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Life and death in a Late Cretaceous dune field, Nemegt basin, Mongolia

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ABSTRACT

For more than 70 years, red sandstones of the Gobi Desert have yielded abundant articulated skeletons of Late Cretaceous dinosaurs, lizards, and mammals. At Ukhaa Tolgod, structureless sandstones are the only fossiliferous facies, and we present new evidence for deposition on dune-sand–sourced alluvial fans that were built at the margins of stabilized eolian bedforms during mesic climatic episodes. In laterally and vertically adjacent large-scale eolian cross-strata in which skeletons are absent, we have found abundant tracks of dinosaurs that walked on sparsely vegetated dunes that were active under xeric conditions. Our study of calcareous concretions in vaguely bedded eolian sandstones suggests that bedding was nearly destroyed by burrowing invertebrates and trampling dinosaurs. The accumulation of illuvial clays and pedogenic calcite in these sediments reduced infiltration of rainwater and, with attendant climatic change and heavy rainfall events, led to fan development.

INTRODUCTION

In the 1920s, expeditions from the American Museum of Natural History led by Roy Chapman Andrews and Walter Granger discovered a rich assemblage of Late Cretaceous vertebrate fossils in Mongolia's Gobi Desert at Bayn Dzak (Flaming Cliffs). These fossils from red sandstones of the Djadokhta Formation included the first well-documented dinosaur nests with eggs, the first known skeletons of *Protoceratops* and *Velociraptor*, and well-preserved skulls of Late Cretaceous mammals (Simpson, 1925; Andrews, 1932). In the 1960s, field crews from Poland and Mongolia discovered more rich Late Cretaceous fossil localities in the Barun Goyot Formation of the Nemegt basin to the southwest of Bayn Dzak (Kielan-Jaworowska, 1974).

In 1993, 70 years after Andrews's Central Asiatic Expedition, members of the American Museum of Natural History–Mongolian Academy of Sciences Expedition discovered a new fossil locality in the Nemegt basin—Ukhaa Tolgod (Dashzeveg et al., 1995) (Fig. 1). This locality has yielded an unmatched abundance of well-preserved vertebrate fossils, including the highest concentration of mammalian skulls and skeletons from any Mesozoic site. More than 100 skeletons of theropod, ankylosaurian, and protoceratopsian dinosaurs have been identified, including several specimens of the new Late Cretaceous bird *Mononykus*, and the first known embryo of a theropod. More than 500 skulls (many with associated skeletons) of mammals, lizards, and dinosaurs have been identified.

Large-scale cross-strata of the Djadokhta Formation have been interpreted by earlier workers as eolian. Evidence reported here strengthens that interpretation. Although previous workers have emphasized the importance of violent windstorms to preservation of articulated dinosaur skeletons in the Djadokhta Formation, we interpret the highly fossiliferous rocks at Ukhaa Tolgod as noneolian. We recognize three sandstone facies in the study area. Two are eolian and accumulated during migration of large bedforms; both are unfossiliferous. The third facies, which is highly fossiliferous, represents alluvial fans that buried dune slopes during mesic intervals.

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STRATIGRAPHIC SETTING

The Djadokhta Formation is a sequence of nonmarine red sandstones, siltstones, and conglomerates of late Campanian–early Maastrichtian age (Lillegraven and McKenna, 1986). Strata at Ukhaa Tolgod are dominated by sandstone; some sandstone bodies contain conglomeratic lenses or isolated pebbles and cobbles (Fig. 2); siltstones are very thin and laterally restricted.

EOLIAN FACIES

Large-Scale Cross-Stratified Sandstone with Fine Structure (Facies E-1)

Description. This facies contains thin, distinct laminae that are inverse graded and consistently dip 25° to the northeast (Fig. 3a). Single sets of distinct cross-strata reach about 12 m in thickness (Fig. 2). Small-diameter burrows (4–10 mm) and rhizoliths (less than 2 mm) are present within these cross-strata. Concave-up folds that are circular to oval in plan and range from 10 to 50 cm in diameter are common along certain cross-

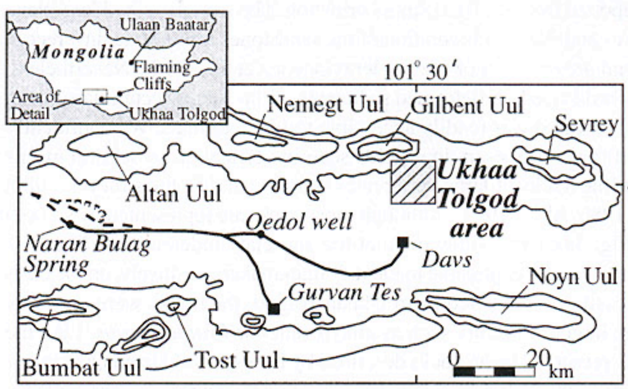

Figure 1. Map showing location of Ukhaa Tolgod and the Nemegt basin, Mongolia.

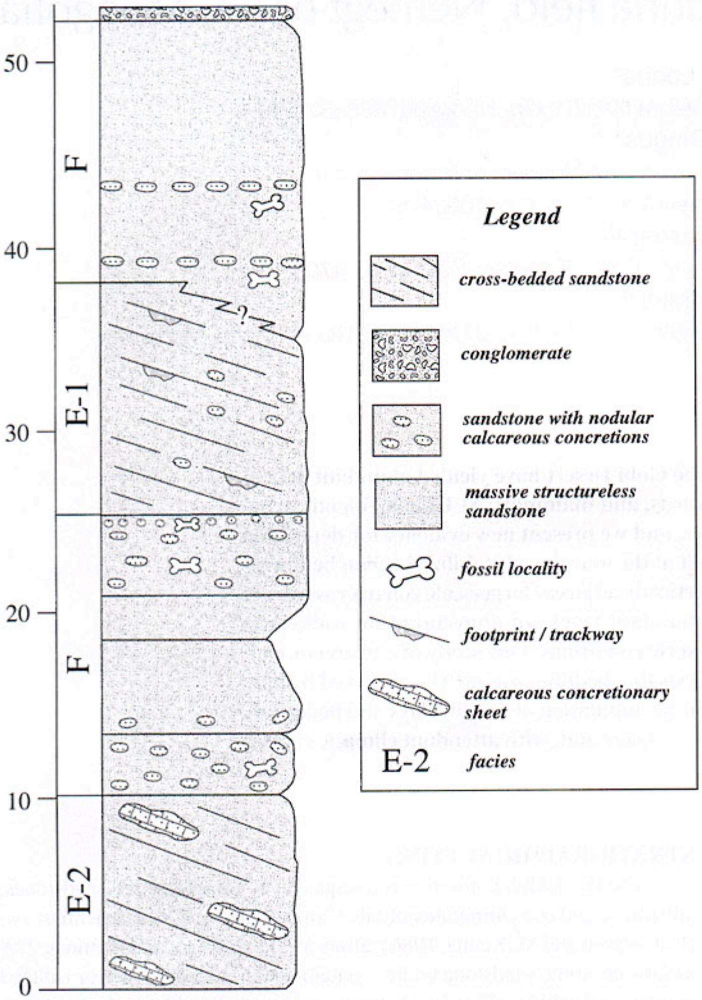

Figure 2. Composite stratigraphic section of rocks exposed at Ukhaa Tolgod. Vertical scale is in meters.

strata (Fig. 3b). Sharp contacts separate the folded from the overlying, unfolded strata, and coarse-grained sediment typically fills the central shaft at the core of each fold.

Interpretation. Large-scale cross-strata in the Late Cretaceous red beds of the Gobi were interpreted as eolian by Gradzinski and Jerzykiewicz (1974), Jerzykiewicz et al. (1993), Eberth (1993), and Fastovsky et al. (1997), and we concur with their interpretation.

Despite abundant fossil skeletons, dinosaur tracks have not been previously reported from the Djadokhta Formation. The scarcity of bedding-plane exposures and the poor induration of the sandstones mitigate against recognition and preservation of tracks (Jerzykiewicz et al., 1993). Nevertheless, the thin-bedded, easily deformed sediments of this facies accumulated in an environment that was readily accessible to large animals. We confidently interpret the concave-up downfolds seen in vertical cross-section in this facies as the tracks of large vertebrates (Laporte and Behrensmeyer, 1980; Loope, 1986; Allen, 1989). Although most tracks are represented by smooth folds (Fig. 3a), some show distinct toe and claw indentations (Fig. 3b). Although it is not yet possible to identify trackmakers positively, on the basis of the fossil taxa collected from Ukhaa Tolgod, the tracks were probably made by larger dinosaurs such as ankylosaurs or *Protoceratops*. Like the similarly preserved bison tracks described by Loope (1986) from Quaternary sediments of the Nebraska Sand Hills, these tracks represent clear evidence that large animals were present while large dunes were actively migrating. Although tracks appear to be equally common from top to bottom of individual foresets, they are preferentially developed along distinct foresets, and may mark diastems between packages of rapidly accreted strata.

By making direct observations during sand storms within the dune fields of coastal Oregon, Hunter (1977) demonstrated that distinct laminae and beds are produced during the migration of eolian dunes and ripples. Deposits of the extensive Mesozoic and Paleozoic sand seas of the western United States (Kocurek, 1988) are clearly composed of the characteristic bedding types described by Hunter (1977). Primarily on the basis of taphonomic evidence, numerous authors have interpreted structureless Djadokhta sandstones (discussed below) as products of violent sandstorms. On the basis of physical (not taphonomic) evidence preserved within the Djadokhta Formation, however, we feel that the distinctly cross-stratified facies (E-1) contains by far the clearest evidence for violent storm deposition.

Vaguely Bedded Sandstone with Oriented Concretionary Sheets (Facies E-2)

Description. Fine to coarse sand nearly devoid of visible depositional structures is cemented by tabular calcareous concretions that are 5 to 10 cm thick and dip 25° to the northeast (Fig. 3c)—parallel to the cross-strata of the distinctly cross-stratified facies. In weathered horizontal exposures, the concretions weather into strong relief, defining straight to gently arcing ridges. The concretions delineate "sets" analogous to those of cross-strata that are typically in excess of 10 m thick; the thickest set we measured, the base of which was not exposed, is 24.5 m thick.

Reddish-yellow (5 YR 6/6), uncemented sand fills abundant simple, nonmeniscate burrows that cut lighter-colored (7.5 YR 7/4) concretions (Fig. 3d). In thin section, burrow margins are sharp, and calcite ranges from micrite to spar. Sand grains bear thin, often incomplete clay coats that are thickest in depressions on the grain surfaces.

Interpretation. Similarities in the texture and scale between the vague cross-strata of this facies and those of the fine-structured facies (E-1) allow confident interpretation of facies E-2 as eolian dune deposits.

Origin of Sediment Fabric. Although facies E-2 is nearly devoid of visible depositional structures, the postdepositional development of the concretionary sheets indicates preservation of a slope-parallel sedimentary fabric. Even though invertebrate burrows that were emplaced relatively deep in the sediment are present in great abundance (see following), the retention of the crude fabric element that repeats at 10–15 cm intervals suggests that the sediments were not deeply "stirred." Trampling by dinosaurs could have sufficiently mixed the surface sediment to a depth of 10 to 15 cm, thereby preventing preservation of physical structures, but allowing the grain-size differences between different depositional packages to be retained. Although our "dinoturbation" (Lockley and Gillette, 1989) hypothesis for facies E-2 is speculative, it is consistent with the facts that dinosaur tracks are common in facies E-1 and abundant, untransported dinosaur skeletons are present in facies F.

Clay Coatings and Concretions. The orientation of the clay that coats sand grains (parallel to grain surfaces), the presence of clay at grain contacts, the tendency of the clay coats to thicken over embayments in sand grains, and the absence of meniscus bridges between grains indicate that most of the clays within and adjacent to the concretions are inherited clay rims (Wilson, 1992). Thus the clays were deposited on the grains prior to their arrival at the site of deposition. Such clays record reworking of grains that were coated by infiltration of clay-charged water and are common in Quaternary dune sands. Although post-illuvial burrowing could have destroyed any meniscus bridges produced by in situ clay accumulation, the absence of these bridges in the burrow fills of the concretions suggests that this process was not volumetrically important at the depth of concretion development.

Eberth (1993) demonstrated that pedogenic calcite is widespread in structureless sandstones of the Djadokhta Formation, but interpreted the calcite cement of cross-stratal toesets as ground-water calcrete. In contrast, the burrows that cut the sheet-like calcareous concretions of facies E-2 clearly postdate the onset of carbonate accumulation. The crosscutting burrows, the

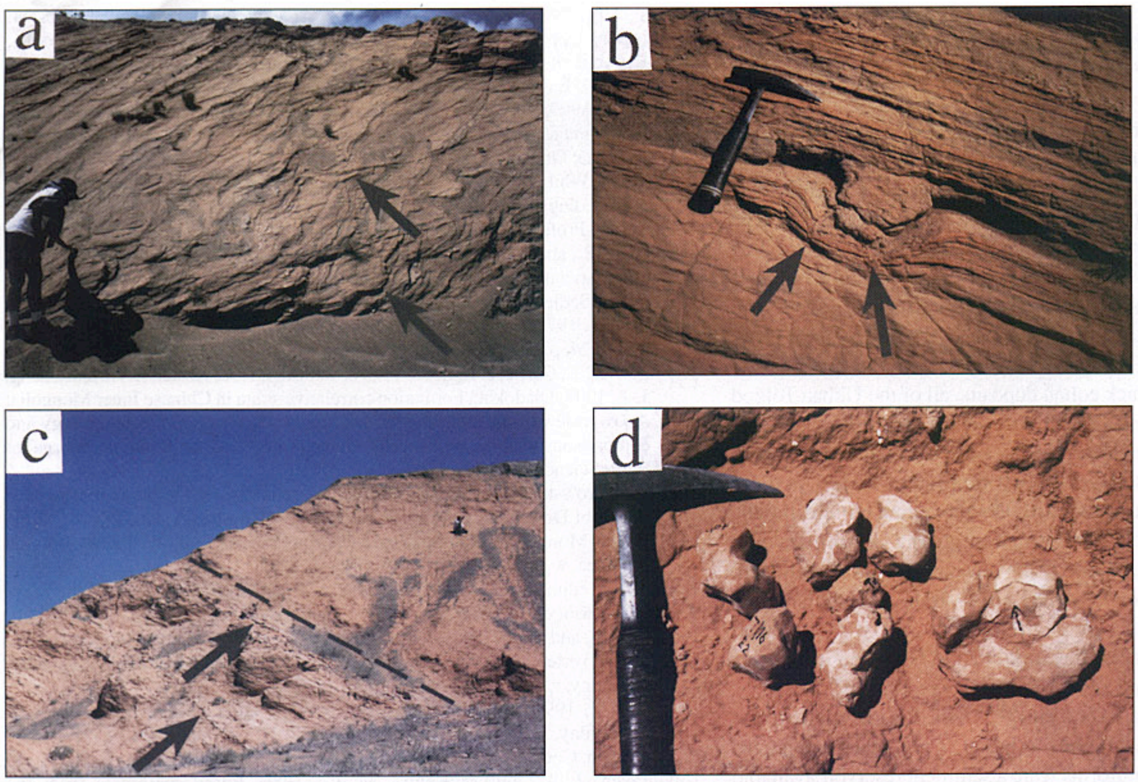

Figure 3. a: Cross-stratified eolian sandstone with preserved fine structure (facies E-1). Note smooth folds (marked by arrows) interpreted to be dinosaur tracks. b: Close-up of fold interpreted to be dinosaur track. Cross-strata dip 25 degrees; track is 4 m above base of set. Note claw marks (arrows). c: Contact (dashed line) between vaguely bedded facies E-2 on left (arrows show tabular calcareous concretions) and structureless alluvial fan facies on right (man sits at position of fossil mammal skeleton). Exposed thickness of cross-strata on left is 24 m. d: Fragments of tabular calcareous concretion from vaguely bedded eolian facies (E-2) that have been scraped with knife to reveal uncemented burrow fills.

location of concretions within sediments deposited high on the slopes of large bedforms (far above the water table), and the fine grain size of the calcite indicate that concretion development started within the vadose zone.

The abundance of biogenic structures and grain-rimming clays, and the presence of pedogenic calcite indicate that the large eolian bedforms upon which these sands accumulated were immobile for long periods of time. When they were mobile, their migration rate was very slow. In comparison, in the late Quaternary Nebraska Sand Hills, where dunes have been stabilized by vegetation for at least several hundred years, sands are coated by infiltrated clays, but no calcium carbonate has accumulated (Lewis, 1990).

ALLUVIAL FAN FACIES

Structureless Sandstones Lacking Oriented Concretions (Facies F)

Description. The third sandstone facies, unlike the two previously described, lacks physical sedimentary structures and any indicators of a preserved slope-parallel fabric. Isolated or lenticular deposits of granules, pebbles, and cobbles are present in some sand bodies. This facies contains all the fossils at Ukhaa Tolgod. Skeletons of *Oviraptor* preserved on nests of well-arranged eggs, along with perfectly articulated skeletons of tiny mammals and lizards (e.g., Dashzeveg et al., 1995, Fig. 3), are present. At one locality, a 20-m-thick body of well-sorted sandstones of facies F abuts the depositional pinchout of eolian cross-strata of facies E-2 that dip at 25° and are at least 24 m thick (Fig. 3c). At other localities, the upper surfaces of pebble-free sandstone bodies of facies F dip 5°–15° to the northeast and are downlapped by the steeper-dipping eolian cross-strata of facies E-1.

Interpretation. Perfect articulation of small lizard and mammal skeletons in this facies strongly suggests that its structureless nature is depositional and is not the result of bioturbation. Primarily on the basis of the lack of depositional structures and the stratal relationships with eolian facies E-1 and E-2, we interpret the pebble-free rocks of this facies as the deposits of dune-sourced alluvial fans similar to those described from stabilized Quaternary dune fields in the Sahel of Africa and the Great Plains of North America (Talbot and Williams, 1978, 1979; Ahlbrandt and Fryberger, 1981). Climate change and the attendant accumulation of clay and calcite in the dune deposits led to mass movements that gullied dune slopes and built fans. Smaller fans were buried when dunes were reactivated. Although the depositional products and processes on the fans of Quaternary dune fields have not yet been thoroughly studied, we hypothesize that rapid vertical accretion of structureless sand and accompanying in situ burial of large animals is much more likely to occur on sand fans during rain storms within a stabilized dune field than during wind storms in an active dune field.

The pebbles and cobbles within some of the sand bodies of this facies were clearly derived from beyond the margins of the dune field. The conglomerate at the top of the section (Fig. 2) indicates that the dunes at Ukhaa Tolgod were adjacent to a tectonic highland; large clasts in the structureless sandstone were transported into the dune field by sediment gravity flows originating in the highland.

DISCUSSION

In his discussion of stabilized dunes and their possible geologic record, Talbot (1985) called attention to Quaternary cycles of dune mobility and stabilization, arguing that "it is easier to imagine that the dinosaurs of southern Mongolia were hatching and raising their young in a moist, stabilized dune field rather than an active sand sea." Our observations on the clay-coated sand grains, pedogenic calcite, bioturbation, and lateral relationships between the dune and fan facies lead us to agree with Talbot's (1985) insightful suggestion.

Many workers have suggested the possibility that dinosaurs may have been buried alive during violent sand storms (see Fastovsky et al., 1997), but we have found no new evidence at Ukhaa Tolgod that supports this assertion. Although the travel literature of Central Asia and Arabia commonly cites heat, cold, and drought as causing mass mortality, Finch et al. (1972) found no reports of the smothering of animals in the many vivid descriptions of desert duststorms and sandstorms. Although they contain abundant signs of life, the eolian facies (E-1 and E-2) are devoid of skeletal remains. If stratal geometry and taphonomic evidence were not considered, the structureless sandstones of facies F might be interpreted as eolian sediment that accumulated slowly enough that bioturbation kept pace with deposition.

The articulated skeletons are clear evidence of rapid deposition. The absence of skeletons in the eolian strata that show the clearest evidence of rapid emplacement (facies E-1) is inconsistent with the "sandstorm" hypothesis for fossilization.

Widespread vertical accretion of the desert floor by saltating sand moving over wind ripples or zibars (Eberth, 1993) would be much slower than the localized deposition that takes place on the lee face of a dune because dunes trap a high percentage of the sand that is in transport. The smaller the dune, the faster it migrates. Bagnold (1941, p. 217) calculated that the smallest dunes (about 40 cm high) migrate only about 67 cm per hour under a wind of 13.5 m/s (30 miles per hour). Most animals would seem capable of avoiding burial by such a process. There are other problems: (1) Although migrating bedforms may provide by far the quickest mechanism for deposition of thick eolian deposits, all of the Ukhaa Tolgod fossils are found in structureless—not crossbedded—sandstones. (2) Fossils are found in sandstones containing pebbles and abundant coarse sand. Bagnold's estimates were based on dunes composed of fine to medium sand; bedforms composed of coarser materials move much more slowly. (3) The carcasses of animals buried by small migrating bedforms would soon become exposed on the stoss side of the dune as migration continued. Because the thickness of preserved eolian cross-strata represents only a small percentage of the height of the migrating bedforms, if small eolian bedforms leave behind a depositional record at all, it is in the form of sets less than 15 cm thick (Loope and Simpson, 1994, Figs. 3 and 4).

Our alluvial fan interpretation of facies F provides an alternative to the "sandstorm" (eolian) hypothesis for in situ burial of articulated skeletons. The high, sparsely vegetated landforms were a sediment reservoir available for episodic gravity flows, capable of quickly burying intact, unscavenged skeletons, and, possibly, live animals.

CONCLUSIONS

Dinosaurs entombed in sandstones of the Djadokhta Formation of the Nemegt basin, Mongolia, lived in both active and stabilized dune fields. Their tracks are visible in large-scale cross-stratified eolian rocks, and their skeletons are found in dune-margin alluvial fan sediments. Fans were active during mesic intervals when dunes were stabilized; tracks were preserved under xeric conditions in the deposits of rapidly migrating dunes.

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