Title: **Death in the Dunes.**

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Author(s): Dingus, Lowell; Loope, David

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Abstract: Examines the cause of extinction of ancient animals fossilized in sandstones of the Gobi desert in Mongolia. Fossils found in Ukhaa Tolgod; Factors that argue against sandstorms in explaining the burial of Gobi animals; Effect of rains on sands; Climate of the Gobi desert during the Cretaceous period.

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Section: PALEONTOLOGY

DEATH IN THE DUNES

What killed the famous fossil creatures of the ancient Gobi? Geologists examine the rock-hard evidence.

A desert covering some half a million square miles, the Gobi arcs across vast portions, of Mongolia and China. Every summer since 1990, a joint expedition from the American Museum of Natural History and the Mongolian Academy of Sciences has ventured into the remote reaches of the Gobi of Mongolia in search of fossils. The land, which appears so desolate, is actually a paleontological paradise, and our discoveries of new and varied fossil animals in the region's rocks have been widely chronicled. But why, in this desert, is such an array of ancient animals coming to light? How is it that so many animals perished and are so finely preserved here? What was the ancient environment like, and how did the creatures die? We are finding answers not only in the fossil bones but also in the rusty red sandstones that contain them.

At Ukhaa Tolgod, a single small site discovered in 1993, expedition members have unearthed more than one thousand fossils of twenty species of mammals and reptiles. These date from the end of the Cretaceous and are from 71 million to 75 million years old. Ukhaa Tolgod contains the richest assemblage of fossil vertebrates of this age known anywhere in the world. Many specimens are of previously unknown species, and some have bridged gaps in our knowledge of the evolution of birds and mammals. What's more, the bones are in excellent condition. Skeletons range from twelve-foot remains of the armored dinosaurs known as ankylosaurs, with almost every piece of bony plate intact, to two-inch skeletons of early mammals, complete down to their fragile, microscopic ear bones. Dinosaur nests, eggs, and embryos have also been preserved. Some of the animals have been captured not in death throes but in the ordinary (although last) acts of their lives--such as the theropod dinosaur Oviraptor sitting on its clutch of eggs.

The unusual fidelity of fossil preservation and the articulation of the bones--they were not jumbled by scavengers or scattered by the elements--indicate that many of the animals at Ukhaa Tolgod were killed quickly and buried quickly in a catastrophic event. In addition to identifying the creatures and their attributes and relationships, we wanted to know what was responsible for the mass mortality and swift burial. To find out, we

needed to examine the rocks, because they hold the clues to the area's ancient environment.

Today the Mongolian Gobi is a land of windswept basins and rugged ranges ("Gobi" is Mongolian for "waterless place"). Sand dunes, shaped and moved slowly by the wind, migrate across the valleys. Violent sandstorms and thunderstorms occasionally interrupt our hikes across the sparsely vegetated ridges and ravines in search of bones exposed by erosion. A sandstorm can instantly, send a tent careening across the landscape. The only way to avoid being sandblasted by windblown grit is to run for the cover of our expedition's trucks and jeeps.

Some of the sandstones at Ukhaa Tolgod represent the solidified remnants of ancient sand dunes and have a distinct structure of thin, inclined layers, called cross beds. Similar layering is apparent today in dunes in the Gobi and other sandy deserts. It comes about when sand grains, blown by strong winds, bounce up the gently sloping windward side of a dune and then tumble down the steep leeward side. Over time, the dune will migrate in the direction of the wind. At Ukhaa Tolgod, the cross-bedded rocks consistently lean about 25 Degrees toward the northeast. This indicates that during the late Cretaceous, the dunes here migrated in that direction, driven by winds from the southwest.

The cross-bedded sandstones and the natural mobility of dunes have led to a popular hypothesis that the fossil animals of the Gobi were killed by violent sandstorms. At first, this is an appealing idea. But we have searched the travel literature and have found no modern analogies, no descriptions of animals being buried alive by drifting sand during such storms in the deserts of either central Asia or Arabia. Whether ancient or modern, no healthy animal is likely to let itself be inundated by sand to the point of suffocation. Furthermore (and contrary to popular belief), deserts in continental interiors, such as the modern and the ancient Gobi, are much less windy than those in humid coastal areas. Along a sandy coast, the frequent passage of atmospheric fronts and the differences between land and sea temperatures lead to more wind and more active dunes. In addition, many geologists view the Cretaceous as a "greenhouse" period in Earth's history, when, even in high-latitude continental interiors, winter temperatures remained above freezing, reducing air pressure gradients and windiness. This view is based on fossil evidence of crocodiles from the Gobi. All these factors argue against sandstorms as an explanation for the burial of the Gobi animals, but we have found that the structure of the rocks at Ukhaa Tolgod makes an even more compelling case against this cause of death.

None of the fossil bones from this site were collected from the layered sandstones generated by Cretaceous dunes. In rare instances, within a layer of cross-bedded sandstone we have found deformations that resemble a stack of bowls in cross section and that record footprints--complete with toe and claw impressions--of dinosaurs that had trekked across the dune field. But these layers contain no bones. All the skeletons we have excavated come from a second type of sandstone: massive, structureless slabs that contain none of the internal layers typical of dunes. When we looked closely at these, we saw that some contained large, isolated pebbles too big to have been wafted into the deposit by wind. We needed to find a different agent to account for these structureless sandstones.

To complement our work in Mongolia, we have been studying a modern site half a world away. Nebraska's Sand Hills give us a modern analogue of how the Gobi 'sandstones may have formed. A large, relatively young dune field in the western part of the state, the Sand Hills rise as high as 400 feet and are stabilized by vegetation. In early summer during wet years, the grass-covered landscape looks more like Ireland than Arabia. As with the layered sandstones at Ukhaa Tolgod, the leeward sides of the Nebraska dunes slope 25 ° to 30 °. Most of the rain falling in the Sand Hills infiltrates the permeable sediments, seeps downward, and slowly leaves the groundwater reservoir through springs. Heavy rains during summer thunderstorms, however, can trigger sudden avalanches of wet sand, called debris flows. One rancher showed us a photo of his pickup half-buried in sand during a cloudburst. Other residents tell of their calving sheds--built on the leeward sides of big dunes for protection from the wind--being rapidly filled by slurries of sand. In other parts of the world, such debris flows carry large pebbles that "float" in the sand as it moves, as did those at Ukhaa Tolgod.

Are the conditions that generate the Nebraska debris flows closely analogous to forces that acted on the Gobi dunes 75 million years ago? Did rain-soaked sand act like wet cement to trap the denizens of Ukhaa Tolgod? While Nebraska debris flows can deliver a slab of heavy, wet sand up to 900 feet long, 4 feet thick, and 50 feet wide, they are not likely to annihilate larger animals in their path. We have never encountered a farmer who has lost a cow to such an event. And because the Sand Hills lie northwest of the route taken by most of the tropical storms that could soak the dunes, rainfall of more than an inch an hour over several hours is rare. Any similar

sand slide in the Gobi would have had to be on a much larger scale to have caused the demise and fossilization of the animals there.

Based on the cross beds' thickness, which represents only a fraction of the height of an original dune, estimates for the heights of the Gobi dunes during the Cretaceous range from a probable 300 feet to possibly more than 800 feet. We also know that in the late Cretaceous, mountains rimmed Mongolia's basins to the west of the Pacific Ocean, which was then quite warm. The ancient dune fields of the Gobi were most likely subject to occasional drenchings whose magnitude would dwarf any that hit western Nebraska today.

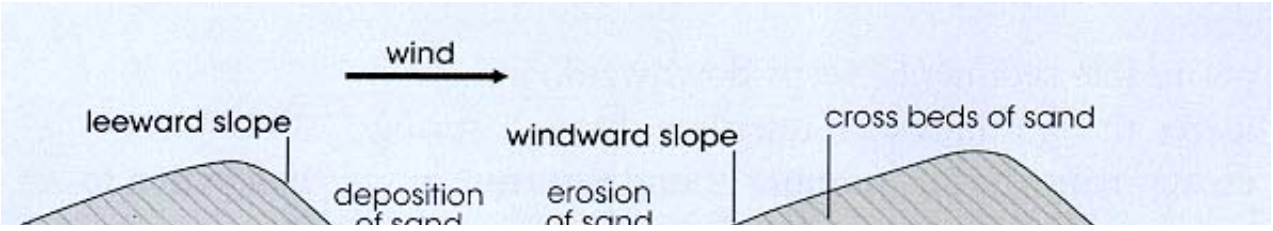
More evidence of wet periods comes from the Flaming Cliffs, another of Mongolia's rich fossil sites. Here the expedition discovered near-vertical, mud-filled burrows less than one inch in diameter but reaching nine feet in length. The burrows were probably made by creatures with life cycles similar to those of modern crayfish. These animals thrive during rainy periods, but during droughts, they excavate burrows to reach the water table and escape death from desiccation. The expedition team found branches off the main tunnels, indicating that the animals repeatedly dug themselves out after muddy floods had clogged their burrows. More clues to climate came from discontinuous mudstone layers, representing ephemeral ponds between dunes, and from the fossilized roots of dune plants.

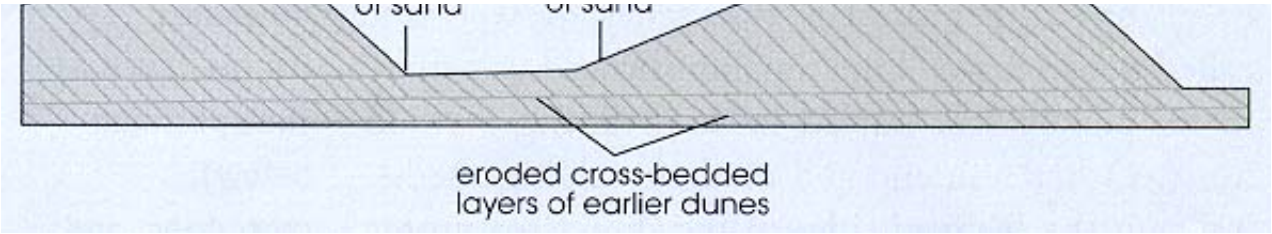
In 1996 we found evidence that the huge dunes at Ukhaa Tolgod migrated only intermittently. Beneath the dune slopes we detected thin bands of sand grains cemented together by calcium carbonate. Such bands, called caliche, form two to three feet below the sediment surface and become cemented only after hundreds to thousands of years of dune stability in a low-wind setting.

Not until 1998 did we realize that the caliche might help us interpret how the fossils were preserved. Because it blocked the infiltration of rainwater through the dune during heavy rainstorms, the caliche caused a steeply sloping slab of wet sand to build up above it, setting the scene for giant debris flows. The recent devastating debris flows (of mud rather than sand) on the mountain slopes of coastal California and in Central America were triggered when heavy rains infiltrated the soil but were then blocked by bedrock. The saturated soil was "lifted" by the water between sediment grains, decreasing the friction between the soil and the bedrock. Under dry conditions, such friction stabilizes the slopes, but the heavy rains undermined their stability and led to deadly cascades of mud. In the Gobi, similarly weighty, water-saturated sand above the cemented caliche zone would have broken loose and quickly moved down the long dune slope, entombing any nesting Oviraptor, foraging ankylosaur, or small scurrying lizard or mammal in its path. In the process, the slide ensured the preservation of their remains.

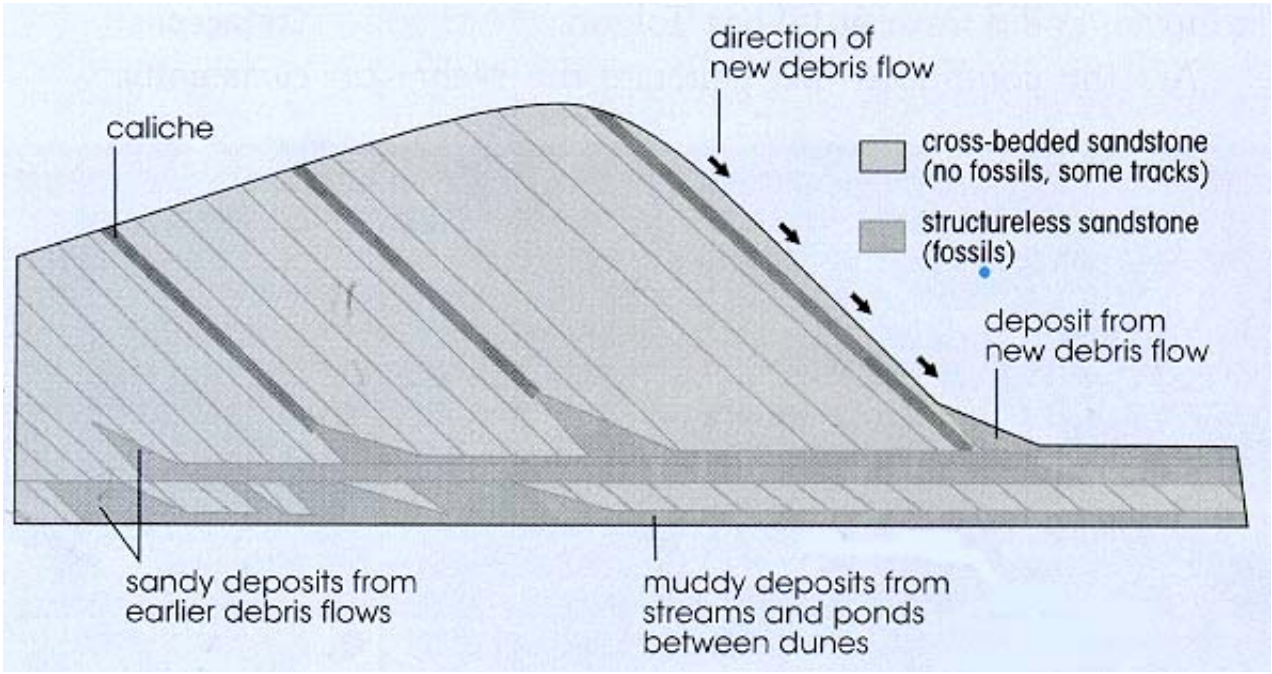
The two types of sandstone formations at Ukhaa Tolgod probably represent two distinct climatic regimes that prevailed there at different times. During the late Cretaceous, the Gobi's climate was not always hostile. Long periods of aridity were interrupted by warm, wet--or at least semiarid--intervals that lasted from thousands to perhaps tens of thousands of years.

The cross-bedded sandstones represent dunes from the dry intervals, when plant and animal life was less abundant. They give us a picture of a dry desert subject to sandstorms, with moving dunes that, in rare cases, captured the footprints of larger animals traversing them but that contain no bones. By contrast, the large, structureless, fossil-rich sandstones were formed by debris flows from huge, nonmigrating dunes. When atmospheric circulation changed, bringing rain from the warm Pacific, vegetation grew upon and anchored the dunes, and caliche cemented the sand just below their surfaces. The animal community was full and varied. The plants supported a variety of large and small herbivores that in turn were prey for carnivores and scavengers. To fully explain the presence of the Gobi fossils, all the key elements--large, steep dunes, heavy rainfall, caliche, and abundant animal life--had to coincide in time and space. Some 75 million years ago in the Gobi, they did just that--and left us a rare treasury of fossils.





During intervals when the climate of the ancient Gobi was dry, dunes migrated in the direction of the wind.

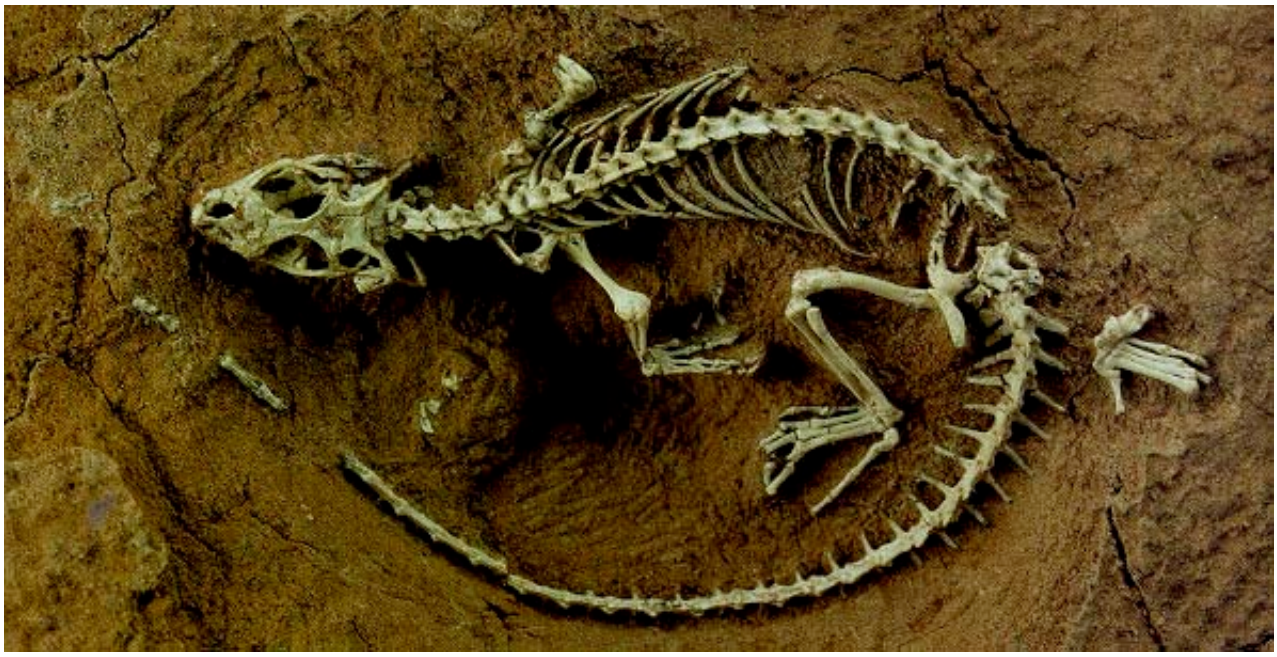


During less arid intervals, lasting hundreds to thousands of years, dunes were held in place by vegetation, and layers of cementlike caliche formed under their leeward slopes.

FIGHTING DINOSAURS: NEW DISCOVERIES FROM MONGOLIA, an exhibit of fossil animals from the Gobi, is on view through October 29 at the American Museum of Natural History.

Ukhaa Tolgod, right, is the world's richest site of late Cretaceous vertebrates...

...such as the juvenile Protoceratops above.



In addition to dinosaurs, lizards (such as the specimen below), crocodiles, and early mammals were part of the Gobi's Cretaceous community.

S (COLOR): Nebraska's Sand Hills, left, are dunes stabilized by vegetation. Their verdancy masks a sandy interior. Above: At Ukhaa Tolgod, layered rock sits atop the structureless sandstone formed by an ancient sandslide.

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By Lowell Dingus and David Loope

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