Oligocene and Miocene rocks have been described by Robertson and Sternberg (1942), Chaffee (1943), Bjork (1976), and Demathieu et al. (1984). Of the two-toed members of the Gering faunal assemblage, only entelodonts were large enough to make these tracks (R. M. Hunt, personal communication). The small, bilobed tracks (Figs. 18, 19) were probably produced by smaller artiodactyls such as camels.

It is difficult to divide a horizontally bedded sequence composed of very-well-sorted sediment into distinct depositional packages. Traces of invertebrates provide clues in marine sequences (Howard, 1978); tracks of terrestrial vertebrates in the Gering can be utilized in a similar way. The track distribution at Scotts Bluff mirrors that of the Sand Hills: laterally scattered tracks are typically seen at closely spaced vertical intervals. If tracks are assumed to mark boundaries between depositional events, the distribution of tracks indicates that streamfloods deposited packages of strata between a few centimeters to over three meters in thickness. Thoroughly trampled horizons (Fig. 16), as might be expected along diastems, are relatively rare. Why are the tracks that mark the tops of sediment packages so widely spaced? One possibility is that time intervals between depositional events were very brief (Laporte and Behrensmeyer, 1980, fig. 4a). Another is that the population density of large vertebrates was very low. A third possibility is that evaporitic surface crusts formed after each pulse of sedimentation. Early evaporite diagenesis may have quickly made the sandy substrate less compactible and thus unsuitable for preservation of tracks. If this was the case, only a very small percentage of the vertebrate activity that occurred here may be recorded by the tracks. The preservation potential of tracks or other surficial traces in sandy fluvial sequences would seem to be quite low because of their vulnerability to scour. Early evaporite cementation may partially explain both the preservation of tracks and, conversely, the rarity and small scale of channels in these ancient fluvial strata.

CONCLUSIONS

1. Holocene eolian and Oligocene fluvial sediments of Nebraska contain abundant tracks of large vertebrates. The most

FIGURE 20—Convolute lamination (nonbiogenic), middle part of Gering Formation. Note consistent asymmetry of folds.

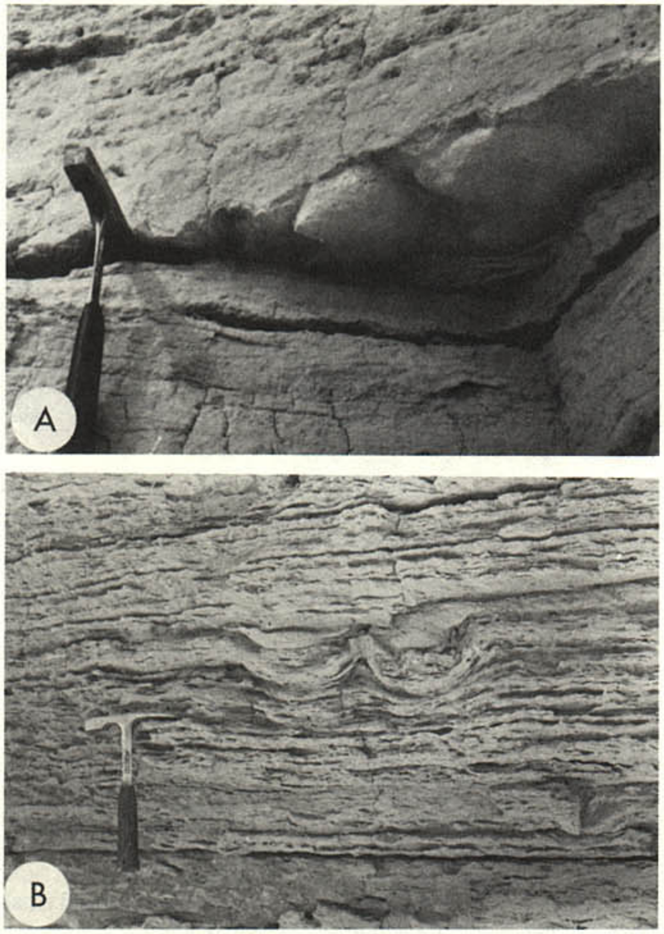

FIGURE 21—Tracks of large entelodonts. A) Small, overhanging ledge revealing two large tracks (12 and 16 cm in length). Both tracks are cloven in front; large track was made by front foot. B) Cross section of asymmetric pair of tracks. Deeper track on right probably made by front foot. Middle part of Gering Formation.

obvious manifestation of the tracks is the downwarping of laminae seen in vertical section.

2. Although tracks may superficially resemble nonbiogenic soft-sediment deformation structures, their isolation along bedding planes, circular to oval plan, and restricted size distribution aid in their recognition. Convolute bedding of physical origin is generally restricted to initially porous, rapidly deposited sediments.
3. Tracks within Holocene strata of the Sand Hills were made in clay-coated sands deposited by migrating wind ripples. Resident bison that were sustained by food and water resources made the tracks while the dune field was active.
4. Oligocene rocks at Scotts Bluff are preserved at the tops of thin packages of fluvial deposits. Abundant evidence of evaporite precipitation suggests deposition by ephemeral streams. Size-frequency plots indicate that tracks were made by several different types of ungulates; entelodonts produced the largest tracks. Cementation by evaporites may have enhanced the preservation potential of individual tracks by preventing scour and intense trampling.

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