TRACKING AN

The case was cold—the bones in the mass grave were 70 million years old. But critical clues pointed to the killer's identity

By Raymond R. Rogers and David W. Krause

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LARGE MEAT-EATING DINOSAUR *Majungatholus atopus* (*above*) met an untimely end some 70 million years ago in what is now northwestern Madagascar (*opposite page, top*). Members of the authors' team carefully excavated the remains, including a jaw with serrated teeth used to slice through flesh (*right*), and packed them in plaster for transport to the U.S. (*opposite page, bottom*), where the researchers studied the fossils in detail for clues to the cause of death.

ANCIENT KILLER

One body rests on its left side, head and neck pulled back toward the pelvis—a classic death pose. The arms and legs are still in their anatomically correct positions, but closer inspection reveals that bones of the hands and feet are dislocated, although most parts are present and accounted for. The skull, too, is somewhat disjointed, and here again the component pieces lie near one another. Curiously, the tip of the tail is missing altogether. Nearby rest more corpses in markedly different states of preservation and disarray. Some are still largely intact, others represented by only a skull, a shoulder blade, a single limb bone. Did the unfortunate creatures die here, or were they brought together after their demise? Did they all perish at the same instant, or did their deaths transpire over time? And what killed them?

Our team of Malagasy and American paleontologists and geologists started asking such questions as soon as we discovered the mass grave in the summer of 2005 in the ancient sediments of northwestern Madagascar, an island whose Venetian-red soils

COLD CASE

inspired its nickname, the Great Red Island. We turned up some intriguing information as we searched for the answers, but how we went about the task is perhaps as interesting as what we found.

Before doing anything, we named the site, designating it MAD05-42 to indicate the year it was found and its sequence in the discovery of fossil localities in this area. The second task was identifying the dead, and based on our discoveries elsewhere in the region, we quickly discerned that most of the remains were dinosaurs of various species.

This dinosaur burial ground is not unique for northwestern Madagascar. It matches a pattern we have seen repeatedly over a decade of geologic investigation in the semiarid grasslands near the remote village of Berivotra. There we have uncovered layer on layer of mass death, with the remains of animals big and small, young and old, entombed together in spectacular bonebeds. And so as we worked to uncover what killed the animals in MAD05-42, we also could not help but wonder why we find so many bonebeds here and why they are so beautifully preserved.

Opening a Very Cold Case

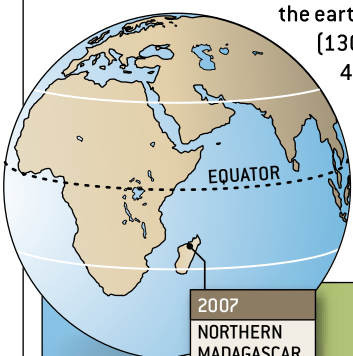
WE WERE MILLIONS OF YEARS too late to use most of the tools of modern-day coroners. To tease out the clues hidden in the bones and rock, we had to turn to geologic dating techniques and to the field of inquiry known as taphonomy, which explores the fate of organic remains as they cross from the living world to the dead.

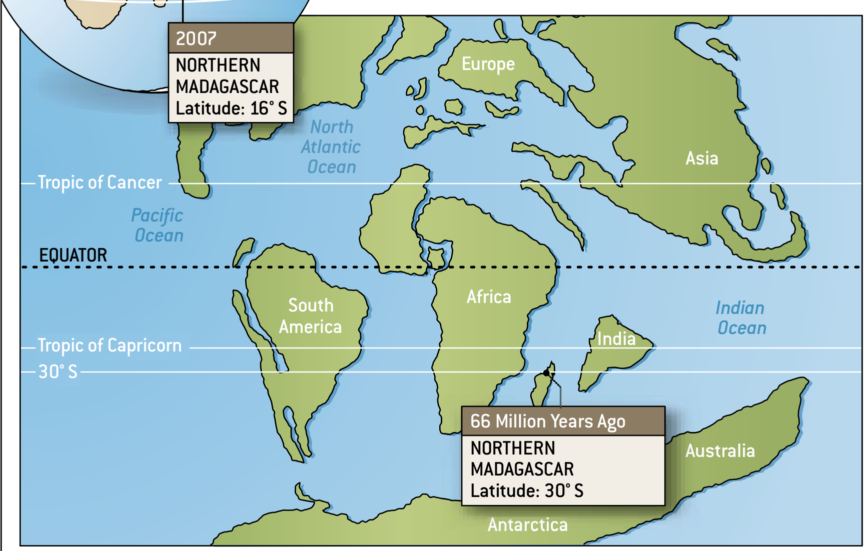
After naming the site, we disinterred the bones from the rocks in which they were embedded. We started with shovels and rock hammers to remove the overlying sediment, then moved on to dental picks and fine brushes to expose the bones themselves. We took great care not to damage the fragile bone surfaces. Once we fully exposed the skeletal remains, we mapped and photographed them exactly where we found them to record any significant spatial relationships. We next soaked the delicate bones with consolidating glues and carefully jacketed them in protective coats of burlap and plaster. After the plaster set, we catalogued the bones and packed them for the long journey to our laboratories in the U.S., where later we painstakingly removed any remaining sediment and studied the bones in detail, looking in particular for any marks on the surfaces that might reveal the killer's identity.

At the site we determined that the dead were preserved in a distinctive body of sedimentary rock known as the Maevarano Formation, situated a few tens of meters below rocks laid down at the Cretaceous/Tertiary boundary—the time, 65 million years ago, that all dinosaurs (apart from birds) and many other creatures suffered extinction on a global scale [see "Repeated Blows," by Luann Becker; SCIENTIFIC AMERICAN, March 2002, and "The Day the World Burned," by David A. Kring and Daniel D. Durda; SCIENTIFIC AMERICAN, December 2003]. The deathbed lay 44.5 meters beneath the mass extinction horizon and 14.5 meters beneath the local top of the Maevarano Formation. Measuring the radioactive decay of minerals from volcanic rocks in the layers below the formation yielded ages of approximately 88 million years. Marine sediments above and interbedded with the formation, laid down by seas that ebbed and flowed along the western shores of the island, contained seashells and tiny skeletons of single-celled microorganisms dated from other sites to near the end, but not the very end, of the Cretaceous period. All the temporal evidence thus indicates that the deaths occurred approximately 70 million years ago. Whatever killed the dinosaurs in quarry MAD05-42 was unrelated to the great global extinction that took place several million years later.

GEOLOGIC EVIDENCE

The history of the Madagascar landmass provides clues about what killed so many animals there 70 million years ago. At the beginning of the Mesozoic era (250 million years ago), Madagascar rested in the heart of Gondwana. Tectonic activity rearranged the earth's lithospheric plates, and by the early Cretaceous (130 million years ago), Madagascar was positioned about 400 kilometers away from the African mainland; it then rejoined the African plate and began moving northward. When the deaths under investigation occurred (*map below*), northern Madagascar lay near 30 degrees south latitude, where climatic conditions alternated between prolonged droughts and intense rainy periods.

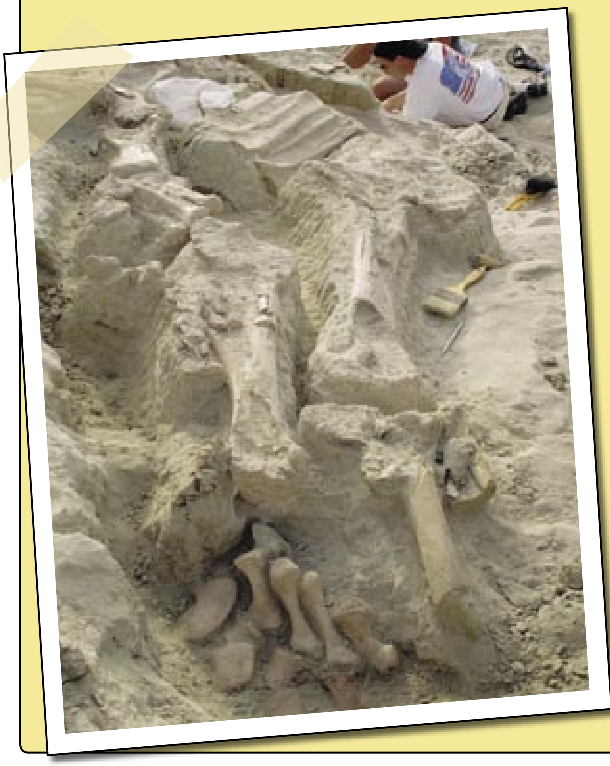




LUCY READING-IKKANDA

More Mass Death

One of the first sites discovered, MAD93-18, reveals the recurrent nature of mass mortality in ancient Madagascar more dramatically than any other site. MAD93-18 has three discrete deathbeds stacked one on top of the other. Excavations there produced nearly complete skeletons of the large sauropod *Rapetosaurus* (*bottom left* and *bottom right*) as well as the skeletal remains of many other animals new to science, including a primitive bird, *Rahonavis ostromi* (*right*), which had small, fragile bones.



CATHERINE FORSTER *Stony Brook University (top)*; DESIRE RANDRIANARISTA *Centre ValBio (International Training Center for the Study of Biodiversity) (bottom left)*; RAYMOND R. ROGERS *(bottom right)*

Taphonomy advanced our inquiry as well. Taphonomic study examines bone modification (were the bones burned, broken or bitten?), carcass disturbance (dismemberment and selective removal of body parts by scavengers or predators), and burial history (how the bodies were buried and what happened to them after burial). The study of fossilization processes—essentially, what turns bone into stone—also falls within the realm of this science.

When we considered the dead in quarry MAD05-42 from a taphonomic perspective, we could tell that they perished over a prolonged period, perhaps weeks or months, because their corpses revealed variable postmortem histories. For example, some carcasses were largely intact and others were dismembered and scattered widely, which would not have happened instantaneously. In addition, some bones were in exquisite condition, whereas others showed evidence of advanced weathering and surface degradation. When the animals in an ancient bonebed have died at different times, we describe the site as "time-averaged" and use taphonomic clues to assess the amount of time between the first death and the last. Although we cannot determine exactly how much time transpired in the formation of this particular deathbed, we do know that death did not come at the same instant for the animals entombed here.

Scene of the Crime

THE GEOLOGIC HISTORY of the Madagascar landmass also provided important clues about what killed these dinosaurs. At the onset of the Mesozoic era (250 million years ago), Madagascar rested in the heart of Gondwana (the southern half of the supercontinent Pangaea), sandwiched between Africa and India, with Antarctica near its southern tip. Tectonic activity soon rearranged lithospheric plates on a massive scale, and by the late Jurassic (160 million years ago), Madagascar had rifted away from Africa and was moving southward, with India in tow. By the late Cretaceous (88 million years ago), Madagascar had resutured to the African plate, albeit

ANCIENT SOILS and rocks present convincing evidence of a semiarid climate during the late Cretaceous. Vertically oriented root casts (*lower right*) indicate that plants had adapted to dry conditions by seeking deep sources of moisture. Many of the relic roots also reveal clumps of calcium carbonate, which tend to form in arid regions. Other sediments, laid down in sandy rivers (*top photographs*), indicate that water flow varied dramatically. When the rivers were flowing, currents drove dunes downstream, resulting in stacked sets of inclined layering (*top right*). Dinosaurs and many other animals visited the shallow rivers in search of nourishment—in fact, the bones of quarry MAD05-42 lie in one of these ancient channels.

RAYMOND R. ROGERS

about 400 kilometers distant from the mainland, and the Indian subcontinent and Antarctica had rifted away, leaving the world's fourth largest island isolated in the Indian Ocean.

After reuniting with the African plate, Madagascar shifted northward toward its present location in the Southern Hemisphere tropics. But when the deaths under investigation transpired, some 70 million years ago, northern Madagascar was positioned near 30 degrees south latitude—still far from the Tropic of Capricorn (which now passes through *southern* Madagascar) and arguably well within the influence of subtropical weather patterns. Today major deserts and semideserts occur in swaths between 15 and 35 degrees north and south of the equator. These arid belts reflect large-scale atmospheric circulation patterns (known as the Hadley cell) that drive masses of hot, dry air down to earth after they have relinquished their moisture near the equator. The high-pressure zones that result from the descending air cells tend to keep rainfall at bay most of the time, but when rain does come, it can be intense.

Rocks of the Maevarano Formation present convincing evidence of a semiarid and seasonal climate during the late Cretaceous. Most telling are the red oxidized paleosols (ancient soils), which contain beautifully preserved, vertically oriented casts of roots. Vertical roots are common today where plants have adapted to dry conditions by seeking ever deeper sources of moisture and nutrients. Furthermore, many of the relic roots of the Maevarano Formation are encrusted with calcium carbonate or interspersed with irregular clumps of this mineral that are called carbonate nodules. In the modern world, oxidized soils enriched in calcium carbonate tend to occur in semiarid to arid regions where evaporation and transpiration limit the effects of precipitation.

Other sediments of this ancient terrain were laid down in shallow, sandy rivers. These, too, provide telling evidence of a subtropical history, with clear indication that the flow of water fluctuated dramatically and probably seasonally. When the rivers were flowing, currents drove ripples and dunes downstream, resulting in stacked sets of inclined layering that geologists refer to as cross-stratification.

Dinosaurs and many other animals

THE AUTHORS

RAYMOND R. ROGERS and *DAVID W. KRAUSE* have excavated and investigated the spectacular bonebeds of Madagascar since 1996. Rogers is an associate professor and chair of the geology department at Macalester College and a research associate at the Field Museum in Chicago and the Science Museum of Minnesota. He earned a Ph.D. in geology from the University of Chicago in 1995. Krause is Distinguished Service Professor in the department of anatomical sciences at Stony Brook University and a research associate at the Field Museum. He received a doctorate in geology from the University of Michigan at Ann Arbor in 1982. Krause's work in Madagascar, the world's fourth poorest country, led him to establish the Madagascar Ankizy Fund (www.ankizy.org), a nonprofit organization that builds schools and provides temporary clinics for children in remote areas of the island.

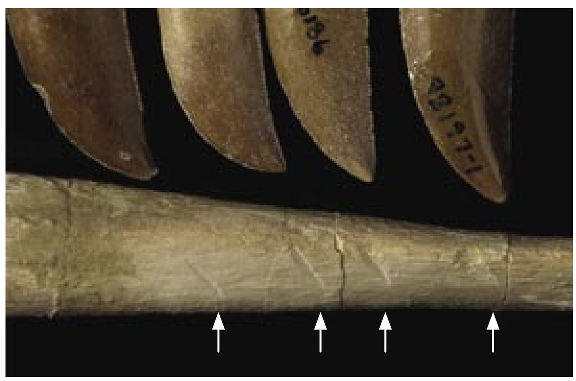
Dining on the Dead

Widespread death in Madagascar during the late Cretaceous provided a smorgasbord for those that fed on the dead. Necrophagy, the act of consuming corpses or carrion, is a niche that must be filled if biological recycling is to proceed efficiently, and modern practitioners range from bacteria to large-bodied vertebrates. Along with our colleague Eric M. Roberts, who accompanied us to Madagascar a decade ago as an undergraduate (and is now a lecturer at the University of Witwatersrand in Johannesburg), we have found traces of necrophagous insect activity in the dinosaur bones of Madagascar: centimeter-long oval pits, usually in what had been spongy tissue inside the bones. These pits are signs that adult beetles infested the corpses, fed on the carrion and then laid their eggs nearby. After hatching, the larvae fed as well and used their robust mandibles to excavate the pits, which served as pupation chambers.

Insects were not the only creatures feeding on the dead. Analysis of bite marks has yielded irrefutable evidence that dinosaurs also dined here. Working in collaboration with Kristina Curry Rogers of the Science Museum of Minnesota, we have documented tooth marks of the seven-meter-long theropod *Majungatholus atopus* on a selection of bones from at least three separate bonebeds. Comparing the shape and size of the tooth marks with the jaws and teeth of various carnivores, we have been able to rule out all the other sharp-toothed suspects.

A few of the bitten bones in our sample belong to *Rapetosaurus,* a previously unknown long-necked sauropod dinosaur that Curry Rogers described as part of her dissertation work at Stony Brook University. Yet the vast majority of tooth-marked bones, primarily ribs and vertebrae, belong to *Majungatholus* itself. Cannibalism as an ecologic strategy is not at all uncommon among living animals, and it certainly should not be unexpected among dinosaurs. Unearthing the evidence to prove it, however, has been another matter, and in the bonebeds of Madagascar we have documented the only well-substantiated case of cannibalism among dinosaurs. Unfortunately, the bite-mark evidence does not definitively disclose whether *Majungatholus* actually killed the individuals it dined on—and thus practiced predation on its own species—or simply opportunistically scavenged their remains. *—R.R.R. and D.W.K.*

OVAL PITS in the dinosaur bones (*photograph*) are signs that carrion beetles infested the corpses, fed on the flesh and then laid their eggs (*illustration below*).



TELLTALE MARKS on the bones, and the finer grooves within them (*arrows*), match exactly the size and spacing of the teeth, and the flesh-slicing serrations on the front and back edges, of the dinosaur *Majungatholus*.

RAYMOND R. ROGERS (*top*); RAÚL MARTIN (*middle*); MARYLOU STEWART *Stony Brook University* (*bottom*)

no doubt frequented these rivers in search of water, nourishment or refuge. Indeed, the bones in quarry MAD05-42 are scattered in one of these ancient river channels. Part of the time the rivers were dry; at other times they roiled with thick milk shake–like slurries of mud and sand. We will return to these slurries—they play an important role in our story.

Identifying a Killer

A LONE ANIMAL can meet its end in many ways—perhaps too many, if the goal is to positively identify a killer in the fossil record. But the options diminish significantly in cases of mass death, such as those in the Maevarano Formation. For help in narrowing the possibilities down to one, we looked again to taphonomy. The bonebeds of Madagascar generally preserve the remains of more than one type of animal, be it multiple species of dinosaurs, as in MAD05-42, or a more diverse array, as in quarry MAD93-18 [*see box on page 45*], which has yielded the skeletal remains of fishes, turtles, snakes, crocodiles, three different types of nonavian dinosaurs, birds and mammals. This killer was indiscriminate, paying no attention to size,

DROUGHT WAS THE KILLER. Animals congregated in the parched riverbeds, where they perished as food and water disappeared. The large dinosaur *Majungatholus* fed on *Rapetosaurus* (*foreground*) as well as on its own kind (*far left*). Birds (*Rahonavis*) also scavenged the remains. The immediate cause of death could have been dehydration, heat stress, malnutrition, even poisoning, as the stagnant water turned toxic. Other carnivorous animals and insects feasted on the carcasses until they, too, met their end when torrential rains triggered mudflows that encased the dead and dying, preserving their remains for 70 million years.

age, taxonomy or habitat—a fact that tends to exclude a predator, such as a meat-eating dinosaur or crocodile, because modern predators generally show at least some degree of prey selection.

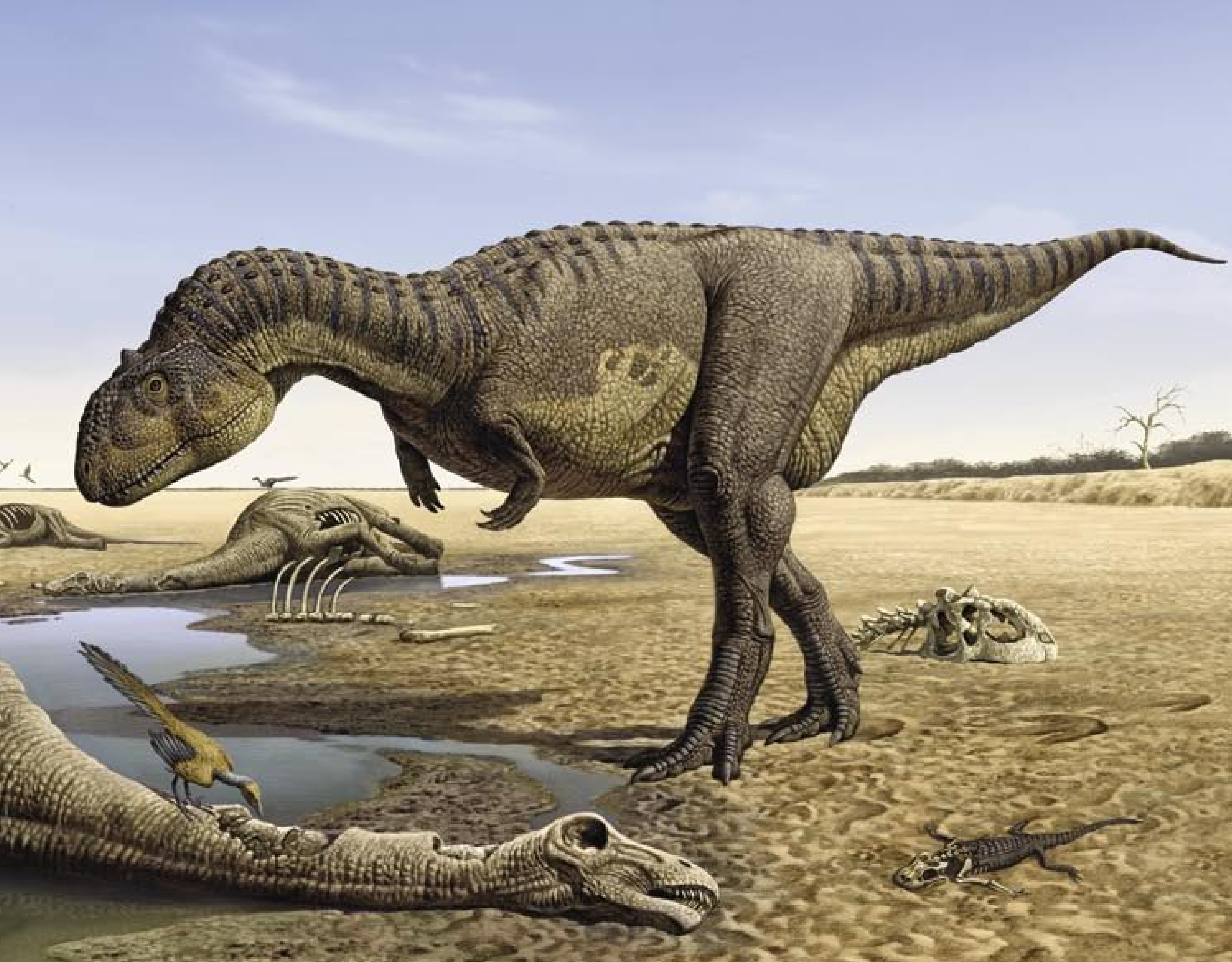
Nor is there any support for a disease-based scenario (it is difficult, though, to test for disease with fossilized bones). Because the creatures died at different times, we do not suspect dramatic instantaneous events such as earthquakes, floods or fire. Whatever killed the animals acted over time and struck victims individually after they had arrived at the river under their own volition. We also have irrefutable evidence that the killer struck repeatedly in different locales but with the same basic modus operandi. These animals were not dropped in their tracks during one bad day in the late Cretaceous—there were many bad days.

ALGAL SPORES found in the rocks encasing the bones suggest that the shrinking pools of water may have been toxic.

When all the evidence is brought to bear, we can confidently pinpoint one killer: drought. The opportunity certainly existed; this was a subtropical ecosystem with clear indications of aridity and seasonality. Moreover, we can see that animals congregated in the desiccating riverbeds, probably around remaining pools of water, where again and again they perished as good drinking water and nourishment disappeared. Today lethal droughts, especially in parts of Africa and interior Australia, prompt animals to gather around remaining resources. During an extended drought, thousands of animals can succumb at the site of their last hope for a drink, and their bodies may accrue in localized "dead zones" over several years.

Studies of modern drought-related mortality indicate that the unlucky animals preserved in the Maevarano bonebeds could have ultimately died from any number of causes: dehydration, heat stress, malnutrition, perhaps even poisoning as their dwindling water supplies turned foul and noxious. In fact, we have some tantalizing evidence that algal blooms occurred in the stagnant pools of water that drew the animals together. Michael Zavada, a Cretaceous pollen expert from East Tennessee State

RAÚL MARTIN (*top*); MICHAEL ZAVADA *East Tennessee State University* (*bottom*)



University, has isolated tiny algal spores in the rocks associated with the bones [*see bottom illustration on opposite page*]; whether these spores represent telltale clues of toxic algal blooms, however, has yet to be confirmed.

But how were the animals' bodies preserved, many of them so exquisitely? Biological remains tend to fare poorly at the ground surface, where scavengers hold sway and the sun slowly but inexorably bleaches even the largest of bones until they splinter and eventually turn to dust. When long-term preservation in the fossil record is at stake, burial should occur as soon as possible after death. Indeed, it could be argued that from a fossil's perspective, rapid burial is the single most critical key to immortality.

Fortunately for those of us who study these fossils, a very efficient undertaker was operating in conjunction with the killer weather. The drought conditions that periodically spelled disaster in the parched riverbeds eventually had to come to an end, and when the rains returned, as they did with a vengeance, they triggered debris flows. Viscous slurries of green mud and sand mobilized by rain-induced erosion poured over the bones and encased them. The sedimentary characteristics of the burial beds reflect a special category of fluid flow in which turbulence is suppressed, and both water and sediment move en masse in an essentially plastic fashion. This type of mass flow, often known as a mudflow, is not uncommon today. The lethal mudslides in Guatemala in 2005, unleashed by the torrential rains of Hurricane Stan, are a recent example.

Again and again after the fatal droughts had taken their toll, thick beds of mud and sand flowed over the bodies and the scattered bones, whether they belonged to animals that had died minutes or months before, and effectively packaged them all together in a protective and permanent sedimentary tomb. It would be another 70 million years until the tombs were cracked open and the amazing stories within revealed. SA

MORE TO EXPLORE

Monsters of Madagascar. John Flynn and David Krause in *National Geographic,* Vol. 198, No. 2, pages 44–57; August 2000.

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