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TREASURE ISLAND

A SPONTANEOUS BARRAGE OF EXPLETIVES rang through the air, bringing my coworkers scrambling over the hill. Madagascar's sweltering midday heat no longer mattered. There before me, beneath a clod of freshly dislodged sediment, were four shining teeth, exposed to the light of day for the first time in more than 65 million years. Most kids could have confirmed that these sharp, recurved, chocolate brown objects, each topped with fine serrations, once lined the mouth of a meat-eating dinosaur, a theropod. Best of all, these teeth were still attached to a jawbone. Further digging revealed a complete and undistorted jaw, with every tooth in place. Over the next couple of days we found more bones of the same, exceptionally preserved skull—part of the eye socket, another jaw with teeth, a gnarly bone from the nose region. Soon it became clear that most of the skull was buried here, although the individual bones had fallen apart and now lay strewn over several square meters. We could barely contain our excitement. Field paleontology relies as much on serendipity as on know-how and hard work, and the fates had smiled down upon us. Yet, as more and more bones of the ancient predator were unearthed, we began to get nervous. A key portion of the skull remained missing, leaving a mystery unsolved.

In Lewis Carroll's classic tale, *Through the Looking-Glass and What Alice Found There,* Alice gazes into a mirror to find a world similar to her own yet distinctly different. Her view of this reflected world varies dramatically depending on where she stands and how she holds the mirror. And Alice dreams of actually stepping through the looking glass to experience firsthand the wonders beyond. Like Alice, paleontologists attempt to gaze through the looking glass of time in order to catch glimpses of other, distant worlds. We, too, find that our perspective is always limited, changing considerably depending on how we hold the mirror and indeed which mirror we choose. And we, too, dream of witnessing these worlds firsthand. The ongoing efforts to open windows into ancient landscapes and their inhabitants comprise the science of PALEONTOLOGY, the study of ancient life.

Dinosaur paleontology, my particular specialty, is a peculiar profession. After all, how many people can claim to have a job that is the envy of most 6-year-olds? Telling others that you're a dinosaur paleontologist often results in the usual questions. "How do you know where to dig for them? What was the biggest dinosaur? Why do *you* think dinosaurs went extinct?" Of the most common queries, the one that I find most amazing and dismaying is "Don't we already know everything about dinosaurs?"

People tend to think of science as the gradual, steady accumulation of facts that has been ongoing for centuries. So it's often imagined that today we scientists are merely adding insignificant grains to an enormous, established mountain of knowledge. This view could hardly be further from the truth. The vast majority of nature's secrets have yet to be revealed. In the evocative words of biologist and environmentalist David Suzuki: "It is as if we are standing in a cave holding a candle; the flame barely penetrates the darkness, and we have no idea where the cave walls are, let alone how many caves there are beyond. Standing in the dark, cut off from time, and place, and from the rest of the universe, we struggle to understand what we are doing here alone."[1] Rather than being daunted by our overwhelming ignorance, I am inspired by the multitude of new discoveries that patiently await us, entombed within the earth, carefully preserved in museum drawers, and tucked away in the corners of our imaginations. It's an exciting time to be a paleontologist.

If the overriding aim of science is to understand and describe as accurately as possible the workings of nature, certainty turns out to be a scarce commodity. To speak of "scientific facts" is to border on using an oxymoron. Most scientists would agree that there is a single, physical reality to comprehend. To borrow the slogan of a recent popular television show, "the truth is out there." Yet the best we can offer are successive approximations of that truth, formulated as alternative explanations, or HYPOTHESES. The scientific method involves sorting among these various alternatives. Consequently, testability is an integral part of the process, and only the strongest THEORIES, like gravity and EVOLUTION, withstand decades of testing and become accepted as fact.

But how can paleontologists test ideas? Like geology, paleontology is a historical science, concerned predominantly with understanding and interpreting past events. Historical sciences differ in at least one fundamental way from nonhistorical fields such as physics and chemistry. Paleontologists cannot test a hypothesis through direct experimentation for the simple reason that it is impossible to reproduce past events. For example, barring the highly unlikely cloning of a dinosaur from its DNA or the invention of a time machine (even less likely), we clearly can't investigate the metabolism of *Tyrannosaurus rex* directly. Similarly, geologists cannot observe the rifting and collisions of ancient continents. Given the strong emphasis on reproducibility—the ability to run the same experiment multiple times in order to test for similar results—some have even argued that the inability of historical sciences to reproduce results should disqualify them as scientific disciplines.

Yet the historical sciences are able to circumvent the conundrum of time's arrow, at least to some degree, through an elegant loophole. Although the inexorable march of time prohibits actual reproduction of past events, it's possible to observe multiple examples of such events. If these examples are consistent with a stated hypothesis, it gains support. If not, the hypothesis is falsified or at least brought under closer scrutiny.

Take evolution, for example. Darwin's theory states that all organisms past and present share common ancestry and that life evolved from simple, single-celled beginnings. Thus, we predict that the order of appearance of particular groups of organisms should mimic the branching pattern of evolution, with a trend toward increasing complexity through time. Convincing evidence against evolution would be the discovery of any animal that lived long before its supposed time of its origin—say, for example, the fossilized remains of a rabbit (or human or dinosaur, for that matter) dating to 400 million years ago. With hundreds of paleontologists working around the globe in rocks that span most of Earth history, this amounts to hundreds of thousands of opportunities annually to discredit evolutionary theory. Yet, invariably, we continue to find groups of organisms restricted to rocks of a specific age range. In all the years I have been hunting for dinosaurs in Mesozoic-aged deposits, I have never found any indication of advanced mammals such as cats, whales, or aardvarks, let alone humans. And the same is true for all of my paleontological colleagues, because such a find would be headlined in the media worldwide and bring with it the potential for all forms of academic accolades, as well as research funding. In short, through study of multiple examples of past phenomena, paleontology and geology are anchored on testability.

Science grows in fits and starts. Research occurs within a particular theoretical framework, or paradigm, that guides scientific thinking. Occasionally, a new overarching theory, sometimes triggered by a dramatic discovery, causes an entire scientific field to reassess its assumptions and ask new kinds of questions. A fundamental breakthrough of such magnitude is called a PARADIGM SHIFT, because it requires restructuring or even wholesale replacement of an old theoretical framework. Prime examples of paradigm shifts in the history of science include the Copernican and Darwinian revolutions. The first of these devastated the then-current worldview of a fixed and finite universe with Earth presiding at the core, forcing humans to regard their planetary home as being far removed from the celestial center stage. The second knocked us further off the pedestal of centrality, relegating *Homo sapiens* as one of millions of species that together represent merely the latest wave in an unfathomably deep ocean of evolutionary change. Importantly, with rare exceptions like the Copernican revolution, paradigm shifts do not entail the wholesale tossing out of previous ideas. Science proceeds by building on what has come before, and many ideas within science are known with great confidence, unlikely ever to change. As the architecture of the building is modified, however, occasional large-scale renovations are necessary.

Beginning in the late 1960s, dinosaur paleontology experienced its own, humbler paradigm shift. As a child of the baby boom generation, my first exposure to paleontology occurred just prior to this shift, when dinosaurs were regarded as sluggish, dimwitted behemoths. I fondly remember flipping the pages of large dinosaur books with awe-inspiring illustrations of long-necked sauropods (aka "brontosaurs") fully submerged in lakes except for the tops of their heads. Prevailing thinking viewed these animals as simply too gargantuan to support themselves on land. Those dinosaurs that did walk on terra firma were generally depicted as slow and awkward. Giant bipedal CARNIVORES such as *Tyrannosaurus* were reconstructed as Godzilla-like, with upright bodies and massive tails dragging behind. Four-footed plant eaters like *Stegosaurus* were portrayed with sprawled, lizardlike front limbs, low-slung bodies, and dragging tails. The overall impression was one of awkward giants lumbering across ancient landscapes, with brains barely capable of carrying them from day to day.

Then, virtually overnight it seemed, dinosaurs received a stunning makeover. Sauropods emerged from the water to strut on land with elephantine limbs, and scientists came to argue that an aquatic lifestyle would have been impossible for these behemoths because of water pressure compressing the chest cavity. Meanwhile, *T. rex* pivoted to a sleeker, horizontal body posture. No longer trailing uselessly behind, its rigid tail projected rearward to counterbalance the head and trunk. *Stegosaurus* and its armored, four-footed kin were also transformed, bestowed with upright limbs and nimble, airborne, potentially lethal tails. Reconstructions like these signaled much more active, agile animals. In addition to their redesigned bodies, these freshly envisioned dinosaurs were considered more intelligent, engaging in such behaviors as pack hunting, herding, and parental care.

What caused this fundamental change in our conception of dinosaurs? The answer is a paradigm shift triggered by a combination of discovery and insight. The pivotal FOSSIL discovery was a sickle-clawed "raptor" theropod, recovered in Montana in 1964 by an expedition from Yale University. The revolutionary insights came from Yale paleontologist John Ostrom. In his 1969 description of this extraordinary predator, which he called *Deinonychus* ("terrible claw"), Ostrom argued that at least some dinosaurs were considerably more active than previously assumed. Shortly thereafter, noting a large number of birdlike features on the skeleton of *Deinonychus* and related predators, Ostrom revived the nineteenth-century idea that birds evolved from dinosaurs. He catalogued numerous bony characteristics linking theropod dinosaurs with birds, and subsequent workers have added many more, bringing the total number of shared, specialized features to greater than one hundred. Today, most experts agree that birds are the direct descendants of dinosaurs and thus are, in a very real sense, dinosaurs themselves.

Faced with this new evidence and a fresh perspective, paleontologists quickly began to view all dinosaurs as more like birds than lizards. Investigators returned to existing museum collections and began to reassess long-held views and biases. Soon, the mounted skeletons of bipedal carnivores and HERBIVORES were reengineered to assume a more horizontal posture. Further support for the revised stance came from the discovery of dinosaur trackways that showed no signs of dragging tails.

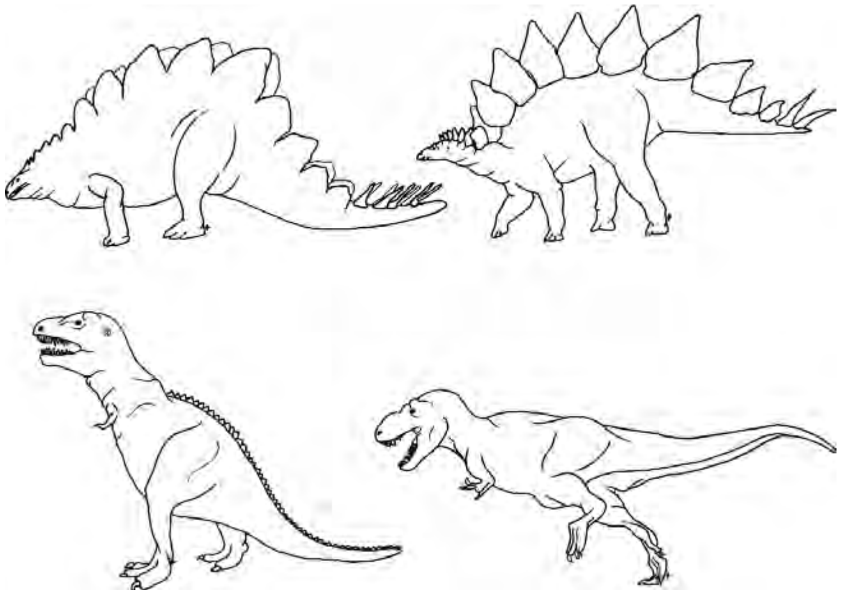

FIGURE 1.1
Reconstructions of *Stegosaurus* (top) and *Tyrannosaurus* (bottom), depicting earlier, “prerenaissance” postures (left) and more recent, “postrenaissance” postures (right).

This paradigm shift spawned novel research programs and heated debates. Were dinosaurs warm-blooded? Did some forms exhibit parental care? What were the intellectual and behavioral capacities of the different dinosaur groups? In an attempt to address these questions, paleontologists have applied a range of analytical tools old and new, from detailed anatomical comparisons with living animals to computed tomographic (CT) scanning of fossils. Several decades of extremely active research have led to numerous insights, many of which are discussed in this book.

As is often true of cultural and scientific trends, once in motion, the pendulum of a paradigm shift tends to swing in a wide arc. This has certainly been the case with dinosaurs. If John Ostrom ignited the paradigm shift, the fuel for the subsequent explosion was Robert Bakker, Ostrom’s flamboyant, iconoclastic student and avid champion of the dinosaur renaissance. Not long after Ostrom’s original argument for more active, potentially warm-blooded dinosaurs, Bakker rescued sauropods from their aquatic torpor and even had them rearing up on their hind legs to battle marauding theropods. Similarly, *Tyrannosaurus* and its large carnivorous kin, no longer awkward and lumbering behemoths, were depicted as agile predatory machines capable of running speeds in excess of 65 kilometers (40 miles) per hour. Then there were the small raptorlike, sickle-clawed theropods such as *Deinonychus* and *Velociraptor*, traveling in packs and utilizing a combination of cunning and cooperative behavior to take down prey of much greater body sizes. The *Jurassic Park* movie series brought these new ideas to popular audiences via the big screen and stretched science to the breaking point.

Today, the pendulum is swinging back toward the middle, as paleontologists generate more rigorous, tempered, yet undoubtedly richer reconstructions of dinosaurs and their worlds. One example is the recent work indicating that *Tyrannosaurus* and other large theropods could not attain the remarkable, jeep-pursuing speeds previously reported and that they were likely incapable of true running. It has even been suggested that *T. rex* was not the predatory tyrant-king long depicted but rather a lowly scavenger, eking out a living from remains of the dead. The same type of scrutiny is being applied to plant eaters as well. Not only have investigators questioned whether sauropods could rear up on their hind legs. Some have also argued that these successful giants could not elevate their elongate necks much above the horizontal because of, among other things, the difficulty of pumping blood up to the head.

On July 16, 2005, John Ostrom passed away at the age of 77. A few years before, Ostrom confessed to me that he would give just about anything to be back near the beginning of his career. He talked about the new age of discovery in dinosaur paleontology and the exciting work yet to be done. Yet, unlike the great majority of us, John leaves behind a deep and lasting legacy. His discoveries and vision triggered a revolution in our perception of dinosaurs, a true paradigm shift has enabled us to see these long-dead animals with new eyes, and to explore questions never previously conceived. Many of Ostrom's students went on to become leaders in the field, and the dinosaur renaissance he initiated has ushered in new generations of scientists eager to conduct research on these long-dead yet suddenly more fascinating beasts. Today there are about 100 dinosaur paleontologists worldwide, more than ever before. And the number of new dinosaur species named in the past 25 years exceeds that found in all prior history, with no end in sight.

It's tempting to romanticize the hunt for dinosaurs, even for those of us engaged in it. Yet the majority of fieldwork is anything but romantic—heat, insects, and tedious labor in remote, lunarlike landscapes typically comprise the bulk of the daily routine. Add to this list the lack of running water, dearth of culinary options, and living outdoors with a small group of people, and most folks would choose to bow out. So why do we venture around the globe in search of places referred to as "badlands" and endure often harsh conditions for weeks or even months on end?

Well, for one thing, fossil hunting is a form of time travel. As I walk up a steep slope of sandstones and mudstones, a piece of fossilized skull found in one rock layer may come from an animal that lived thousands, hundreds of thousands, or even millions of years apart from an animal whose toe bone I spot a few steps farther on. On a good day, as I stoop to pick up a 75-million-year-old jaw fragment, the chasm of time will suddenly open, instantly transporting me back to the Cretaceous. Now crouching unseen in the shadows, I gaze on the giant duck-billed dinosaur cropping conifer needles with its broad beak and slicing up this green energy with formidable batteries of teeth. I listen as this gargantuan animal takes deep draughts of the crisp morning air, and I inhale its musty odor. For a moment, I even become this dinosaur and *feel* its world. As the feeling subsides and I return to the present day, the experience invites a new, broader perspective of myself as part of the single, unbroken flow of life and energy through deep time. Who would have thought that a chunk of old bone could wield such power?

There's another, perhaps more common reason why people are drawn to the search for fossils: discovery. Few feelings compare to being the first person ever to set eyes on a previously unknown ancient animal or to be part of a crew that unearths a well-preserved, fossilized skeleton. Walking across the rocky terrain with eyes trained on the surface, you never know if, perhaps just around the next corner, the remains of some magnificent prehistoric creature await you. During the heyday for fossil hunting early in the twentieth century, it was relatively easy for any intrepid paleontologist to find pristine badlands when in search of a fossil "grail." Today, even the most fortunate fieldworker has only a handful of opportunities to be the first paleontologist in an unexplored region.

Such places still exist in Madagascar.

Madagascar, situated off the southeast coast of Africa, is the fourth largest island in the world, bigger than the state of California. A mountainous spine runs for most of the 1,000-mile length of the island from north to south. Along the eastern side lie tropical rain forests, though these have been decimated by human activity. The western and southern sides of the island, in the rain shadow of the highlands, are home to tropical dry forests, thorn forests, deserts, and shrublands. Because of its great size, diverse geography, and lengthy isolation from other landmasses (for about 85 million years), Madagascar is home to a highly unusual biota, with approximately 80 percent of its plant and animal species known nowhere else. By far the most famous of these are the lemurs, a group of primates found only on Madagascar that today numbers more than seventy species. Humans settled on the island about 2,000 years ago, likely from Southeast Asia, and soon drove virtually all of the largest animals to extinction. Recently extinguished species include gorilla-sized lemurs, pygmy hippos, and giant, flightless elephant birds. Thanks to its fine weather, abundant food, and numerous secluded coves, Madagascar served as a pirate hideout and stronghold for several decades during the late fifteenth and early sixteenth centuries. Such infamous figures as William Kidd, John Bowen, and Thomas Tew plundered merchant ships in the Red Sea, the Persian Gulf, and the Indian Ocean, stealing silks, cloth, spices, jewels, gold, silver, and coins.

In search of a different kind of treasure, David Krause, a mammal paleontologist from Stony Brook University, launched an expedition to Madagascar in the early 1990s. He wondered where Madagascar's wondrous marooned trove of unique plants and animals had come from. Were the ancestors of lemurs and other modern forms present when Madagascar became an island 85 million years ago? Or did they arrive much later, crossing major water gaps separating the island from other landmasses, such as mainland Africa? The first place you might think to look for answers is the fossil record preserved on the island. Unfortunately, however, other than the very recent past (about 26,000 years) there is virtually no fossil record of land animals on Madagascar since the major extinction of the dinosaurs 65 million years ago. One has to go all the way back to fossil-rich deposits of Late Cretaceous age, at the end of the Age of Dinosaurs, to search for the origins of today's Malagasy FAUNA.

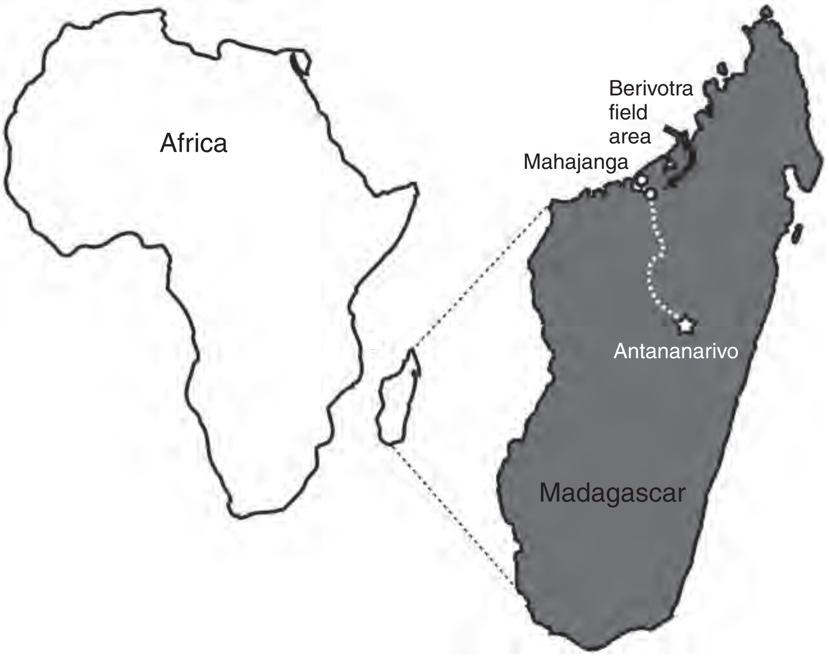

FIGURE 1.2
Map of Madagascar in relation to Africa. Close-up view of Madagascar (shaded, on right) depicts the country's capital city (Antananarivo), the city of Mahajanga, and the Berivotra field area that has produced abundant fossils of Late Cretaceous dinosaurs and other vertebrates.

Krause decided to investigate a small outcropping of rocks on the northwest part of the island, surrounding a tiny village called Berivotra, an hour's drive from the bustling port city of Mahajanga. Like most of Madagascar, the land around Berivotra was long ago deforested by human activity. Annual mass burnings of grasslands, both voluntary and involuntary, together with agriculture and grazing by livestock, now ensure that the forest ecosystem cannot regain a foothold. This widespread habitat loss has devastated ecosystems all over the island. Many regions, including the northwest where we work, are dominated by spear grass, an exotic invader species entirely deserving of its name. The removal of forest has also led to rampant soil erosion. Every year, monsoonal rains scour the outermost skin of red soil, which then bleeds into rivers like the Betsiboka and ultimately into the Indian Ocean. From the air, it looks as if the entire island is hemorrhaging, a description not far from the truth. Ironically, this ongoing decimation of the landscape has benefited us paleontologists, who search out areas with minimal vegetation and depend on erosion to bring ancient bones to light.

Starting in the Berivotra field area was not a shot in the dark. The French invaded Madagascar and declared it a colony in 1896. The year prior, a French military physician named Félix Salètes was charged with constructing a temporary hospital about 45 kilometers from Mahajanga (known to the French as Majunga). Salètes recognized the paleontological potential of the region. Lacking time to check out the area himself, he dispatched his regimental staff officer Landillon to carry out a survey for fossils. Landillon excelled in this task, collecting a diverse range of fossils that were shipped back to Paris, where they came under the study of renowned French paleontologist Charles Depéret. Depéret identified two large dinosaurs from the collection: one herbivore, a long-necked sauropod; and one carnivorous theropod, which he dubbed *Megalosaurus crenatissimus*. *Megalosaurus* was previously known from several sites in Europe, and the Malagasy example was established solely on the basis of two teeth, three VERTEBRAE (elements of the "backbone"), and a single toe bone. In the middle of the twentieth century, following construction of a major new road through the region, another Frenchman, René Lavocat, surveyed the deposits around Berivotra. Lavocat apparently conducted few excavations but nevertheless collected many fossils eroding from the surface. One of these was a fragmentary lower jawbone (dentary) that Lavocat regarded as sufficiently distinct from *Megalosaurus* to erect a new name, *Majungasaurus*.

Our story then jumps to 1976, when French paleontologist Philippe Taquet received a shipment of Malagasy fossils at the Natural History Museum in Paris that were being held in storage elsewhere in the city. The collection included a chunk of bone that Taquet recognized to be part of the skull roof above the brain compartment. The specimen was strange, however, topped by a roughened, domelike structure. Notes accompanying the fossil documented that the specimen had been collected in the "Majunga District" of northwestern Madagascar early in the twentieth century, but little else was known. Together with Hans-Dieter Sues (now of the Smithsonian Institution's National Museum of Natural History), Taquet published a paper in 1979 describing the specimen and concluding that it belonged to a group of dome-headed herbivorous dinosaurs known as pachycephalosaurs. They gave it a new name, *Majungatholus atopus*. Identifying *Majungatholus* as a pachycephalosaur seemed reasonable based on its conspicuous bony dome. Yet the assertion was also remarkable because, other than this single fragmentary specimen, pachycephalosaurs were (and still are) otherwise known only from Northern Hemisphere continents. So *Majungatholus* seemed a long way from home.

Enter David Krause and the joint Stony Brook University/University of Antananarivo expedition of 1993, hoping to find the first evidence of Mesozoic mammals in Madagascar. On first arriving in Berivotra, the crew jumped out of the vehicles and headed to a nearby rock outcrop in search of fossils. (It's a very long trip from North America, and folks are typically anxious to find fossils as soon as they arrive.) Within minutes, keen eyes led to the discovery of a partial mammal tooth—a tremendous start to the project. Although this would be the only scrap of mammal fossil recovered in the 6-week field season, the crew did find plenty of dinosaur remains, as well as those of many other backboned animals. The dinosaur finds prompted David to enlist the help of dinosaur paleontologists, first Peter Dodson (University of Pennsylvania) and then Cathy Forster (now at George Washington University) and me.

During the following field season, in 1995, we found plenty more fossils, including lots of dinosaur bones. Curiously, however, there was no further sign of the putative dome-headed pachycephalosaur. Close examination of the original specimen housed in the National Museum of Natural History in Paris made us suspect that *Majungatholus* might not be a plant-eating pachycephalosaur at all. We noted that the dome itself is covered with a roughened, wrinkly texture unlike that known for any other member of the group. Moreover, a few anatomical features suggested that the partial skull might instead belong to a carnivorous dinosaur. We were pretty convinced that *Majungatholus* and *Majungasaurus* would turn out to be one and the same animal, but we needed more fossils to prove it.

Early in the 1996 season, we checked out a known locality that appeared to have promise. Walking around the low hill, I spotted a small vertebra eroding from the surface and was excited to recognize it as a part of a theropod tail. Using rock hammer and pick, it took only a few minutes to uncover another tail vertebra, and then another. With eager anticipation, we literally chased the tail into the hill. A few hours later, after exposing several more vertebrae, we removed a chunk of rock to reveal a large limb bone, a clue that much of the skeleton might be interred within the site. But it soon became clear that the limb bone belonged to a giant herbivorous sauropod, the most common kind of dinosaur in these deposits. Our hearts sank, because it appeared that the locality consisted merely of a jumble of bones from various kinds of animals.

Then my awl lifted a piece of sediment to expose those four shiny teeth mentioned at the outset of this chapter. The team continued to excavate this small area, uncovering additional skull bones of the Cretaceous predator while watching closely for the skull roof. Peter Dodson exposed a spectacular, tooth-filled lower jawbone. Cathy Forster found large portions of the side of the face. Finally, the rear portion of the skull roof appeared, attached to the rest of the bony compartment that long ago housed the animal's brain. And there, as predicted, was a rounded, roughened, domelike structure. We now had conclusive evidence that *Majungatholus*, the supposed thick-headed herbivore, and *Majungasaurus*, the top predator, were the same animal. A hypothesis had been confirmed and a mystery solved. Pachycephalosaurs did not inhabit Madagascar. Rather, the island was home to a strange, dome-head carnivore. Because *Majungasaurus* was named first, and ultimately we could not tell it apart from *Majungatholus*, the former name has taken precedence and is the one we use today.

After all the fragile skull elements were excavated, shipped back to New York, cleaned of the rocky MATRIX, and copied using a process known as molding and casting, the duplicates were put together to reconstruct the original appearance of the skull. Amazingly, the bones fit back together almost perfectly, definitive evidence that the skull elements had undergone minimal postburial distortion. We joked that the entire set of casts could be marketed as a kids' dino-skull kit. Uncovering this exquisite specimen ranks as the highlight discovery of my career—not one I expect to top.

Near the end of the twentieth century, the foundations of science once more began to rumble, the tremors triggered by what appears to be another large-scale paradigm shift.

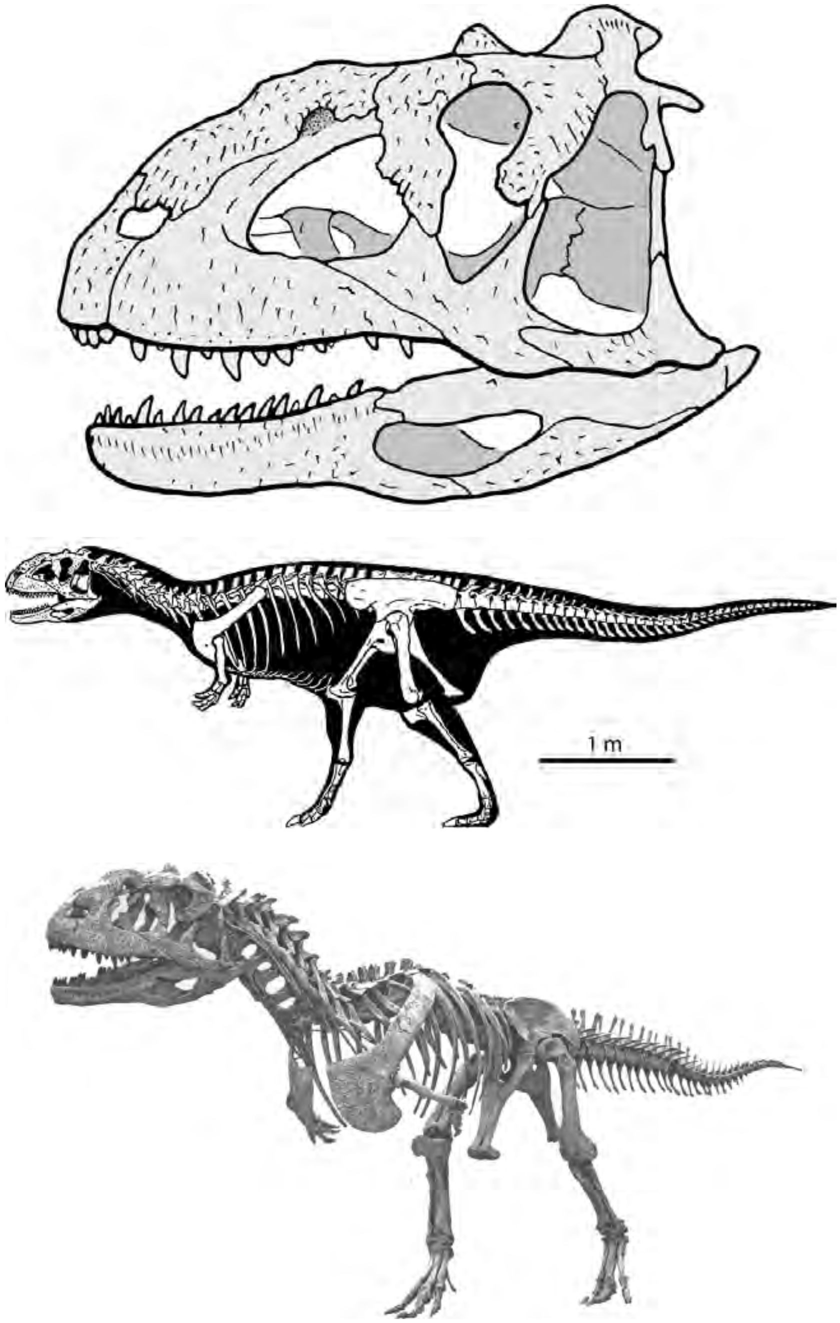

FIGURE 1.3
The abelisaur theropod *Majungasaurus*, from the Late Cretaceous of Madagascar (about 70 million years ago), showing side view of skull (top), illustration of skeleton (middle), and photograph of mounted skeleton (bottom).

For more than 400 years, the scientific conception of nature has been dominated by a mechanistic worldview inspired by sixteenth- and seventeenth-century scientists like Francis Bacon, René Descartes, and Isaac Newton. The underlying assumption of this perspective is that the Universe is a machine, and its secrets can be revealed only by dissecting and compartmentalizing nature into ever smaller parts. This atomistic approach, often called REDUCTIONISM, has yielded remarkable insights into the structure and function of the universe, from cosmic to subatomic scale. Accompanying these insights have been numerous technological innovations such as satellites, computers, and artificial hearts. In the academic realm, entirely new disciplines have continually emerged as scientists focused their efforts on successively smaller units of nature. Within biology, fields of inquiry today include ecology, systematics, developmental biology, physiology, cytology, genetics, and molecular biology.

So entrenched have we become in the minutiae of nature that we have forgotten that the separate disciplines recognized throughout science are human inventions—categories that relate to how scientific research is practiced and not how the universe itself is structured. Moreover, despite its grand successes, the tendency to fragment nature has severely limited our ability to comprehend interconnectedness.

In recent decades, it has become increasingly evident that natural phenomena tend to be complex and highly sensitive to initial conditions. That is, small-scale changes in initial conditions can be amplified into large-scale effects. The commonly invoked metaphor is the “butterfly effect”—a butterfly flaps its wings, say, in the Kalahari savannah of Africa, which causes a tornado in Wichita, Kansas. In other words, small, seemingly insignificant events can have disproportionately large consequences. It turns out that the key to understanding the behavior of such dynamic systems—from weather to finance to ecosystems—is not to dissect all the parts and examine them with greater and greater scrutiny, but to investigate how the various components interact with one another. Consequently, investigators have begun focusing less on parts and more on wholes.

This radical new view is all about connections. Today, numerous disciplines are feeling the effects, becoming increasingly integrative and holistic. As a result, we’re witnessing a reunification of once-separate fields into new disciplines with names like “geobiology” and “biocomplexity.” Much effort is now devoted toward unveiling the complex, weblike links among all living and nonliving systems. Scientific think tanks aimed specifically at such problems, such as the Santa Fe Institute in New Mexico, bring together evolutionary biologists, economists, anthropologists, meteorologists, and mathematicians, as well as representatives from many other fields. It turns out that, once these diverse experts agree on a common language (no easy task, as one might imagine), they are able to see the world differently and develop exciting new insights. These integrative thinkers emphasize such topics as networks, dynamic systems, and feedback loops. They develop novel models addressing everything from climate change to stock market fluctuations. Under the reductionist worldview, physics was viewed as the “purest” of sciences, providing the deepest insights into nature. With a new, broader perspective, scientists now look to more integrative disciplines such as ECOLOGY that investigate connections.

Traditionally, paleontology has followed the reductionist lead of other sciences, fragmenting the history of life into smallest identifiable units—discovering and naming new species, and assessing their evolutionary and temporal relationships. This approach has enabled the recovery of patterns—answers to the who, what, where, and when questions—but at the expense of processes—the how and why questions. I cast no dispersions here; most of my own work falls under this same descriptive umbrella. In part, a focus on patterns makes perfect sense, because dinosaur species are often represented by only one or two fragmentary specimens. And every field must go through a period of collecting basic data before undertaking more integrative studies. Nevertheless, in recent years, there has been a subtle shift toward more holistic, connections-based studies. Dinosaur specialists interact more with experts from other disciplines, such as geochemistry, PALEOBOTANY, geophysics, and paleoecology. Instead of an unwavering spotlight on dinosaurs, much more effort now goes into reconstructing the rest of Mesozoic ecosystems. These collaborations have just begun to bear fruit, and I anticipate an exciting new era for dinosaur paleontology.

After the successful 1996 field season, I ventured with three other crew members to the southern part of Madagascar to visit my first tropical rain forest. Our destination was Ranomafana National Park, situated on the edge of the island's high plateau, where steep, forested slopes shelter a tremendous diversity of wildlife. The rugged terrain here limited deforestation, and the area was formally protected in 1986. Having pitched our tents beside a clear flowing river, we set out in search of lemurs; twelve species are known from the park. We followed a well-trodden trail into the dense forest and began looking high in the canopy for any movement. Lush lichens and mosses festooned the trees, and giant bamboo and orchids lined the waterways. Having grown up camping and hiking in the wilds of British Columbia, I had spent plenty of time spotting wild game. I expected to put this experience to good use, and my compatriots felt equally confident. Yet hours later, we returned to the camp exhausted, without so much as a glimpse of a lemur. We soon learned the necessity of a detailed knowledge of place.

The next morning, we set out with two Malagasy park guides. Within minutes, they located the first lemurs of the day. These were Milne-Edwards sifakas, astounding primate athletes that launch themselves from tree trunks. While airborne, they rotate their bodies until their limbs are posed to alight, seemingly nonchalantly, on another tree. Sifakas can leap impressive distances (up to about 7 meters, or 20 feet) between trees, and we felt fortunate to be the exclusive audience for an acrobatic display. In the next three hours, we saw three more lemur species and added a fourth during a nighttime forest walk.

In addition to lemurs and a few birds, we spotted several reptiles, including chameleons and a large leaf-tailed gecko, all of them masters of camouflage. We also saw numerous insects—caterpillars, butterflies, ants, preying mantids, and phasmids, or stick insects. Phasmids are wondrous creatures that look like something out of a Tolkien dream, appearing to be half plant and half animal. Also inconspicuous, though because of their small size, are the innumerable tiny beasties—mites, nematode worms, tardigrades, and the like—amassed in the forest's soil. Ultimately, the real action in any ecosystem takes place in the microscopic realm. It is here that most of the habitat's diversity resides in seemingly boundless forms of bacteria. A single handful of forest soil may contain thousands of different bacterial varieties and literally billions of bacterial individuals.

All of this bewildering diversity is intertwined in intricate relationships. Bacteria grab nitrogen from the soil and convert it into a form useable by plants. Lemurs, birds, bats, and various insects participate in plant reproduction by pollinating flowers and dispersing seeds. Beetles and flies, among others, feed on dung and recycle the remains of all forest dwellers as they die. Concentrating only on the myriad details may reveal volumes about those details but little about the functioning of the entire rain forest. How can we even begin to unravel such complexity, to tell the story of this place, or any natural habitat? A good place to start is with two E-words: *ecology* and *evolution*.

Ecology and evolution are flip sides of the same coin. Ecology provides a description of the complex relationships connecting all organisms and their environments. Evolution is organic change through time, encompassing the full range of biological processes that have generated the wondrous living world. These two themes are inseparable. Without evolution, ecology becomes largely a description of relationships, limited by its lack of time depth. Attempting to comprehend an ecosystem without the perspective of evolution is like trying to understand a person without knowing anything of his or her life experiences. Similarly, without ecology the processes and effects of evolution cannot truly be envisioned, because evolution occurs on the stage of the ecological theater.

From the narrow time-slice perspective of ecology, the Ranomafana rain forest (indeed, any ecosystem) is an interwoven collection of relationships, with all the players necessary to keep energy flowing and nutrients cycling. At the base of the food web are producers—from ferns to giant tropical hardwoods—that create their own food by harnessing the sun's energy. Much of this energy escapes into the environment as latent heat, keeping the forest cool and causing the abundant formation of clouds. Yet enough energy is passed on to multiple levels of consumers to keep the system in motion. First are the primary consumers—including various insects, birds, and lemurs—that feed on the plants. The primary consumers in turn are consumed by a range of carnivores, some of which rise to still higher levels by feeding on other carnivores. In the Ranomafana rain forest, these secondary consumers include spiders, snakes, chameleons, and birds. Largest of the carnivores here is a strange, lemur-eating mongoose relative called a fossa (pronounced FOO-sa), that looks like an unfortunate cross between a dachshund and a bobcat. Finally, the energy cycle is completed by a diversity of decomposers, or detritus feeders—mostly insects, bacteria, and other tiny dwellers of the forest floor—that convert wastes and dead organisms into chemicals useable by the next generation of producers. Together this multilevel web of interactions is self-regulated by various feedback loops.

Such an intricate, interwoven biological fabric did not simply pop into existence tens, hundreds, or even thousands of years ago. From an evolutionary perspective, Ranomafana resulted from millions upon millions of years of unique historical events driven in large part by coevolution—the mutual influence of species on one another. Even a modest comprehension of this amazing place requires that one consider the biological dramas unfolding through time. Many bacteria are little changed from those that have inhabited this planet for billions of years. Other, more recent microbial forms are highly specialized, forming intimate, mutualistic relationships with one or more species. The hardwood trees and varied forms of insects trace their heritage as major groups to lifeforms that struggled onto land about 400 million years ago. The leaf-tailed gecko is descended from a long line of egg-laying lizards, which branched off from other vertebrates on the order of 300 million years ago. The birds owe their existence to a small, feathered dinosaur that first took flight perhaps 160 million years ago. Much of the rain forest vegetation shares common ancestry within the ANGIOSPERMS (flowering plants), which first appeared alongside the dinosaurs about 125 million years ago and subsequently exploded into global floral dominance. The lemurs, in contrast, only spawned from primitive primate stock sometime around 60 million years ago. Finally, the true newcomers are humans, primate descendants of hominid forebears that stood up on their hind legs and split from the great ape lineage 7–9 million years ago in nearby Africa, though these descendants did not arrive on the island until about 2,000 years ago. Importantly, all of these organisms share a common ancestor in the even more remote past.

So let's return to the question of the origins of Madagascar's unique biota, existing in splendid isolation in the southern Indian Ocean. David Krause's project, focused on the Late Cretaceous, has yielded important clues regarding how animal lineages first arrived on the island. Nine successful field seasons to date have uncovered a treasure trove of vertebrate fossils. The ancient booty includes not only dinosaurs but fishes, frogs, lizards, snakes, turtles, crocodiles, birds, and mammals. In addition to the dome-headed top theropod *Majungasaurus*, we have unearthed remains of a small buck-toothed predator called *Masiakasaurus* that I will introduce in chapter 3. *Rahonavis* was a raven-sized, sickle-clawed predator with feathers that was either a bird or a small nonavian dinosaur akin to *Velociraptor*. Other than fragments of turtle shell, the most common finds around Berivotra are those of long-necked sauropod giants like *Rapetosaurus*. The crocodiles are unusually diverse here, with seven distinct species discovered to date. Strangest of the crocs is *Simosuchus*; with a short, rounded nose and simple, blunted, leaf-shaped teeth, this pug-nosed animal looks more like an aberrant vegetarian bulldog than any meat-loving crocodilian. This wealth of fossil evidence demonstrates that the bizarre Late Cretaceous inhabitants of Madagascar were worthy predecessors of their modern-day and recently extinct counterparts. Remarkably, all of the animals that can be confidently identified represent species that occur only on the Great Red Island, with the great majority of these being new to science.

But what of the many other ecosystem components, such as plants, bacteria, and insects? Paleontologists are forever limited by the fact that the fossil record is restricted largely to the remains of hard parts such as bones, teeth, and shells. We have no fossilized insects, though their presence is confirmed by numerous bored holes and gouges present on many of the dinosaur bones. Nor is there any direct evidence of bacteria, though we can be certain they were ubiquitous. Even our knowledge of the vertebrates from this habitat