Plants invaded the land

It is difficult to imagine how the landscape looked in Precambrian and early Paleozoic times, before terrestrial plants became widespread. Moist terrestrial environments must have been populated by algae, cyanobacteria, and fungi, but forests and meadows were absent, and there must have been large areas of barren rock and soil with little or no humus (decayed organic matter). Thus one of the most important events revealed by the fossil record of Silurian and Devonian life was the invasion of terrestrial habitats by plants.

The basic requirements for the terrestrial existence of large multicellular plants are quite different from those for plants that live in water. Unlike water, air is much less dense than the tissues of a plant, so if a plant is to stand upright in air, it must have a rigid stalk or stem. A tall plant must also be anchored by a root system or a buried horizontal stem, either of which serves the further indispensable function of collecting water and nutrients from the soil.

The first upright plants to make their way onto land lacked the roots, leaves, and efficient means of transporting nutrients that made their descendants so successful. Essentially, these plants were simple rigid stems. Fragments of such early plants have been found in Silurian rocks. Silurian plants seem to have been pioneers that lived near bodies of water, and they may actually have been semiaquatic marsh dwellers rather than fully terrestrial plants.

Animals moved ashore

Fragmentary remains of simple terrestrial animals are known from Late Silurian rocks, but few animals occupied terrestrial habitats before Devonian time. It is not surprising that animals colonized terrestrial habitats in large numbers only after vascular plants were well established because a food web must be built upward from the base; herbivores require plant food.

Assemblages of early terrestrial invertebrate animals are well preserved in the Lower Devonian Rhynie Chert of Scotland, in the Middle Devonian Gilboa Formation of northern New York State, and in the Lower Devonian Battery Point Formation of Quebec. The invertebrate fossils of these formations fall into two ecological categories. First, there are millipedes and flightless insects that fed on organic detritus. Second, there are scorpions, centipedes, and spiders—all of which were carnivores. Conspicuous in their absence are herbivores, such as leaf-eating or juice-sucking insects. Thus we can see that dead plant material, not living plant tissue, provided the nutritional foundation for the earliest terrestrial animal communities.

Not until Devonian time did vertebrate animals make their transition onto land. Anatomical evidence indicates that the four-legged vertebrates most closely related to fishes are the **amphibians**—frogs, toads, salamanders, and their relatives (see p. 75). In fact, amphibians lay their eggs in water and spend their juvenile period there. Then most kinds of amphibians metamorphose into air-breathing, land-dwelling adults. Living amphibians are small animals that differ substantially from the large fossil amphibians found in Paleozoic rocks.

As we have seen, some early fishes possessed a lung long before amphibians evolved. They put this organ to use to breathe air occasionally, perhaps when a stream or lake dried up, but it was available for full-time exploitation by animals that moved onto land. This is yet another example of the "opportunism" of evolution. Unlike the gill supports that evolved into jaws earlier in vertebrate evolution, the lung required very little evolutionary modification to open up an entirely new mode of life.

For decades paleontologists recognized that certain Devonian lobe-finned fishes possessed traits resembling those of amphibians: unusual, complex tooth structures, for example (Figure 14-18). Nonetheless, there were no known fossils of forms representing early stages of the transition to life on land. Then, in 2004, a group of paleontologists discovered the fossil remains of a creature that was actually intermediate between lobe-finned fishes and amphibians in its overall body form. The scientists had been searching for the remains of such a transitional animal in Late Devonian meandering river deposits on Ellesmere Island in northern Canada—and, quite remarkably, they found them! This creature, to which they gave the generic name *Tiktaalik*, had fishlike fins and scales as well as a fishlike lower jaw. But it also had many amphibian-like traits: well-developed toe bones in its front fins, for example, and flexible wrist bones (Figure 14-19). It did not have toes, however, and probably could not have walked effectively on land. Nonetheless, its limb structures would have permitted it to prop up its body and thus to stand in shallow water with the upper part of its head above the surface. In this position, its flat crocodile-like head, with eyes on the upper surface, would have permitted it to view its surroundings. Also useful for this activity would have been its flexible neck: its shoulder bones, unlike those of fishes, were not locked into its skull. In fact, *Tiktaalik* is the earliest animal known to have possessed a flexible neck. Nostril-like apertures on top of its skull would have permitted it to breathe with its eyes just above the surface of the water. Thus, like the lobe-finned fishes from which it evolved, it apparently had lungs like those of amphibians for respiration in air as well as gills like those of fishes for respiration in water. In morphological terms, at least, *Tiktaalik* is a "missing link," or rather, it is a link that is no longer missing from the fossil record. It documents the pathway by which vertebrates invaded land.

The Amniotic Egg

Living amphibians differ from living amniotes in several characters of the skeleton that can be recognized in fossils, and in other characters that affect the soft parts and cannot be recognized in fossils. The major soft-part character of living amniotes is that they have eggs surrounded by a membrane, rather than the little jelly-covered eggs of fishes and amphibians. This fundamental difference in biology needs special attention because it was so important in the evolution of tetrapods into entirely terrestrial habitats.

How did the amniotic egg evolve, and who evolved it? (Perhaps the earliest amniotes laid amphibian-style eggs, and the amniotic egg evolved later in the lineage. Perhaps some early tetrapods laid amniotic eggs before the common ancestor of living amniotes appeared. This is not an easy argument to grasp at first, but only someone uneasy about the process of evolution would have any logical problem with it.)

Amphibians have successfully solved most of the problems associated with exposure to air. But their reproductive system was and is linked to water, and it remains very fish-like. Almost all amphibians spawn in water and lay a great number of small eggs that hatch quickly into swimming

Creatures that took to the air Late in the Triassic Period, vertebrate animals invaded the air for the first time as the **pterosaurs** came into being (Figure 16-20). These animals had long wings and hollow bones that served to facilitate flight. Some species had long tails as well. The structure of pterosaur skeletons reveals their capacity for flight, but the great length of their wings suggests that most species flapped their wings primarily when taking off and then, once airborne, soared on air currents with little wing movement. The behavior of pterosaurs when not in flight has been widely debated. Most species appear to have been able to walk and also to climb adeptly with the aid of hooklike claws.

Until recently, birds were thought to have arisen near the end of the Jurassic. The first clue to their existence then was a feather discovered in 1861 in the fine-grained Solnhofen Limestone of Germany, followed a few months later by the discovery of an entire skeleton of the species to which the feather belonged (Figure 16-21). This feathered animal was given the name *Archaeopteryx*, which means "ancient wing." It was long considered a classic missing link—in this case, the link between birds and their flightless ancestors.

The teeth, large tail, and clawed forelimbs of *Archaeopteryx*, which are absent from modern birds, are dinosaurian features. In fact, *Archaeopteryx* had a skeleton so much like that of a dinosaur that it would always have been regarded as one were it not for its birdlike plumage. Since late in the twentieth century, numerous extremely well-preserved dinosaurs with feathers have been found (see Earth System Shift 16-1), so the feathers of *Archaeopteryx* are not evidence that it was a bird. In fact, *Archaeopteryx* has recently been ousted from its exalted position as the oldest bird. New studies of the anatomies of *Archaeopteryx* and other similar genera, including *Anchiornis* (see Earth System Shift 16-1), indicate that these forms were not early birds, or even ancestors of birds. They were simply a group of small, feathered dinosaurs. They lacked a birdlike bill; instead, like reptiles, they possessed teeth for grasping food. They also lacked a breastbone and therefore had only weak breast muscles, which probably did not enable them to fly. These creatures were probably primarily gliders, swooping from trees, which they climbed with their clawed limbs. Their long, feathered tails and feathered legs probably functioned to aid them in gliding.

The oldest unquestionable birds are of Aptian (Early Cretaceous) age, having lived at least 20 million years after *Archaeopteryx*. Birds certainly evolved from small dinosaurs, which they resemble in many ways. However, because the fossil record of birds is generally poor due to their fragile hollow bones, their precise ancestry remains unknown. They must have shared not-too-distant ancestors with *Archaeopteryx*, but did not evolve from it or any of its close relatives.

K-Pg ME

Discoveries during the past few decades have established beyond a reasonable doubt that the collision of an asteroid with Earth caused the terminal Cretaceous mass extinction. The first of these discoveries, reported in 1981, was a high concentration of the rare heavy metal iridium—an *iridium anomaly*—at the stratigraphic level of the extinction. Iridium is rare in Earth's crust but is more highly concentrated in meteorites that are asteroids or fragments of asteroids. Other discoveries followed quickly (Earth System Shift 17-1).

Some geologists have favored the idea that the terminal Cretaceous mass extinction resulted not from an asteroid impact, but from the volcanic eruptions that produced the Deccan Traps of peninsular India. The Deccan Traps constitute a huge body of basalt, up to 2 kilometers (1.2 miles) thick, that occupies an area of west-central India about the size of the states of Oregon and Washington combined. They were formed when the triangular landmass that now forms peninsular India moved over a hot spot, long before it collided with Asia. It turns out, however, that the bulk of the Deccan eruptions occurred during an interval that spanned about 500,000 years and ended about 100,000 years before the time of the terminal Cretaceous crisis (66 million years ago).

An asteroid big enough to scatter the estimated amount of iridium in the worldwide spike at the K–T boundary may have been about 10 km (6 miles) across. Computer models suggest that if such an asteroid collided with Earth, it would pass through the atmosphere and ocean almost as if they were not there and blast a crater in the crust about 100 km across. The iridium and the smallest pieces of debris would be spread worldwide by the impact blast, as the asteroid and a massive amount of crust vaporized into a fireball.

The K–T impact crater has been found. It is a roughly egg-shaped geological structure called **Chicxulub**, deeply buried under the sediments of the Yucatán peninsula of Mexico (Fig. 16.4). The structure is about 180 km across, one of the largest impact structures so far identified with

Opinions have varied as to how the impact of an asteroid 10 kilometers in diameter would disturb environments on Earth. Here are some consequences that many scientists have attributed to the Chicxulub impact:

1. *Perpetual night.* Dust particles and tiny droplets of liquid called aerosols would have been blown high into the atmosphere and spread around the world, screening out nearly all sunlight. Many of these particles would have remained aloft for many months, perhaps preventing plants from conducting photosynthesis.

2. *Heat from the settling microspherules.* As microspherules that were blasted into the atmosphere returned to Earth, friction caused by their descent would have produced a vast amount of heat. Calculations show that the heating would have begun quickly after the microspherules' reentry began and, for a few minutes, air temperatures at Earth's surface would have risen to the broiling temperature of an oven. Except along their margins, the oceans would have been little affected by this sudden heating because of their great volume and the high heat capacity of water.

3. *Global refrigeration.* After the sudden heating, darkening of the skies by dust and aerosols would have plunged the entire planet into cold, wintry weather for several months. Sulfate evaporites, including anhydrite (see Table 2-1), were blasted by the impact, and we know that sulfates that are emitted by volcanic eruptions and dissolved in water droplets cause climatic cooling. The same phenomenon would have contributed to the inferred terminal Cretaceous cooling, which has been termed an *impact winter*.

4. *Greenhouse warming due to release of carbon dioxide.* Longer-term global warming would have resulted from the release of CO_2 from a body of carbonate rock 3 kilometers (2 miles) thick that the asteroid penetrated. This warming would have occurred after the brief impact winter, although it would presumably have immediately strengthened the greenhouse effect and reduced the severity of the global cooling. The carbonates would have released CO_2 when they were heated and sheared at the time of impact, as happens less abruptly when limestone or dolomite is subjected to metamorphism in a mountain belt (p. 237). It is estimated that the volume of the carbonate rock thus affected by the impact was so large that the CO_2 released would have elevated the average global temperature of Earth's lower atmosphere by 7°C (13°F)—possibly even more. In fact, fossil plant leaves provide evidence of a brief but dramatic rise in

5. *Acid rain.* As already noted, some of the rocks that the asteroid penetrated in forming the Chicxulub crater were sulfate evaporites. The impact must have released oxides of sulfur from these evaporites, and the chemical reaction of these compounds with water in the atmosphere would have produced sulfurous and sulfuric acid. These compounds, along with the elevated CO_2 concentrations mentioned above, would have produced acid rain, which may have harmed many forms of life.

6. *Fires.* Wildfires would have raged across some areas of the Americas, triggered by the fiery cloud that burst from the impact site. The most severe fire damage to life should have been relatively close to the Chicxulub site.