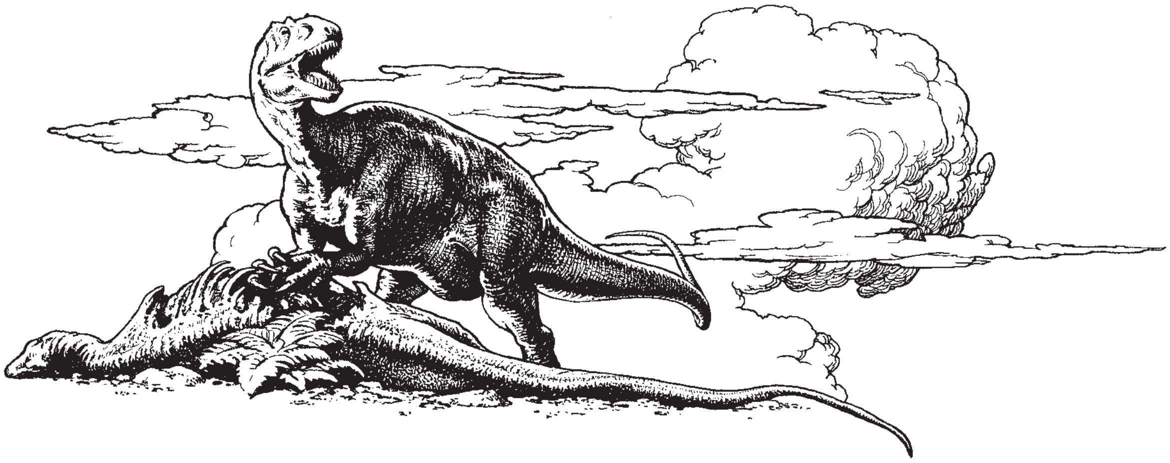
PART I

Setting the stage

CHAPTER 1

Introduction



We live in dinosaur-crazy times. We watch dinosaur sit-coms and soap operas; we endure "Barney"; we absorb dinosaur documentaries on dinosaur extinctions, dinosaur descendants, dinosaur habits, and all else dinosaurian. We have thrice feasted on the *Jurassic Park* movies. Godzilla – not quite a dinosaur, but then not obviously anything else either – has returned episodically since 1954. We enjoy dino toys, and savor dino candy while surfing a kaleidoscope of dino websites. There are coloring books, erasers, stick-ons, refrigerator magnets, wooden and plastic models, pen covers, clothes … and we're not even discussing the dino paraphernalia available in museum gift shops. Tabloids fill us with the latest dinosaur "research," and new dinosaur books appear almost faster than we can count them. Even a few paleontologists – a profession that in previous generations was stereotyped by mild-mannered bookishness – have become minor media personalities. In this multi-media feeding frenzy of things dinosaurian, the science can become lost.

Here we attempt to present dinosaurs as professional paleontologists view the group. Because dinosaurs have been marveled over (at least by Westerners) since 1819, a good deal is known; by the same token, a 30-year-old revolution in methods of studying them has only in the past 20 years (or less) begun to overturn long-held ideas about them and their 160 million-year tenure on earth. Much of the recent media excitement is a reflection of the changes wrought in our understanding of dinosaurs. We hope that the give-and-take of scientific dialog are well recorded in these pages, for this most accurately reflects the sometimes tortuous path of scientific progress.

Scientists and scientific research are not without social context, a point that is ably made by W. T. J. Mitchell in *The Last Dinosaur*. Hence, what was compelling about dinosaurs in a culture of nationalism and manifest destiny might not be as compelling in a culture in which concern for the family and cultural diversity predominate. Still, the fact of bones and other remains exists whatever the interpretations and, although various aspects of dinosaur biology have resonated popularly at different times, the objective reality of dinosaurs and even the long-standing interpretations of their morphology and behavior are generally not at issue.[1]

The ideas presented here are not the final answer about things dinosaurian because, as we shall stress repeatedly, science is a process and not a static solution. Our field would lose its vibrancy if time and further research didn't modify what we present. These pages contain only our best call on what is known about dinosaurs, and ideas presented here will surely be modified with time. It is ironic that, although the fossil record may be written in stone, its interpretation is not.

So what follows is on one level a tale of dinosaurs: who they were, what they did, and how they did it. But on another and more significant level, it is a tale of natural history. In writing of dinosaurs, we are really developing a much fuller concept of the biosphere. Commonly we think of the biosphere as occurring only in the present; a kind of three-dimensional organismal insulation wrapping the globe. But in fact the biosphere has a 3.8 billion-year history, and we and all the organisms around us are products of that fourth dimension: its history. The history of life is a grand pageant and to be unaware of it is to be unaware of who we are. Part of our goal in this book, therefore, is to explore the relationships of organisms to each other and to the biosphere. Historically, humanity has maintained a distorted sense of its position in the biosphere; with wilderness ever-diminishing, we would do well to refine (or even redefine) our understanding of our relationship to the earth and its inhabitants. Dinosaurs have some significant information to impart in this regard; as we learn who dinosaurs really are, we can better understand who *we* really are.

Finally, ours is a tale of science, itself: we live in an increasingly technical world, and we can no longer afford to ignore science and the way it impinges on lives. But science is often poorly understood. One of us remembers a song from the hopeful post-World War II days when it truly seemed that technology could solve all the world's problems:

> It's a Scientific Fact – A Scientific Fact!
> It has to be Correct! It has to be Exact!
> Because it is, because it is a Sci-en-ti-fic Fact![2]

---

1 The issue of the reality of dinosaurs and dinosaur biology (as opposed to their being social constructs) is addressed in detail by K. M. Parsons in his book, *Drawing Out Leviathan: Dinosaurs and the Science Wars*.

2 From the 1959 children's record *Space Songs* by H. Zarett.

If science were as it is portrayed in *Space Songs*, neither of us would have become scientists, either by disposition or by inclination. Science is essentially a creative enterprise requiring, depending upon the problem, approximately equal parts intuition and art. In the following pages, therefore, we hope to build a sense of the beauty of science and a feel for the meaning of scientific observation.

Like any other discipline, paleontology can be mastered only in a stepwise fashion. It has its own language and its own concepts, quite apart from the related disciplines of geology and biology. So, although our book is written as a series of individual essays on selected topics relating to dinosaurs, the development of concepts and ideas is sequential, and each chapter builds upon the previous ones.

The word "dinosaur" in this book

The term "dinosaur" (*deinos* – terrible; *sauros* – lizard) was established in 1842 by the English anatomist Sir Richard Owen to describe a few fossil bones of large, extinct "reptiles." With modifications (e.g., "large" no longer applies to all members of the group), the name proved resilient. It has become clear in the past 10 years, however, that not all dinosaurs are extinct; most vertebrate paleontologists now agree that *birds are living dinosaurs*. This leaves us with a problem, because much of what we will discuss concerns non-avian dinosaurs; that is all dinosaurs *except* birds. We could use the cumbersome, but technically correct, term "non-avian dinosaurs," but it would be far easier if the term "dinosaurs" is used as a kind of shorthand for "non-avian dinosaurs." The distinction between non-avian dinosaurs and all dinosaurs will be most relevant only when we discuss the origin of birds and their early evolution in Chapters 13 and 14; there, we will take care to avoid confusing terminology.

Fossils

That we even know that there ever were such creatures as dinosaurs is due to plain luck: some members of the group just happened to be preserved in rocks. Exactly what is preserved and how that occurs provides insight into the kinds of information we can expect to learn about these extinct beasts. Dinosaurs last romped on earth 65 million years ago. This means that their soft tissues – muscles, blood vessels, organs, skin, fatty layers, etc. – are long gone. If any vestige remains at all, it is usually hard parts such as bones and teeth. Hard parts are not as easily degraded as the soft tissues that constitute most of the body. Obviously the kinds of change that organic remains can undergo are of great interest to us as paleontologists. The study of those changes, and in fact the study of all of what happens to organisms after death, is called taphonomy.

Taphonomy is extremely important because, by looking at a group of fossils and the sedimentary rocks in which they are encased, we can learn something about the deaths (and lives) of the animals represented. Because all dinosaurs were land-dwelling vertebrates, our primary interest will be in the taphonomic changes that occur in terrestrial settings. Such settings generally consist of deserts, wetlands and lakes, river systems (channels as well as floodplains), and, to a lesser extent, deltas. Each of these settings is an environment in which bones can be preserved.

Taphonomy

Before burial

Consider what happens to a dinosaur – or any land-dwelling vertebrate – when it dies. If it is killed, it can be disarticulated (dismembered), first by the animal that killed it, and then by scavengers. In modern environments, the best known of these scavengers are vultures or hyenas, but there are smaller animals of far greater significance, such as scarily efficient carrion-eating dermestid beetles. Of course most of the heavy lifting in the world of decomposition is done by bacteria that feast on rotting flesh (leaving no doubt that something died). The bones are commonly stripped clean of meat and occasionally left to bleach in the sun. Some bones might get carried off and gnawed somewhere else. Sometimes the disarticulated remains are trampled by herds of animals, breaking and separating them further. The more delicate the bones, the more likely they are to be destroyed. So there sit the sum of all the earthly remains of the animal: a few disarticulated bleached bones lying in the grass.

If the animal isn't killed by some predator but just dies (old age, drowning, and disease all qualify) it may or may not be disarticulated immediately, depending upon which scavengers get to it and when (Figure 1.1). Left intact, it is not uncommon for a carcass to swell up (bacterial decomposition produces gasses that inflate it), eventually deflate (sometimes catastrophically: this can be just a tad grotesque), and then dry out (if not in water), leaving bones, tissues, ligaments, tendons, and skin hard and inflexible. The tissues shrink as they dry, bending the limbs and pulling back the head and lips into a hideous rictus (producing the illusion that the animal died in agony). Under such conditions, the creature is essentially mummified, and the carcass can be exposed for a very long time without further decomposition. Then we get "jerky": dried meat that resists decomposition. Later in this book, we will encounter genuine dino jerky.

Occasionally catastrophic things happen to herding animals. Floods catch herds as they cross swollen rivers and there are mass drownings. The carcasses may bloat and float, eventually to pile up along the edge of a channel, wash up onto a floodplain, or accumulate on the surface of a point bar at bends in the waterway. Left alone, the bones may be stripped, partially disarticulated, and bleach in piles of semi-articulated skeletons of one type of animal.

Burial

Sooner or later bones become either destroyed or buried. If they aren't turned into somebody's lunch, destruction can come from weathering; eventually, the minerals in the bones break down and the bones disintegrate. But the game becomes interesting for paleontologists when

Figure 1.1. A wildebeest carcass, partly submerged in mud and water and on its way to becoming permanently buried and fossilized. If the bones are not protected from scavengers, air, and sunlight, they decompose rapidly and are gone in 10–15 years. Bones destined to become high-quality fossils must be buried soon after the death of the animal. (Photograph courtesy of A. K. Behrensmeyer.)

the bones are buried. At this point, they become fossils (the bones, not the paleontologists). The word "fossil" comes from the latin word *fodere* (to bury), and refers to anything that is buried. There is no implication of how much time the remains have been buried; a dog burying a bone is technically producing a fossil. A body fossil is what is produced when a part of an organism is buried. We distinguish these from trace fossils, which are impressions in the sediment left by an organism.

Burial can take several forms. The simplest type of burial is when a bone or accumulation of bones is covered by sediment. For example, in a desert, burial might occur when a sand dune migrates over another, covering anything that was there before: desert lore resonates with mysteries of shifting sands relentlessly burying all who passed through. Equally inevitably, floodwaters also bury; ask the unhappy homeowner whose basement was silted as the waters receded. A more subtle type of deposition can occur, however, when sediments are reworked, which means that they are actively eroded from wherever they were originally deposited, and redeposited somewhere else.

Rivers are notorious reworkers. They flow, well behaved, within the confines of their channels. But in storms, they can breach their channels, flooding the landscape and eroding the edges of the channel. The eroded material from the channel margin is carried within the channel or spewed out with the floodwaters onto the floodplain. Rivers practice equal-opportunity erosion: if any buried bones are within the eroded part of the channel margin, they too will be swept along wherever the floodwaters see fit.

Here is where a paleontologist can be fooled. Seeing bones in a river channel, he or she might interpret these to be the remains of organisms that died together. But reworking concentrates fossils within the confines of the channel, and a collection of fossils in a channel is not necessarily the remnants of a community that actually lived (and died) together. Instead, it might be a reworked assemblage of bones that includes fossils eroded out of a much older floodplain, mixed with material of the same age as the channel. In the upper Great Plains of North America, 65 million-year-old dinosaur bones have been found jumbled with deposits of 10,000-year-old bison bones: as glaciers melted 10 thousand or so years ago, stream channels of glacial meltwater eroded 65 million-year-old floodplain sediments and mixed the bones of Mesozoic dinosaurs and ice-age mammals.

So paleontological work is not just digging up old bones. We want to know how the bones got the way in which we find them, because that may tell us something of how dinosaurs lived. Different types of concentration of bones can come about through different processes (or can be explained by different scenarios). When the bones are articulated (connected), this suggests that they have not been transported far from where the animal died. The idea here is that none of the destructive forces we described above has had much effect on the fossils that we have found. On the other hand, if we find a collection of disarticulated bones of several types of vertebrates, we can be fairly sure that the deposit has been reworked, and that the bones got there through sedimentary processes sometime after death and initial burial. Then there are the bonebeds: accumulations of bones of many individuals of a very few *kinds* of organism, sometimes articulated and sometimes not. A bonebed with one or two species may represent a herd subjected to a catastrophic event; alternatively, if we could determine that the bonebed accumulated over a long period of time, then it might simply represent a location where many animals of the same type chose to live (and die). Finally, isolated finds – a thigh bone here or a vertebra there – could represent almost any of the possibilities that we described above. In Figure 1.2, two taphonomic sequences, leading to two different results, are shown.

After burial

Bone is made out of calcium (sodium) hydroxyapatite, a mineral that is not stable at temperatures and pressures at or near the surface of the earth. This means that bones can change with time, which in turn means that most no longer have original bone matter present after fossilization.

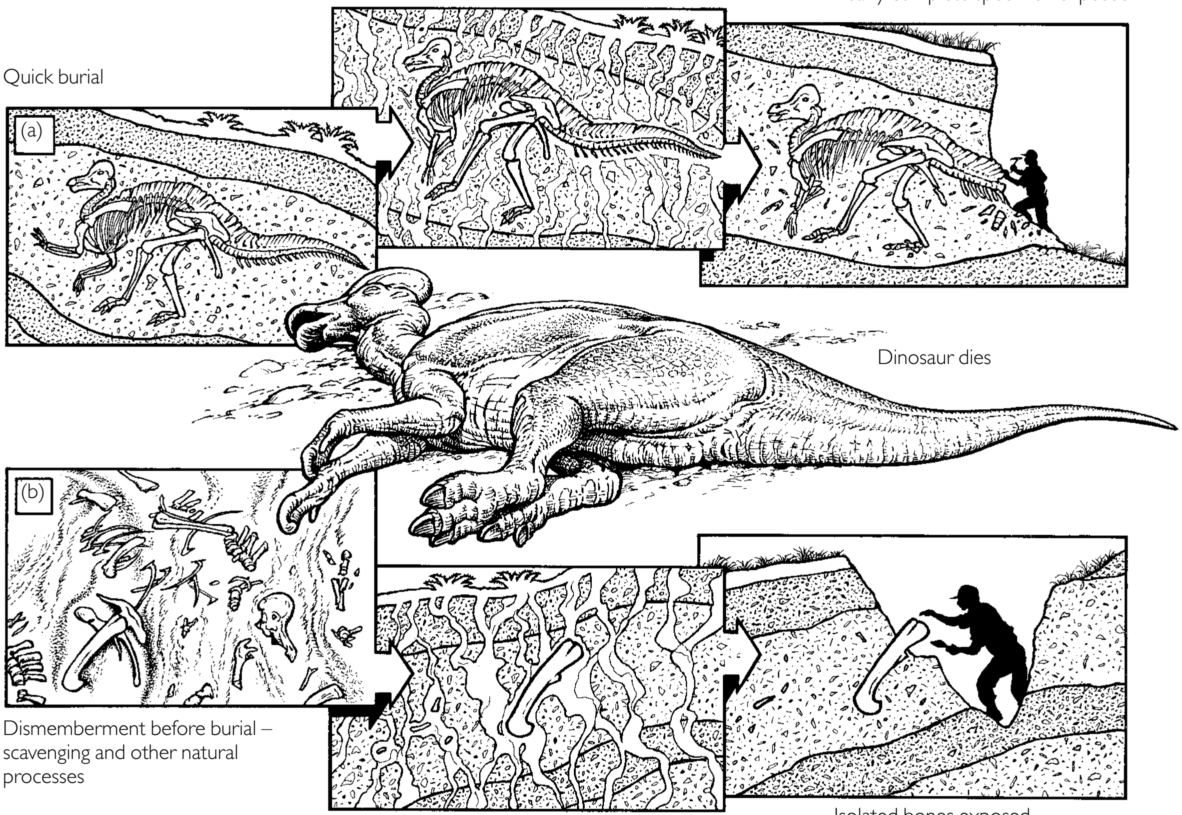


Figure 1.2. Two endpoint processes of fossilization. In both cases, the first step is the death of the animal. Some decomposition occurs at the surface. In the upper sequence (a), the animal dies, the carcass undergoes quick burial, followed by bacterial decomposition underground, and permineralization and/or replacement. Finally, perhaps millions of years later, exposure. Under these conditions, when the fossil is exhumed, it is largely complete and the bones articulated. This kind of preservation yields bones in the best condition. In the lower sequence (b), the carcass is dismembered on the surface by scavengers and perhaps trampled and distributed over the region by these organisms. It may then be carried or washed into a river channel and buried, replaced and/or permineralized, eventually to be finally exposed perhaps millions of years later. Under these conditions, when the fossil is exhumed, it is disarticulated, fragmented, and the fossil bones may show water wear and/or the gnaw marks of ancient scavengers. Different conditions of fossil preservation tell us something about what happened to the animals after death.

This is especially likely if the bone is bathed in the variety of fluids that is associated with burial in the earth (e.g., ground water). If, however, no fluids are present throughout the history of burial (from the moment that the bone is buried, to when it is exhumed by paleontologists, a time interval that could be measured in millions of years), the bone could remain unaltered, which is to say that original bone mineralogy remains. This situation is not that common, and is progressively rarer in the case of older and older fossils. Unaltered bone, however, is obviously crucial for studies involving aspects of bone mineralogy (see Chapter 15); for example, the discovery of genuine red blood cells from *Tyrannosaurus* required unaltered bones.

Most bones, as we have suggested, are altered to a greater or lesser degree. Since bones are porous, the spaces in fossil bones fill up with minerals. This situation is called permineralization. More significant than permineralization is recrystallization, where the bone itself (made of hydroxyapatite) is dissolved and reprecipitated, retaining the exact original form of the fossil. Recrystallization can be very obvious – for example, when small crystals are replaced with large ones – but it can also be very subtle, and occur on a microscopic scale. Bones can also be replaced, in which case the original bone minerals are replaced with other minerals.

Nothing is simple, and, in general, fossil bones undergo a combination of replacement, permineralization, and recrystallization. The resultant fossil, therefore, is a magnificent natural forgery: chemically and texturally unlike the original bone matter, although commonly retaining its exact shape and most delicate features. Still, accept no substitutes: fossil bones tend to be much heavier (they're permineralized) than their living counterparts and are more brittle. In virtually every respect, most fossil dinosaur bone is really closer to rock than to the living inorganic and organic mix of materials that we call bone.

In general, the more quickly a bone is buried, the better the chance it has of being preserved. This is because quick burial generally inhibits the weathering processes that would normally break down the bone minerals.[3] In fact, it is not uncommon to find evidence of weathering *before* fossilization. For example, dinosaur bones that appear to have been transported in water show water-wear that is exactly the same as those found in modern bones that have been transported by water: they are rounded and commonly the surface of the bone is partly or completely worn off. In the case of such dinosaur bones, the bone was transported by flowing water shortly after the animal was alive and was buried waterworn. The resultant fossil perfectly preserves the water-wear.

So if the fossils are buried, how is it that we find them? The answer is really luck: if fossil-bearing sedimentary rocks happen to be eroded, and a paleontologist happens to be looking for fossils at the moment that one is sticking out of an actively eroding sedimentary rock, the fossil *may* be observed and *may* be collected. Does this mean that great numbers of fossils lie buried within sedimentary rocks that happen not to be eroding at the earth's surface? Undoubtedly. Have fossils been eroding out of rocks since the very first fossil was formed? No question. Are important fossils currently eroding that will never be collected? No doubt.

3 An exception to this is when a bone ends up buried in an active soil; under certain conditions, the bone is then destroyed by biotic and abiotic soil processes.